Road Pricing with Green Vehicle Exemptions: Theory and Evidence*

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Abstract

We provide a framework for setting congestion charges that reflect emission and congestion externalities and policy responses, such as vehicle ownership, driving, and residential sorting. Using Swedish administrative microdata, we identify these responses by exploiting a temporary exemption for alternative fuel vehicles and variation in individuals' exposure to congestion charges. We find that commuters respond by adopting exempted alternative fuel vehicles, shifting trips away from fossil fuel toward alternative fuel vehicles, and changing where they live and work. We combine the estimated responses with the framework to recover an optimal congestion charge of €9.46 per crossing in Stockholm.

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I Introduction

In the simplest model of Pigouvian taxation, it is irrelevant how consumers respond to taxes. The optimal Pigouvian tax reflects marginal damages irrespective of whether the demand response comes from substitution to a related good, decreased consumption, or adoption of a new technology. In practice, however, responses to Pigouvian taxes often cause other social costs or benefits, complicating the calculation of optimal prices. Such is the case for road pricing. When cities price roads to address congestion and environmental externalities, commuters can respond in many ways. In the short run, they may reduce their vehicle trips, switch to traveling on non-tolled roads, or take public transit. In the long run, they may change where they live, or adopt clean vehicles that face lower toll rates or are toll-exempt. Some of these responses, like taking public transit, are not associated with any externalities. Other responses, like those regarding moving or vehicle purchase decisions, may alleviate or exacerbate congestion and environmental externalities outside the congestion zone.

Although it is well known that these considerations impact optimal prices, there are several shortcomings in the existing literature on this topic. First, models of second-best pricing tend to focus on a single dimension of response (Wilson, 1983; Verhoef et al., 1996). Second, data constraints make studying long-run responses to congestion pricing difficult. As a result, most existing empirical work on second-best road pricing tends to focus on problems of leakage rather than residential sorting or vehicle choice. Lastly, recent work on congestion pricing using spatial general equilibrium models can incorporate multiple dimensions of responses, but the completeness of these approaches comes at the cost of tractability.

In light of these shortcomings, this paper makes two high-level contributions to the literature on congestion pricing. First, we provide a tractable framework for recovering congestion charges that address emission and congestion externalities while accounting for the multiple dimensions of policy response. This framework decomposes optimal prices into marginal congestion and emissions damages, plus additional terms corresponding to the social costs or benefits of drivers' different types of responses to road pricing. Second, we use Swedish administrative data together with variation in exposure to Stockholm's congestion price to estimate each component required to recover optimal prices. The set of empirical results not only allows us to recover optimal congestion prices, but also describes medium and long-run responses to road prices that are new to the literature.

Our framework for recovering congestion charges builds on the vehicle decision model of Anderson and Sallee (2016) in Section II. In this model, a representative consumer chooses the size of two vehicle fleets – "brown" and "green" vehicles. The consumer also chooses how many congestion zone and non-congestion zone trips to take in each car and how far to live from work. The social planner chooses a congestion charge on brown vehicles that address local congestion and emission externalities inside and outside the congestion zone, taking into account how the congestion charge may impact the representative consumer's vehicle choice, how many trips they take, and where they choose to work.

Solving the planner's problem yields a formula for the optimal congestion charge that consists of three terms: a fleet composition term, a driving behavior term, and a commuting distance term. The first term reflects the impact of congestion pricing on emission and congestion externalities through changes in the composition and size of the vehicle fleet. The second term represents the change in the number of brown and green vehicle trips inside and outside the congestion zone. The third term represents changes in drivers' average trip length, as treated commuters may either move into the congestion zone or relocate to workplaces outside the congestion zone to avoid the congestion charge.

In Section III, we describe our strategy for empirically estimating the responses stipulated by our model. In August 2007, Stockholm imposed a congestion charge on vehicles entering or exiting the city center. Alternative fuel vehicles purchased during the first 18 months of the policy were exempted from tolls through August 2012. We merge several Swedish administrative data sets that combine socioeconomic information with all vehicle ownership records. We supplement this data with information about the location of the residence and workplace, the road network, and the location of toll gates. This allows us to identify the toll payments faced by each individual when traveling between home and work and to study how these tolls and exemptions impacted commuters' decisions.

Our empirical design exploits the fact that two congested motorways (*Essinge bypass* and *Lidingö route*) were exempted from the congestion charges. To identify the causal effects of the policy, we construct a differences-in-differences design that compares the vehicle ownership, driving behavior, and location choices by individuals exposed to tolls on the road between home and work (*treated commuters*) to exempted commuters (*non-treated commuters*).

In Section IV, we show that individuals respond to the congestion charge by adopting alternative fuel vehicles, taking fewer trips into the congestion zone, and moving. Individuals exposed to the congestion charge on their commute are .64 percentage points more likely to own an alternative fuel vehicle and .83 percentage points less likely to own a fossil fuel vehicle. Although the congestion charge led to a shift from fossil fuel vehicles to alternative fuel vehicles, the overall size of the vehicle fleet remained stable. The congestion charge resulted in an annual increase of 5.9 congestion zone trips by commuters in alternative fuel vehicles and a decrease of 11.8 congestion zone trips in fossil fuel vehicles, corresponding to an increase of 103 kilometers traveled in alternative fuel vehicles, and a decrease of 206 kilometers traveled in fossil fuel vehicles. At the same time, the congestion charge led to an annual increase of .7 non-congestion zone trips in alternative fuel vehicles and a reduction of 2 non-congestion zone trips in fossil fuel vehicles. Finally, we show that treated commuters are .2 percentage points more likely to move into the congestion zone and 1.6 percentage points more likely to relocate to workplaces outside the congestion zone, either to a new office or company, to avoid paying the congestion charges. This decreased the average commuting distance inside and outside congestion zone trips for treated commuters by approximately .086 and .007 kilometers, respectively.

Although we focus on a model of a representative commuter when calculating optimal charges, an advantage of our administrative data is that it allows for heterogeneity analyses that speak directly to debates about congestion prices that vary by observable characteristics. High-income individuals adopt alternative fuel vehicles in response to the policy, whereas middle-income individuals primarily reduce their vehicle kilometers traveled and switch to other modes of transportation. Individuals with low incomes continue to drive fossil fuel cars, indicating that they may be more reliant on existing commuting patterns or are financially constrained. We also find that the effects on alternative fuel adoption and usage are larger for young, university-educated couples with shorter commutes. Finally, we document that young individuals without children and short commutes reduce the distance between the residences and the workplace in response to the congestion charge.

In Section V, we use our empirical results together with our optimal tax framework to estimate optimal congestion prices from Stockholm's congestion zone. In our baseline specification, the congestion fee equals €9.46 per congestion zone crossing. Decomposing this optimal charge into its components, 67 percent of the optimal charge reflects changes in trip-taking, 22 percent reflects net changes in the vehicle fleet, and 11 percent reflects changes in commuting distances. Across these components, the social benefits associated with changes in congestion are larger than the social benefits associated with changes in emissions: congestion-related terms account for €8.39 of the total charge, while emissions-related terms account for just €1.07.

While the focus of this paper is to estimate optimal congestion charges with green vehicle exemptions, our results allow us to conduct a simple cost-benefit analysis of achieving green vehicle adoption via exemptions. Inducing the adoption of single exempted green vehicles incurs an annual cost of €759 in congestion externalities or €3,795 over the five-year exemption period. We estimate that the emission benefits from exempting green cars from congestion charges are equal to €608 per year, which is below the congestion-related cost of exempting these vehicles. Importantly, this cost-benefit ratio depends on the size of the existing green vehicle fleet. Conditional on the amount of adoption induced by an exemption, the larger the size of the existing green vehicle fleet, the higher the cost of green vehicle exemptions. Therefore, congestion pricing exemptions may be an attractive way of inducing adoption in nascent electric vehicle markets, but the costs of these exemptions may outweigh the benefits in mature electric vehicle markets.

Our theoretical framework connects two literature strands: optimal tax theory and congestion pricing. While congestion pricing is commonly viewed as a straightforward application of the Pigouvian principle, several papers have noted that congestion pricing is frequently second-best, requiring empirical estimates of tax elasticities (Mun et al., 2003; Verhoef, 2005).[1] We extend the characterization of second-best congestion prices to account for the effect of the congestion charge on the composition and usage of the fleet, commuting distances, and the dual challenge of emission and congestion externalities.[2] Specifically, our derivation of congestion charges that factor in responses to the policy enables us to highlight trade-offs between road pricing policies and environmental objectives. A key contribution of our theoretical work is that it delivers formulas for congestion charges as a function of sufficient statistics that can be estimated in various empirical applications.

In addition to contributing to optimal tax theory, our work connects to the empirical literature on the responses to second-best road pricing policies. These studies find that congestion charges significantly reduced traffic in Singapore (Phang & Toh, 1997; Olszewski & Xie, 2005), London (Santos et al., 2004; Santos & Shaffer, 2004), Stockholm (Eliasson, 2009; Börjesson et al., 2012), Gothenburg (Börjesson & Kristoffersson, 2015), and Milan (Gibson & Carnovale, 2015; Beria, 2016) and commuters shift driving to non-rush hours in response to time-varying tolls (Foreman, 2016; Small & Gómez-Ibáñez, 1997).[3] Whereas previous papers measure the impact of congestion charges on total traffic volume measured at toll stations and vehicle ownership on the zip code, our data set on driving behavior and vehicle adoption paired with an identification strategy that exploits individual-level variation in exposure to the congestion charges on people's way to work allows us to establish four ways in which individuals adapt to the congestion charge: (i.) adopt exempted alternative fuel vehicles, (ii.) reduce annual vehicle kilometers traveled in fossil fuel vehicles or change mode

[1]We build on an extensive theoretical literature analyzing second-best road pricing (Vickrey, 1963; Small, 1982; Arnott et al., 1993; Hall, 2018, 2021; Kreindler, 2023).

[2]This relates to a significant body of research on the optimal policy design that encompasses various consumer responses. Prominent examples include social reputation (Benabou & Tirole, 2011), salience (Chetty et al., 2009), inattention (Farhi & Gabaix, 2020), social norms (Allcott, 2011), and non-standard decision-making (Bernheim & Taubinsky, 2018).

[3]Our paper relates to the empirical literature on the effects of road pricing policies on air pollution. Previous studies have shown that low emission zones, road tolls, and congestion charges can help improve urban air quality (Wolff, 2014; Gibson & Carnovale, 2015; Fu & Gu, 2017; Gehrsitz, 2017; Pestel & Wozny, 2019), reduce asthma rates in children (Simeonova et al., 2021), and lower infant mortality (Currie & Walker, 2011).

of transportation, (iii.) move into the congestion zone, and (iv.) relocate to workplaces outside the congestion zone. This paper is the first to examine the impact of congestion charges on individual-level driving behavior, vehicle acquisitions, moving decisions, and workplace relocations.[4]

II Deriving the optimal congestion charge

This section presents a stylized model of the urban personal transportation sector. The goal of this model is to describe the externalities and margins of choice that are relevant when setting congestion prices.

II.A Model of urban travel

Our model of driver behavior builds on Anderson and Sallee (2016) and aims to capture how congestion charges impact consumers' vehicle purchase, driving, and commuting decisions. We first solve a model of the representative consumer's behavior, and then use the first-order conditions from the consumer's problem to write the congestion charge in terms of policy responses.

1. *The consumer's problem.* Our model describes a representative agent who makes choices over the vehicle fleet size, the number of trips taken, and the distance between work and home. The agent makes these choices given an exogenous income and faces prices of vehicles, fuel, travel time, moving, and congestion tolls.

In more detail, the representative consumer derives utility from trips (t), which can be completed with brown (subscript b) or green vehicles (subscript g). n_g and n_b are the number of green and brown vehicles, respectively. There are two kinds of trips: cordon (superscript c) and outside cordon (superscript o) trips. Because drivers may substitute their trips to unpriced roads (i.e., "leakage"), we distinguish between trips occurring within congestion zones and those outside them to allocate congestion externalities to the appropriate locations.[5] In all expressions, congestion zone-specific details are shown as superscripts, while characteristics specific to the type of vehicle are shown as subscripts. t_c^b, for example, is the number of cordon trips by brown vehicles. v^c are the vehicle kilometers traveled on congestion zone

[4]We establish road pricing policies as an essential policy tool in promoting the adoption and usage of environmentally friendly vehicles and contribute to the existing literature on the adoption of such vehicles, which focuses primarily on the effects of vehicle subsidies (Muehlegger & Rapson, 2018; Clinton & Steinberg, 2019), charging infrastructure (Li et al., 2017; Springel, 2021), and low emission zones (Wolff, 2014).

[5]Tarduno (2022) documents that drivers substitute to non-tolled roads as a response to the bridge tolls in San Fransisco.

trips, and v^o are the vehicle kilometers traveled on non-congestion zone trips. v is not exogenous and reflects where people choose to live and work. The agent can adjust the length of congestion or non-congestion zone trips, but there are costs r associated with either type of adjustment.[6] The cost of each type of vehicle are c_b and c_g, respectively. l is the vehicle fuel efficiency of the respective vehicle type, and y is the representative consumer's exogenous income. p_g and p_b are the fuel cost of green and brown vehicles. The per-kilometer costs of driving (time cost) for each kind of trip are p^c and p^o, respectively.

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.[7] We assume that the representative consumer has a quasi-linear utility in transportation services and other goods such that welfare is given by the following equation:[8]

$$
\begin{aligned}
\max_{n_g,n_b,t_g^c,t_g^o,t_b^c,t_b^o,v^c,v^o} B \;=\; & \underbrace{\mu_g(n_g)[u_g^c(t_g^c)+u_g^o(t_g^o)]}_{\text{utility from green trips}} - \underbrace{n_g(p^c+p_g l_g)v^c t_g^c - n_g(p^o+p_g l_g)v^o t_g^o}_{\text{utility cost of green trips}} \\
& + \underbrace{\mu_b(n_b)[u_b^c(t_b^c)+u_b^o(t_b^o)]}_{\text{utility from brown trips}} - \underbrace{n_b((p^c+p_b l_b)v^c+\tau)t_b^c - n_b(p^o+p_b l_b)v^o t_b^o}_{\text{utility cost of brown trips}} \\
& - \underbrace{n_b c_b - n_g c_g}_{\text{cost of vehicles}} - \underbrace{r^c(v^c) - r^o(v^o)}_{\text{cost of location choice}} + y \qquad (1)
\end{aligned}
$$

For each vehicle fuel type, the term $\mu(n)u(t)$ refers to utility derived from the number of trips, scaled by a function of the number of vehicles, where $\mu'(\cdot), u'(\cdot) > 0$ and $\mu''(\cdot), u''(\cdot) \leq 0$. The term nc is the total cost for n vehicles; $n_g p_g l_g(v^c t_g^c + t_g^o v^o)$ and $n_b p_b l_b(v^c t_b^c + t_b^o v^o)$ are the total fuel expenditures on green and brown vehicles. The term $n_g(p^c v^c t_g^c + p^o v^o t_g^o)$ and $n_b(p^c v^c t_b^c + p^o t_b^o v^o)$ are private cost of driving green and brown vehicles, respectively.

[6]We abstract from a full spatial sorting model for tractability. For an application of congestion pricing with a sorting model, see Barwick et al. (2021).

[7]Although our model addresses multiple key responses to congestion charges, we abstract from intertemporal substitution of commuters to non-rush hours (Foreman, 2016; Small & Gómez-Ibáñez, 1997). In addition, consumer choices may deviate from the optimization problem if they misperceive the future congestion costs when choosing their privately optimal vehicle and commuting choices. This is related to the market imperfection of fuel-economy internalities when consumers ignore external costs when choosing their privately optimal level of fuel consumption (Allcott et al., 2014; Allcott & Sunstein, 2015). Given the high salience of costs when crossing the congestion zone (Figure B2), we assume that consumers correctly internalize the congestion charges into their optimization problem. Intuitively, if consumers undervalue a dollar of future congestion charges by $\beta < 1$, the optimal congestion scales by the degree of misperception.

[8]The quasi-linear utility specification rules out income effects.

2. *The planner's problem.* The social planner's problem is to maximize consumer welfare, $B^{-\tau}$, by setting the congestion charge (τ) on brown vehicles.[9] The planner's problem is identical to that of the consumer, except that the consumer does not internalize the emission (ϕ) and congestion externalities (γ) from driving.[10] Emission externalities differ by vehicle type (i.e., ϕ_g and ϕ_b) and congestion externalities differ by location (i.e., γ^c and γ^o).[11] Accordingly, we define ϕ_g and ϕ_b as the sum of marginal emission externalities (in € per kilometer) from driving green and brown vehicles.[12]

$$\begin{aligned}\max_{\tau} W = B^{-\tau} \; - \; & \underbrace{n_b(v^c t_b^c + v^o t_b^o) l_b \phi_b}_{\text{emission from brown trips}} - \underbrace{n_g(v^c t_g^c + v^o t_g^o) l_g \phi_g}_{\text{emission from green trips}} \\ - \; & \underbrace{(n_b v^c t_b^c + n_g v^c t_g^c)\gamma^c}_{\text{congestion from inside trips}} - \underbrace{(n_b v^o t_b^o + n_g v^o t_g^o)\gamma^o}_{\text{congestion from outside trips}} \end{aligned} \tag{2}$$

The emission externalities for brown and green vehicles scale by the vehicle kilometers traveled in the respective vehicles. We do not differentiate local emissions damages for trips inside versus outside the congestion zone because the wind can transport local pollutants across the zone boundary, implying similar emission damages inside and outside the congestion zone. Congestion externalities scale by the vehicle kilometers traveled inside and outside the congestion zone, irrespective of the type of vehicle.[13] We assume no pre-existing taxes or subsidies on vehicles.

II.B Expression for the optimal congestion charge

Optimizing the social planner's welfare function and plugging in the consumer's first-order conditions yields the following proposition. All derivations are in Appendix A.1.

Proposition 1. *The second-best congestion charge τ on brown vehicles per crossing that addresses congestion and emission externalities through changes in the fleet composition, the number of trips, and the commuting distance is given by*

[9] As the revenue from the congestion charges is a transfer from the social planner's perspective, the congestion charges do not directly enter the planner's objective function.

[10] We do not include accident externalities as the social benefits from reduced accidents in congestion zones are small compared to reduced congestion and air pollution (Green et al., 2020). Simeonova et al. (2021) document that the effects of the congestion zone on visits for injuries are minor in Stockholm.

[11] To account for the substitution to non-tolled roads, the social planner separates congestion externalities by congestion and non-congestion zone trips.

[12] We assume that marginal damages are linear in vehicle kilometers traveled, consistent with the EPA's social cost of carbon calculations and research on local air pollution (Muller & Mendelsohn, 2009; Fowlie & Muller, 2019).

[13] We assume that the social planner has no redistributive motives. This implies that social marginal welfare weights are constant across high- to low-income commuters. In Section V.B, we discuss how the regressive effects of the policy influence the optimal congestion charge for different income groups.

$$
\begin{aligned}
\tau \;=\; & \frac{1}{(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b)} \Bigg(\frac{\partial n_g}{\partial \tau} \Big((v^c t_g^c + v^o t_g^o) l_g \phi_g + v^c t_g^c \gamma^c + v^o t_g^o \gamma^o \Big) \\
& + \frac{\partial n_b}{\partial \tau} \Big((v^c t_b^c + v^o t_b^o) l_b \phi_b + v^c t_b^c \gamma^c + v^o t_b^o \gamma^o \Big) \\
& + \frac{\partial t_g^o}{\partial \tau} \Big(n_g v^o (l_g \phi_g + \gamma^o) \Big) + \frac{\partial t_g^c}{\partial \tau} \Big(n_g v^c (l_g \phi_g + \gamma^c) \Big) \\
& + \frac{\partial t_b^o}{\partial \tau} \Big(n_b v^o (l_b \phi_b + \gamma^o) \Big) + \frac{\partial t_b^c}{\partial \tau} \Big(n_b v^c (l_b \phi_b + \gamma^c) \Big) \\
& + \frac{\partial v^c}{\partial \tau} \Big(n_b t_b^c l_b \phi_b + n_g t_g^c l_g \phi_g + (n_b t_b^c + n_g t_g^c) \gamma^c \Big) \\
& + \frac{\partial v^o}{\partial \tau} \Big(n_b t_b^o l_b \phi_b + n_g t_g^o l_g \phi_g + (n_b t_b^o + n_g t_b^o) \gamma^o \Big) \Bigg)
\end{aligned} \tag{3}
$$

In equation (3), the optimal congestion charge represents the responses to the policy, including fleet composition, number of trips, and commuting distance due to the congestion charge multiplied by the respective sum of congestion and emission externalities.

To build intuition, we convert the emission and congestion externalities from marginal externalities (in € per kilometer) into externalities per number of vehicles (indicated as tilde), per number of trips (indicated as bars), and per kilometer traveled (indicated as hats). In addition, we discretize the derivatives of fleet composition, the number of trips, and commuting distances with respect to the congestion charge. All conversions are documented in Appendix A.2. Assuming linearity in the response changes allows us to rearrange equation (3) as:

$$
\begin{aligned}
\tau \;=\; & \underbrace{\Delta N_g \cdot (\widetilde{\phi}_g + \widetilde{\gamma}_g) + \Delta N_b \cdot (\widetilde{\phi}_b + \widetilde{\gamma}_b)}_{\triangle Fleet\ composition} + \underbrace{\Delta T \cdot (\overline{\phi} + \overline{\gamma})}_{\triangle Trips} \\
& + \underbrace{\Delta V^c \cdot (\hat{\phi}^c + \hat{\gamma}^c) + \Delta V^o \cdot (\hat{\phi}^o + \hat{\gamma}^o)}_{\triangle Commute\ Distances},
\end{aligned} \tag{4}
$$

where ΔN_g, ΔN_g, ΔT, ΔV^c, and ΔV^o refer to discrete changes in green and brown vehicle adoption, the number of inside and outside trips of green and brown vehicles, and the commuting distance inside and outside the cordon zone scaled by the denominator in equation (3). The denominator $(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b)$ corresponds to the total trip changes inside the congestion zones in brown vehicles that come through changes in the brown vehicle fleet and the total trip changes. $\widetilde{\phi}_g + \widetilde{\gamma}_g$ and $\widetilde{\phi}_b + \widetilde{\gamma}_b$ indicate the emission and congestion externalities per green and brown vehicles (expressed in total € damages). $\overline{\phi} + \overline{\gamma}$ indicate emission and congestion externalities per trip (expressed in total € damages). $\hat{\phi}^c + \hat{\gamma}^c$ and $\hat{\phi}^o + \hat{\gamma}^o$ indicate the emission and congestion externalities per kilometer inside and outside the congestion zone (expressed in € damages per kilometer).

Equation (4) shows that the congestion charge on brown vehicles is a combination of the three responses to the policy: the fleet composition, the number of trips, and the average commuting distances. The first two terms, $\Delta N_g(\widetilde{\phi}_g + \widetilde{\gamma}_g)$ and $\Delta N_b(\widetilde{\phi}_b + \widetilde{\gamma}_b)$, correspond to the fleet composition changes and emission and congestion externalities through adopting green and brown vehicles as a response to the congestion charge. The congestion effect solely depends on the net effect on total vehicle ownership, as congestion externalities are independent of the vehicle type. The emission effect depends on how much the adoption of green vehicles crowds out the ownership of brown vehicles. The third term, $\Delta T(\overline{\phi} + \overline{\gamma})$, corresponds to the changes in emission and congestion externalities through changes in the number of trips. The congestion part scales solely with the total effect on the number of trips, while emissions depend on how people substitute driving from brown to green vehicles. Finally, the fourth and fifth terms, $\Delta V^c(\hat{\phi}^c + \hat{\gamma}^c)$ and $\Delta V^o(\hat{\phi}^o + \hat{\gamma}^o)$, correspond to changes in emission and congestion externalities caused by changes in the commuting distance inside and outside the congestion zone. Treated commuters may either move into the congestion zone or relocate to workplaces outside the congestion zone to avoid the congestion charge. The emission and congestion externalities then depend on the changes in the average commuting distance of drivers. We now estimate the impact of the congestion charge on vehicle ownership, number of trips, and commuting distance to provide an estimate for the congestion charge derived in equation (4).

1. *Special cases.* The congestion charge has several special cases that provide insight into how optimal congestion tolls reflect the consumer's different margins of response. We highlight three cases of particular interest. First, if the social planner solely cares about emission externalities ($\gamma^c = \gamma^o = 0$), the congestion charge equals the changes in emission externalities caused by the three margins of response and the emission damages from brown vehicles (equation A15). This includes "direct" changes in cordon trips taken as well as "indirect" changes in fleet size, commute distances, and outside-zone trips similar to the tax policies in Green and Sheshinski (1976) that account for externalities in markets for related goods. Second, if the social planner solely cares about congestion ($\phi_g = \phi_b = 0$), the congestion charge equals the changes in congestion externalities multiplied by the three policy responses and the congestion damages from driving brown vehicles to work (equation A16). Third, as congestion zones leave nearby roads unpriced, our model of urban transport assumes that commuters partly substitute their driving to non-tolled roads, allowing for externality leakage. If we shut down this margin of response (i.e., $\frac{\partial t^o}{\partial \tau} = 0$), we can see the

implications of trip leakage for setting optimal congestion prices. Assuming that individuals respond to the congestion price by lowering the number of trips they take into the zone and reducing the number of brown vehicles they purchase, the no-leakage tax is unambiguously larger than the tax suggested by equation (A17).

2. *Differentiated tolls.* This paper studies congestion charges that impose a uniform charge on brown vehicles while exempting green vehicles. However, it may be of interest to policymakers to know whether an optimal toll system that charges different tolls for green versus brown vehicles would have a positive or negative price on green vehicles. Proposition 2 describes the optimal type-specific toll. Because this two-toll formula requires substantially more empirical information (e.g., cross-price derivatives specific to tolling each type of vehicle), we do not bring this formula to the data. Still, Proposition 2 provides insight into when one should expect tolls on green vehicles to be positive. For example, the optimal toll on green vehicles is more likely to be positive when congestion externalities are large relative to emissions externalities or when cross-price elasticities between green and brown vehicle types are low.

II.C Comparing the emission benefits from green car adoption to foregone congestion benefits

Although our focus in this paper is to estimate the optimal congestion charge when green vehicles are exempted, our setting allows us to compare the benefits of inducing green car adoption against the foregone congestion reductions that result from exempting the green fleet. To quantify this tradeoff, we compare the cost-benefits of a charge that exempts green cars relative to a uniform congestion charge ($\tau^{uniform}$) that applies to all vehicles:

$$\underbrace{(l_b\phi_b - l_g\phi_g) \;\cdot\; (v^c t_b^c + v^o t_b^o)\frac{\partial n_g}{\partial \tau}}_{\text{marginal benefits of green cars}} \geqslant \underbrace{(n_g v^c \gamma^c)\frac{\partial t_g^c}{\partial \tau}}_{\text{foregone green congestion trips}} + \underbrace{(n_b v^c \gamma^c)\left(\frac{\partial t_b^c}{\partial \tau} - \frac{\partial t_b^c}{\partial \tau^{uniform}}\right)}_{\text{foregone brown congestion trips}} \tag{5}$$

Inequality (5) compares the emissions savings from replacing brown with green vehicle trips against the congestion benefits that the exemption foregoes (i.e., trips that would have been avoided had green vehicles been charged). These foregone congestion benefits are a lower bound on the total cost of achieving green car adoption through congestion pricing exemptions.[14] We nonetheless see this simple comparison − emissions benefits against foregone

[14] Additional costs include (i.) the marginal costs of outside congestion zone trips, (ii.) the marginal increase in the vehicle fleet size, and (iii.) the foregone incentive for green vehicle owners to sort such that

congestion benefits − as a straightforward test that can be used as input when policymakers design downtown road pricing schemes.

Specifically, we see two uses for this exercise. First, it provides an estimate of the cost of inducing green car adoption through a congestion pricing threshold. This provides a valuable point of comparison: Electric vehicle (EV) subsidies are ubiquitous but have been scrutinized as poorly targeted at marginal buyers. Although exempting EVs in road pricing systems is not a first-best approach for inducing their adoption, it may outperform the most commonly used policy tool in terms of cost-benefit. Second, note that exempting EVs is costly (in terms of foregone congestion benefits) when the existing EV fleet is large. Inequality (5) allows us to derive the cutoff for when the foregone costs from additional congestion exceed the emission benefits of EV adoption.[15] Above this market share threshold, the congestion costs of the green exemptions outweigh the emission benefits of additional green car adoption.

III Estimating responses to congestion charges

III.A Design of the congestion charge

We use the introduction of Stockholm's congestion pricing system to estimate each of the responses outlined in the previous section. Here, we provide a brief background on the congestion pricing zone and describe aspects of the policy that are key to our empirical approach.

The purpose of Stockholm's congestion pricing zone was to reduce traffic entering the central city and improve the air quality in the city center. The implementation of the congestion charge started with a seven-month trial period from January until the end of July 2006 (The Stockholm Congestion Trials*, Stockholmsförsöket*). In a referendum in September 2006, the residents of Stockholm municipality voted in favor of its permanent implementation. As a result, in October 2006, the Swedish government declared that it would permanently implement the Stockholm congestion charge, which it did in August 2007.

Figure I maps the 20 toll stations surrounding Stockholm's inner city.[16] The charging system is designed as a toll cordon around the inner city (dotted line). The congestion tax

they live closer to their workplace, thereby decreasing commute distance. Based on our empirical results in the following section, we expect the foregone congestion costs to be the largest of these three opportunity costs.

[15] This relates to the literature on the optimal trajectory of designing environmental policies (De Groote & Verboven, 2019; Newell et al., 2019; Langer & Lemoine, 2022).

[16] The Swedish Transport Agency (*Transportstyrelsen*) provides a detailed description for each toll station here: https://www.transportstyrelsen.se/sv/vagtrafik/Trangselskatt/Trangselskatt-i-stockholm/Betalstationernas-placering1/.

is charged for vehicles driven into and out of central Stockholm between 6.00 and 18.29, Mondays to Fridays. Between 2006 and 2015, the charge varied between €1.06 (SEK 10) and €2.12 (SEK 20) per passage in Stockholm,[17] depending on the time of the day (Figure B1). The charge was set to reduce car traffic across the cordon by 10 to 15 percent (Eliasson et al., 2014). Vehicles are charged in both directions when crossing the congestion zone. The tax is not charged on weekends or public holidays, on a day preceding a public holiday, or during July. The toll is automatically collected using license plate scanning technology as cars cross the perimeter of the congestion zone.

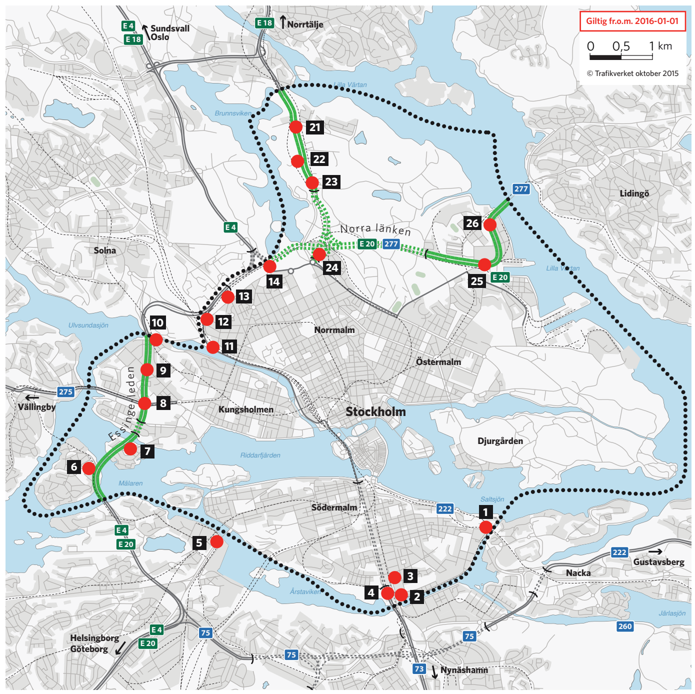


Figure I: Toll stations in Stockholm

Notes: The map shows toll stations in and around the city center of Stockholm. The red dots indicate where the control points are located. Figure B5 shows the average number of vehicles passing through each toll cordon over a day based on 30-minute intervals.

1. *Essinge bypass and Lidingö rule.* The Essinge bypass is a congested motorway west of Stockholm city center (represented by the green line in Figure I) that crosses the congestion zone. Vehicles that crossed Stockholm's city center via the Essinge bypass were exempt from the congestion fee.[18] However, vehicles that exit or enter the Essinge bypass within the congestion tax area are levied a fee (toll stations 6 to 10). In addition, all traffic to and from

[17] We convert Euros to Swedish kronor using the exchange rate from January 1, 2006 (9.42 $\frac{€}{SEK}$).

[18] The Essinge bypass is the only bridge between the south and north of Stockholm, except through the inner city. In 2006, the decision-makers believed that maintaining the bypass as the only uncharged route between southern and northern Stockholm was crucial for public acceptance.

Lidingö, an island east of Stockholm, is exempt from the congestion fee if it passes both the Ropsten payment station (26) and another payment station within 30 minutes. All vehicles that remained longer in the cordon zone were required to pay the congestion fee. The reason for the Lidingö rule was that the only connection from Lidingö municipality to the national road network runs through the inner city.

2. *Alternative fuel vehicle exemption.* In March 2007, the Ministry of Finance decided that alternative fuel vehicles (i.e., ethanol, biogas, hybrid, and electric vehicles) would be exempted from the congestion charge (Ministry of Finance, 2007).[19] The share of quarterly new registrations of alternative fuel vehicles in Stockholm increased from close to 0% in 2003 to around 40% in 2009 (Figure B3).[20] In 2006, during the congestion tax trial, only 2% of cordon boundary crossings were made by alternatively fueled vehicles. By the end of 2008, this share had increased to 14% (Börjesson et al., 2012). The incentive policy of exempting alternative fuel vehicles from the congestion tax was so successful that policymakers became concerned that the effectiveness of the congestion reduction was being weakened. As a result, the tax exemption was phased out in January 2009 for all new alternative fuel vehicles, less than 18 months after its introduction. However, the policy remained in effect for all existing alternative fuel vehicles that were already exempted until August 2012. After 2009, the exemption privileges of alternative fuel vehicles could no longer be transferred.

III.B Data sources

To construct a dataset on vehicle ownership, individual demographic characteristics, and congestion charge exposure, we combine information from several administrative sources provided by Statistics Sweden. These include the Swedish vehicle register (*Fordonsregistret*), the longitudinal integrated database for health insurance and labor market studies (*LISA*), the Swedish business register (*Företagsregistret*), and the geographic database (*Geografidatabasen*) for the period 2003 to 2008.

1. *Car characteristics.* The Swedish vehicle register collects information on all vehicle ownership and purchase records on the whole population of Sweden. The data includes information on the car's general status (registration date, owner type, whether it is leased, when the vehicle became the property of the current owner, in use or not, etc.), the vehicle specification (make, model, and trim), and numerous vehicle characteristics (service weight, fuel type, fuel efficiency, particle filter, carbon emission, etc.), and the annual vehicle kilo-

[19] Exemptions to the charge include emergency vehicles, buses, diplomatic vehicles, disabled person vehicles, military vehicles, motorcycles and mopeds, and foreign-registered vehicles. In 2006, taxis were exempt, but the taxi exemption was abolished when the charges were permanently introduced in 2007.

[20] Figure B4 illustrates the corresponding market shares of all newly registered vehicles.

meters traveled. Each registration also records a vehicle identification number and a social security number equivalent, which uniquely identifies all individuals in Sweden. The vehicle identification number allows us to track the ownership of vehicles over time. We restrict our dataset to privately owned passenger vehicles and vehicles registered for non-commercial purposes.

2. *Individual attributes.* To match individuals to their vehicles, we link the vehicle registry through the personal identification number to the LISA data, which merges several administrative and tax registers for Swedes aged 18 and above. LISA contains a list of socio-demographic information (gender, age, family situation, income, gross salary, education, and employment status). Similarly for firms, we add information on the universe of Swedish firms using the business register. This includes a rich set of information on the firm (the number of employees, net revenue, personnel cost, workplace industry code, and social contribution cost).

3. *Residence & workplace location.* Using the geographic database, we supplement the data with the location of the residence and the workplace, which are measured by $250m$ grid cells in urban and $1000m$ cells in rural areas.[21] We also supplement this with individual-level data on annual congestion fees paid between 2016 and 2021. Lastly, we complement our data with information from The Swedish National Travel Survey (2007), which contains information on the travel patterns of the Swedish population.

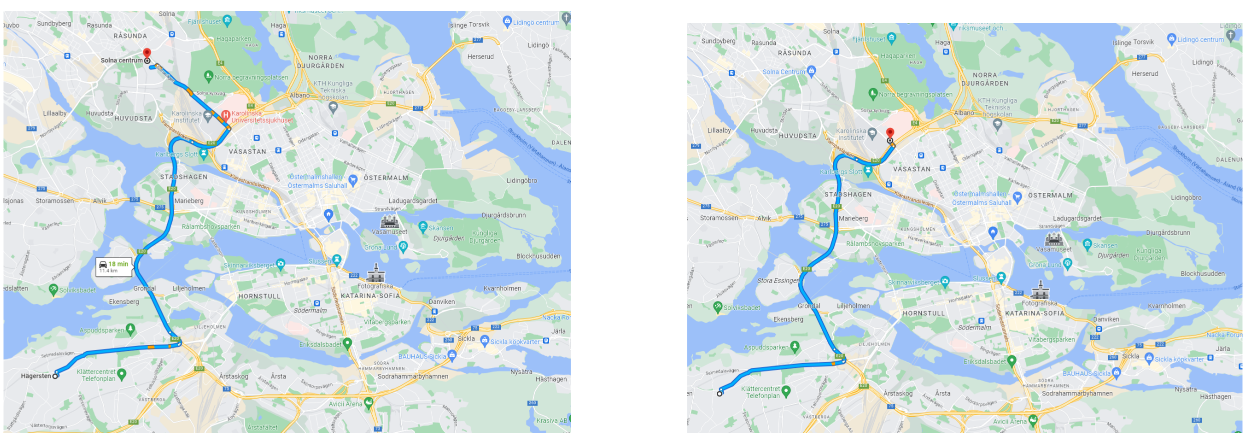
III.C Empirical design

To identify the causal effects of the congestion charge on individual-level vehicle ownership, driving behavior, and location choices, we exploit variation in individuals' exposure to toll rates on the road section between home and work. To do this, we define two groups of individuals, which we refer to as *treated commuters* and *non-treated commuters*. *Treated commuters* are defined as individuals who cross the congestion zone on their way to work. This includes all individuals who reside within the congestion zone but work outside and those who live outside the congestion zone but work inside. *Non-treated commuters* are 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. We use HERE Technology's Routes API to identify the time-minimizing route and travel time between the home and work address. The sample leaves us with 416,245 individual×year observations over six years (2003-2008). Appendix C.1 and C.2 give additional details on the definition of treatment and control groups and sample restrictions.

[21] Stockholm has 17,402 neighborhoods in 2008, with an average population of around 63 individuals.

After the permanent implementation of the congestion charge in August 2007, treated commuters confronted an increase in the cost of driving to work and a greater incentive to adopt alternative fuel vehicles. Our identification strategy compares the two groups' responses before and after the policy in a Difference-in-Differences (DiD) framework. Our DiD strategy exploits variation along two dimensions: (i) *pre* vs. *post*, and (ii) *treated commuters* vs. *non-treated commuters*.[22]

To provide some intuition for the empirical design, Figure II displays a commuting route for an individual who is exempted from the congestion charges on the way to work (Panel A) and an individual who pays the charges (Panel B). Suppose both individuals reside in the southwestern region of Stockholm (*Hägersten*). However, the non-treated commuter's workplace is just outside the congestion zone in the northern area of Stockholm (*Solna centrum*), whereas the treated commuter's workplace is just inside the congestion zone (*Vasastan*). The time-minimizing way to work for an employee in *Solna Centrum* is via the Essinge bypass, eliminating the congestion charge. In contrast, the quickest route for an employee in *Vasastan* involves crossing the congestion zone border and incurring congestion fees. Our empirical approach takes advantage of whether or not the workplace location lies within or outside the congestion charge. The identification strategy compares the vehicle ownership, driving behavior, and location choices of treated and non-treated commuters.



(a) Non-treated commuters (b) Treated commuters

Figure II: Commuting example

Notes: The figures display a commuting route for an individual who is exempted from the congestion charge on the way to work (Panel A) and an individual who pays the congestion charge (Panel B). Figure C1 gives an overview of the share of treated commuters in Stockholm per neighborhood in 2006.

[22] In contrast to a recent study by Isaksen and Johansen (2021) that develops a similar identification strategy based on commuting exposure from home to the workplace, we exploit variation within cities instead of comparing the adoption of environmentally friendly vehicles between cities.

To empirically estimate the impact of the congestion charges, we run the following DiD framework in equation (6):

$$y_{it} \;=\; \beta post_t \cdot T_i \;+\; \theta T_i \;+\; \delta X_{it} \;+\; \lambda_t \;+\; \phi_n \;+\; \varepsilon_{it}, \tag{6}$$

where i indexes the individual and t the year. y_{it} refers to the relevant outcome of interest (e.g., adoption of alternative fuel vehicle, number of trips, commuting distance) in a given year. $post_t$ is a dummy variable that equals 1 after the congestion zone trial (2006) when we measure the effect on fossil fuel vehicles and location choices and equals 1 after the alternative fuel vehicle exemption (2007) when we measure the effect on green vehicles. T_i is a dummy variable equal to 1 if the individual is classified as a *treated commuter*. The coefficient of interest (β) measures the impact of Stockholm's congestion pricing policy on vehicle ownership, number of trips, and commuting distance. We use the estimates of alternative and fossil fuel vehicle adoption and usage as responses for green and brown vehicle adoption and usage in the congestion charge formula.

The vector X_{it} represents a rich set of individual demographic variables, work-route-specific controls, and previous vehicle attributes.[23] The year fixed effect λ_t captures time-varying factors such as nationwide vehicle incentives, gas price shocks, or expansion of public transport. ϕ_n indicates neighborhood of residence fixed effects that control for all time-invariant neighborhood-specific factors. We define individuals living within the same $250m$ grid cells in urban and $500m$ in rural areas as the neighbor. $\varepsilon_{i,t}$ is individual i's error term. Standard errors are clustered at the neighborhood level.

The key identifying assumption underlying our empirical strategy is that treated and non-treated commuters would have experienced parallel trends in vehicle ownership, driving behavior, and location choices in the absence of the congestion charge introduction, conditional on control variables and fixed effects. To assess the validity of the parallel trends assumption, we estimate a version of our DiD estimator, which allows treatment effects to vary by year. By defining the year before the alternative fuel vehicle exemption as the reference year (2006), the dynamic DiD estimator can be written as:

$$y_{it} \;=\; \sum_{s\epsilon\{T|s\neq 2006]} \beta_t T_i \cdot 1[t=s] \;+\; \theta T_i \;+\; \delta X_{it} \;+\; \lambda_t \;+\; \phi_n \;+\; \varepsilon_{it}, \tag{7}$$

where year-specific effects are captured by β_t. To identify the effects on vehicle ownership and driving behavior of fossil fuel vehicles, we define the year before the Stockholm Congestion

[23]The control variables include age, gender, disposable family income, gross salary, employment status, self-employment dummy, married or cohabitant, having at least one child, years of education, and commuting distance.

Trials as the reference year (2005). This is because introducing the Stockholm Congestion Trials differentially influenced treated and non-treated commuters to adopt and drive vehicles, whereas the differential impact for alternative fuel vehicles only occurred during the exemption period.

While the parallel trends assumption is inherently untestable, we document that the trends in alternative and fossil fuel vehicle ownership and driving behavior for treated and non-treated commuters for the years before the congestion zone implementation suggest that the assumption is plausible (Figure IV). In addition, we show that the socio-demographic characteristics, vehicle ownership, driving behavior, and commuting patterns among treated and non-treated commuters are similar prior to the congestion charge (Table B1).[24] Finally, the enhancement of public transport in the fall of 2004 (e.g., expanded bus and train services, park-and-ride sites) had no noticeable impact on switching to public transport before the congestion charges.[25] This is consistent with the findings of Kottenhoff and Freij (2009) and Eliasson et al. (2009), who contend that expanding public transportation had a negligible stand-alone effect on the shift from vehicle use to public transportation.[26]

In addition, our estimation requires no differential anticipatory effects prior to the charge, which implies that the average outcome of treated commuters was not affected by the congestion trial. Two pieces of information suggest that anticipatory effects are likely minor. First, although the congestion charge trial was announced in October 2002, the permanent implementation depended on a 2006 referendum that would determine the ruling government's decision. Due to the significant public resistance and uncertainty surrounding its permanent implementation (Börjesson et al., 2012),[27] we do not expect treated commuters

[24]Panel A shows that the average treated (non-treated) commuter is around 45 (45) years, with about 13.3 (12.7) years of education, and earns a gross salary of approximately 515 (474) thousand SEK conditional on being employed. In addition, 77% (75%) of treated (non-treated) commuters are married or live with a cohabitant, 38% (31%) have at least one child, and around 5% (3%) are self-employed. Panel B illustrates that the number of alternative fuel, fossil fuel, and all vehicles is similar for both commuting groups. Treated- and non-treated commuters travel 15,101 kilometers and 16,373 kilometers per year. The distance between work and residence for treated and non-treated commuters is 16.9 and 19.4 kilometers, respectively.

[25]Since 2004, close to 200 new buses, 16 new bus lines, and new park-and-ride spaces were introduced so that longer-distance commuters from the municipalities surrounding Stockholm could quickly enter the city. Additional departures and carriages have been added to buses, subways, and train lines to accommodate the increased commuter volume. Park-and-ride spaces refer to designated parking spots on the perimeter of the congestion zone that are well-connected to public transport inside the city center.

[26]If treated and non-treated were influenced differentially through the expansion of public transport, then part of the effect of the congestion charge should instead be registered as an interaction effect with expanded public transportation. However, onboard surveys from Stockholm's Local Traffic (*Storstockholms Lokaltrafik*) operator indicate that the number of passengers on the new bus lines in the spring of 2006 who had traveled by car in the fall of 2005 was negligible compared to the decrease in the number of passages during the Stockholm Congestion Trials (Report to the City of Stockholm, 2006).

[27]The percentage of trial-related newspaper articles with a positive angle was only 3% in fall 2005 (Winslott-Hiselius et al., 2009).

to change their fossil fuel trips and acquisitions in response to the policy announcement. Second, we measure the effect on alternative fuel vehicle adoption and usage in the post-exemption period after 2007. As the exemption of alternative fuel vehicles was announced in March 2007, there were no anticipatory effects on commuters before the policy announcement at the start of 2007.

We utilize work-trip exposure to the congestion charge as a measure of policy exposure, even though the congestion charge may also impact non-work visits. Hence, the empirical strategy might be viewed as a type of treatment intensity, assuming that commuters paying a congestion charge on their way to work will be exposed more intensely than others. This implies that *non-treated* commuters are also subject to increasing driving costs, albeit to a smaller degree than those in the treatment group. Hence, the empirical estimates should be interpreted as an average treatment effect on the treated (ATT) of individuals crossing the congestion zone on their way to work.[28]

1. *Rebound effects.* Our estimated responses in adopting and using fossil and alternative fuel vehicles reflect a change in relative prices and the behavior induced by lighter traffic of treated versus non-treated commuters in the post-implementation period. The latter can be seen as a violation of the stable unit treatment values assumption (SUTVA):[29] The treatment of others can affect how an individual responds to congestion pricing, as it impacts the traffic conditions they experience. This concern is related to the concept of "induced demand" in transportation planning (Duranton & Turner, 2011). As both commuter groups experience a similar reduction in travel time, our estimated responses only capture the relative price change. Formally, the DiD estimator 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}:

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

We can decompose the outcome for both treated and non-treated to separate the rebound

[28] If we expect imperfect compliance of the non-treated commuters (i.e., paying for the congestion charge on their way to work), then we would interpret $\hat{\beta}$ as an intention-to-treat effect (ITT). As treated commuters cannot avoid paying the charge when crossing the congestion zone, we can rule out "never-takers" in our empirical design. To derive the ATT, we need to multiply the ITT estimate by the proportion of individuals who adhered to the treatment. However, given that we expect a low incidence of non-treated commuters paying the congestion charge, we anticipate the ATT will closely approximate the ITT. To the extent that non-compliance in our empirical setting exists, the ITT reflects the appropriate estimate for determining optimal pricing strategies.

[29] This pertains to the literature on DiD, which takes into account spillover effects without imposing the SUTVA assumption. Spillover effects can be essential in various economic scenarios: When a policy in one region impacts the surrounding areas or people are linked through a network (Butts, 2021; Huber & Steinmayr, 2021).

effect (Δy) from the direct effect of the policy:

$$\hat{\beta} = [\underbrace{\bar{y}^{post}(T_i = 1|T_{-i} = 0)}_{\text{demand response treated}} + \underbrace{\Delta\bar{y}^{post}(T_i = 1|T_{-i})}_{\text{rebound effect treated}} - \bar{y}^{pre}(T_i = 1)]$$
$$- [\underbrace{\bar{y}^{post}(T_i = 0|T_{-i} = 0)}_{\text{demand response non-treated}} + \underbrace{\Delta\bar{y}^{post}(T_i = 0|T_{-i}}_{\text{rebound effect non-treated}}) - \bar{y}^{pre}(T_i = 0)]$$

Assuming that the rebound effect is similar to treated and non-treated commuters, our estimated coefficient includes the direct effect but not the rebound:

$$\hat{\beta} = [\bar{y}^{post}(T_i = 1|T_{-i} = 0) - \bar{y}^{pre}(T_i = 1)] - [\bar{y}^{post}(T_i = 0|T_{-i} = 0) - \bar{y}^{pre}(T_i = 0)] \quad (8)$$

The policy-relevant responses, however, should incorporate both the direct substitution and rebound effect because the congestion charges depend on the overall traffic changes caused by the policy implementation.

To our knowledge, there are no estimates of rebound effects from congestion pricing. Existing work on the rebound effect in the context of fuel efficiency suggests that the rebound effect in personal vehicle travel tends to be small (Gillingham et al., 2013). Gillingham (2018), for example, recommends that the US government use a rebound effect of 8% when analyzing the impacts of fuel economy regulations. In the context of Stockholm's congestion pricing system, Eliasson et al. (2013) suggests that the stability of the reduction in traffic conditions points towards a lack of a large rebound effect, but notes that more detailed data is required to arrive at a precise estimate. Given the findings from these studies, we do not explicitly include the rebound effect in our optimal congestion charge calculation. Re-calculating optimal congestion prices accounting for rebound using our framework is straightforward, but we leave this task to future research.

IV Empirical results

IV.A Main responses to the congestion charge

Table I displays the impact of the congestion zone estimated from equation (6) on vehicle ownership (Panel A), number of trips (Panel B), and commuting distance (Panel C) for alternative fuel, fossil fuel, and all vehicles. We restrict the post-period for alternative fuel vehicles to 2007-2008 and for fossil fuel vehicles to 2006-2008.

1. *Fleet composition.* Using equation (6), we find that Stockholm's congestion charge reduced the size of the conventional vehicle fleet and increased the adoption of alterna-

tive fuel vehicles. Panel A of Table I documents that the congestion charge induced a .64 percentage points increase in the probability of owning an alternative fuel vehicle in the post-implementation years (column 1). Relative to the average baseline probability of 1.4% of owning an alternative fuel vehicle, treated commuters are 46 percent more likely to own a new alternative fuel vehicle. At the same time, the policy decreased the average number of fossil fuel vehicles by .83 percentage points (column 2). Together, these effects roughly offset, meaning the overall fleet size remains relatively stable (column 3).[30] We find that the implementation of the congestion charge led to a .17 percentage points rise in the adoption of new alternative fuel vehicles, which indicates that 26% of the impact on alternative fuel vehicles was due to the acquisition of new vehicles (Table D1).

2. *Number of trips.* Mirroring responses in the vehicle fleet, we estimate that Stockholm's congestion price led to a decrease in vehicle kilometers traveled for fossil fuel cars and an increase in kilometers traveled in alternative fuel vehicles. Based on an average trip distance of 18.2 kilometers,[31] Panel B of Table I suggests that treated commuters increased the number of trips with alternative fuel vehicles by about 6.6 in the post-implementation years (column 1). In addition, the policy induced a decrease of -13.8 in trips traveled in fossil fuel vehicles (column 2), leading to an overall reduction of 8.2 trips in all vehicles (column 3). This implies that the congestion charge resulted in an annual increase of 121 vehicle kilometers traveled by commuters in alternative fuel vehicles and a decrease of 253 kilometers in fossil fuel vehicles, which led to a total reduction of 150 vehicle kilometers traveled (Table D2). In addition, we document that family members of treated commuters slightly increase their driving in alternative fuel cars (Table D3), suggesting that treated commuters may use exempted cars of family members to avoid the charge.[32]

As calculating the optimal congestion charge requires estimates of changes in the number of trips by vehicle and trip type ($\frac{\partial t_g^c}{\partial \tau}$, $\frac{\partial t_b^c}{\partial \tau}$, $\frac{\partial t_g^o}{\partial \tau}$, $\frac{\partial t_b^o}{\partial \tau}$), we need to attribute the observed changes in vehicle kilometers traveled to changes in trips inside versus outside the congestion zone. To do so, we combine the above estimates of changes in kilometers traveled by vehicle type with changes in the number of crossings into the cordon zone. We take advantage of the fact that specific changes in the congestion zone price only directly impact brown vehicles

[30] As our identification strategy exploits different post-periods, the treatment effects of alternative fuel (column 1) and fossil fuel vehicles (column 2) do not precisely correspond to the total change in vehicle ownership and kilometers traveled (column 3). Table D6 documents that treatment effects perfectly match when using the same reference year for both fuel types.

[31] We use the fact that the average work commute is 17.4 kilometers, non-congestion zone trips are approximately 19 kilometers, and 46 percent of kilometer-weighted trips are business-related (The Swedish National Travel Survey, 2007).

[32] As our optimal congestion charge formula relies on individual-level policy responses, we do not explicitly include intra-household substitution in trips in our optimal congestion charge calculation.

(e.g., August 2007) and other changes impact only green vehicles (e.g., the removal of the exemption in 2012). These pieces of empirical information combined with an accounting identity relating changes in vehicle kilometers traveled to a weighted average of trip type changes allows us to identify these four derivatives. Appendix E.2 provides additional details on estimating the number of trips by fuel type.

Panel B of Table D2 documents that removing the alternative fuel exemption resulted in a decrease in the number of kilometers traveled in alternative fuel vehicles by about 103 kilometers per car owner, and an increase in vehicle kilometers traveled in fossil fuel vehicles of of 206 per car owner. This implies that approximately 89% of trips in alternative fuel vehicles and 86% in fossil fuel vehicles were trip changes crossing the congestion zone.[33] Finally, implementing the congestion charge led to an increase of 5.9 congestion and .7 non-congestion zone trips in alternative fuel vehicles per car owner and a reduction of 11.8 congestion and 2 non-congestion zone trips in fossil fuel vehicles (Panel C of Table I).

3. *Commuting distances.* In addition to changing vehicle ownership or driving behavior, treated commuters may move into the congestion zone or relocate to workplaces outside the congestion zone, which has implications for the average commute distance of drivers. In Table D4, we estimate the effect of the congestion zone on the likelihood of moving residences (Panel A) and relocating to workplaces (Panel B). We restrict the non-treated commuters to individuals living outside the congestion zone.

The empirical findings in Panel A suggest that treated commuters are .2 percentage points more likely to move inside the congestion zone. In addition, Panel B reveals that treated commuters are .5 percentage points more likely to alter their workplace location and 1.6 percentage points more likely to switch their workplace to be outside of the congestion zone. Compared to a baseline probability of moving of 2.5 percent, treated commuters are nearly 64 percent more likely to relocate to a workplace outside the congestion zone. In addition, around 43 percent of treated commuters (.7 percentage points) transfer to a new company outside the congestion zone, while 57 percent (.8 percentage points) relocate to a new office outside the congestion zone within the same organization. In contrast, the effect on relocating to workplaces inside the congestion zone is negative as this would not prevent paying congestion charges.

As a result of moving into the congestion zone and relocating to workplaces outside the congestion zone, either to a new office or company, Panel C of Table I shows that the average commute distance for treated commuters decreases by approximately .086 kilometers.[34]

[33] This is in line with the trip changes of the London congestion zone, which estimated that around one-quarter of trips were diverted around the charging zone (Leape, 2006).

[34] Conditional on residential moving, treated commuters reduce their average commute by .62 kilometers.

Table I: Estimates on vehicle ownership, trips, and commuting distance

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.Vehicle Ownership			
Post x Treated Commuters	.0064***	-.0083**	-.0030
	(.0014)	(.0035)	(.0033)
Mean Car Ownership (t-1)	.014	1.138	1.145
B.Number of Trips			
Post x Treated Commuters	6.6***	-13.8***	-8.2**
	(1.5)	(3.9)	(3.8)
Inside Congestion Trips	5.9**	-11.8**	-5.9
	(2.9)	(5.0)	(4.7)
Mean Trips Inside (t-1)	6.4	399.1	401.7
Change Trips Outside	.70	-2	-2.3
Mean Trips Outside (t-1)	6.9	432.1	434.8
C.Commuting Distance			
Post x Treated Commuters			-.086***
Mean Commute Distance (t-1)			17.5
Changes in Outside Distance			-.007
Mean Outside Distance (t-1)			19

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), number of trips (Panel B), and commuting distance (Panel C). 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 number of trips 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). The mean dependent variables of the previous year are reported below the coefficients. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Appendix E.2 details the conversion from vehicle kilometers traveled to the number of trips by fuel type and the change in commute distances. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Using our empirical estimates of the changes in the number of non-congestion trips and kilometers traveled, we derive that the average commuting distance outside the congestion zone reduced by .007 kilometers. This implies that treated commuters reduced the average distance between congestion and non-congestion zone trips.

IV.B Heterogeneity in responses

To speak directly to the ongoing policy debates about congestion prices that vary by observable characteristic, we calculate the heterogeneous responses of different income groups and use those responses to derive their optimal congestion prices. This also allows us to pinpoint which income groups bear the benefits and costs of congestion pricing. Figure III illustrates heterogeneous treatment effects of vehicle ownership and driving behavior of alternative fuel (indicated in green), fossil fuel (indicated in blue), and the total number of vehicles (indicated in gray) for four different income groups.The Figure documents an income gradient in alternative fuel adoption and driving behavior in response to the congestion charge. While individuals with an annual income of more than SEK 600k are 1.6 percentage points more likely to adopt an alternative fuel vehicle and drive 260 kilometers more with alternative fuel vehicles, there is no effect for individuals with an income of less than SEK 400k. In contrast, low-income individuals are significantly more likely to adopt fossil fuel vehicles and increase their usage. This may suggest that low-income individuals with limited public transportation options cannot switch to cycling or public transportation. One explanation for the increased usage and adoption of fossil fuel vehicles among low-income individuals is that they drove more frequently to the new park-and-ride spaces.

Individuals with a medium-range income adjust their commuting by reducing their fossil fuel vehicles and kilometers traveled. This suggests that high-income individuals prefer to adopt alternative fuel vehicles in response to the policy, while middle-income individuals prefer to change their mode of transportation (e.g., public transit, cycling). However, the observed heterogeneous patterns in vehicle ownership and driving adjustments could also reflect preferences for new technologies, environmental awareness, or financial constraints.[35]

In contrast, relocating to a new workplace does not lead to a significant reduction in commuting distances.

[35]First, differences in the margin of adjustment could reflect different preferences for adopting new technologies, differences in the value of time, or differences in utility from cycling or using public transit. Second, the heterogeneous pattern may reflect financial barriers to purchasing an alternative fuel vehicle. Low-income individuals may have a more limited opportunity set than high-income individuals, as fossil fuels were the only used vehicles available during the policy implementation.

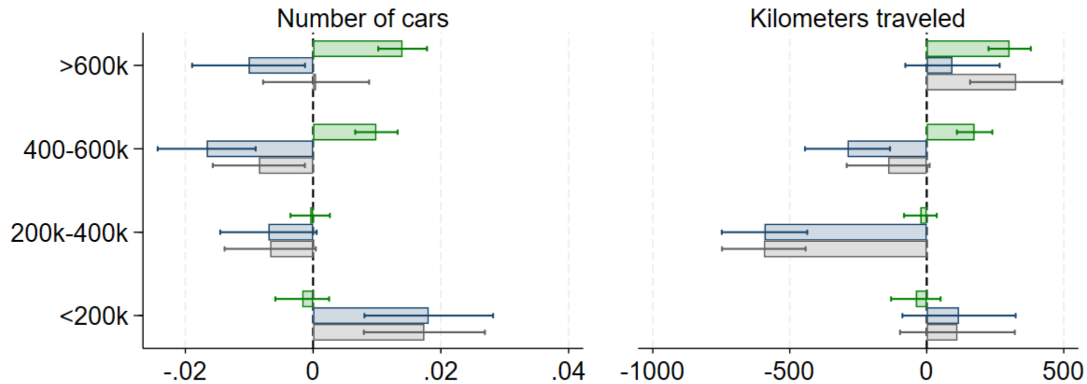


Figure III: The impact of congestion pricing on income groups

Notes: This figure plots the estimates of the effect of Stockholm's congestion charge on vehicle ownership and driving behavior for alternative (green), fossil fuel (blue), and any vehicle (gray) for four different income groups: Individuals with an annual income of less than 200k SEK, between 200k to 400k SEK, between 400k to 600k SEK, and more than 600k SEK. Green indicates alternative fuel vehicles, blue for fossil fuel vehicles, and gray for 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. Income groups are based on 2006 demographics. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles and 2006-2008 is the post-period for fossil fuel vehicles. 95%-confidence intervals are indicated through whiskers and reflect robust standard errors clustered by neighborhoods.

In addition, we present a series of results that describe how different economic and demographic groups responded to Stockholm's congestion pricing system, even though we do not derive optimal congestion prices for those groups. Figure D4 documents heterogeneous treatment effects along four additional socio-economic dimensions: family size, education, age, and commuting distance. Panel A suggests that couples entirely drive the substitution to alternative fuel vehicles in response to the policy. In contrast, single adult households without kids are more likely to adopt fossil fuel vehicles. This may reflect that singles are more flexible in changing their mode of transportation, that dual-income households are more able to invest in alternative-fuel vehicles, or the desire of households to diversify their transportation options. Panel B of Table D5 reveals that individuals without children are the sole group exhibiting a statistically significant reduction in commuting distances, whereas couples with children increase the distance between the residences and the workplace.

Panel B indicates that the response in green vehicle adoption and usage is increasing in educational attainment, with the largest impact on master graduates. As the total effect of the policy on the number of vehicles for these groups is negative, individuals partly substitute to alternative fuel vehicles and change to alternative modes of transportation. This pattern could reflect preferences for new technologies and a higher awareness of the environmental and climate benefits of driving alternative fuel vehicles among highly educated individuals.

We also show a gradient in the relationship between alternative fuel adoption and age in Panel C: individuals below 45 are the most responsive group to the policy. In contrast, people close to retirement reduce their driving due to the congestion charge. Panel D of Table D5 also shows that the mean decrease in commuting differences arises from heterogeneous responses by age group. Only individuals aged between 35 and 45 reduce their commuting distance, and those above 60 move farther away from work, on average. Panel E of Table D5 shows that solely individuals residing within a 10-kilometer radius of the congestion zone reduce the commuting distance. Finally, we find that the effects of the policy on alternative fuel vehicle adoption and driving are similar across individuals with different commute lengths (Panel D).

IV.C Validity and robustness results

1. *Parallel trends.* To visually assess the plausibility of the parallel trends assumption, Figure IV displays annual treatment effects estimated from the DiD specification in equation (7). Treated and non-treated commuters display similar trends in alternative fuel vehicle ownership and usage in the pre-exemption period (2003-2006), supporting the validity of the parallel trends assumption. Figures D2 and D3 demonstrate that treated and non-treated commuters also have comparable trends in vehicle ownership and vehicle kilometers traveled of fossil fuel vehicles and all vehicles.

Additionally, Panel A and B indicate that individuals exposed to the Stockholm congestion charge were .63 percentage points more likely to own an alternative fuel vehicle and increased the average distance traveled in alternative fuel vehicles by 123 kilometers by the end of 2008. Consequently, the congestion charge can explain 16 and 17 percent of the rise in alternative fuel adoption and usage (Figure D1).[36] Since the first post-period year (2007) is only partially treated as the exemption of alternative fuel vehicles started in August 2007 with the announcement in March 2007, the treatment effects on vehicle ownership of alternative fuel vehicles and kilometers driven are larger in 2008 than in 2007.

[36] In Panel A of Figure D1, we observe that the share of toll-paying commuters in Stockholm that owned an alternative fuel vehicle increased by 3.7 percentage points, from 1.5 percent in 2006 to 5.2 percent in 2008 (solid line). Without the congestion charge, we estimate that the share of alternative fuel vehicles would have been 4.6 percent (dashed line).

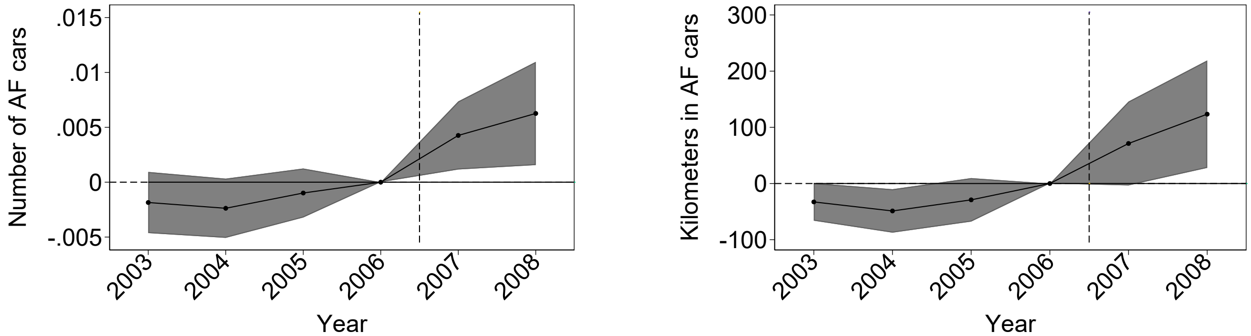


Figure IV: The impact of congestion pricing on alternative fuel vehicles

Notes: These figures plot the coefficients from a dynamic DiD specification (equation 7), where β_{2006} is normalized to zero. Panel A shows the annual treatment effect on the probability of owning an alternative fuel vehicle. Panel B shows the annual treatment effect on kilometers traveled with alternative fuel vehicles. The sample is restricted to 2003-2008, where 2007-2008 is the post-period. Standard errors are clustered at the neighborhood level. The vertical dashed line denotes the year of the alternative fuel vehicle exemption (2007).

2. *Robustness checks.* Next, we examine the sensitivity of our main results to various specifications of sample restrictions, treatment and control group definitions, and firm-level effects. Restricting the sample to individuals observed in all years (2003-2008), the empirical estimates of alternative fuel adoption and kilometers traveled based on a balanced sample are similar to our main results (Table D7).

We also show that our results on alternative fuel adoption and driving behavior are robust to different treatment and control group definitions. When we restrict the sample of treated commuters to individuals residing outside the congestion zone, the effect on alternative fuel adoption and kilometers traveled becomes slightly smaller (Table D8). In contrast, if we define the treatment group as treated commuters inside the congestion zone, our empirical findings become larger (Table D9). This suggests that treated commuters inside the congestion zone are more likely to adopt and use alternative fuel vehicles, decrease fossil fuel car adoption and usage, and reduce commuting distance. When we define the treated group as inside commuters, the variation in charges comes solely from differences in neighborhoods, which mitigates the potential concern that workplaces adjust the amenities they offer commuters in response to the policy (e.g., providing parking spaces).

Furthermore, when incorporating individuals residing and working within the congestion zone into the group of non-treated commuters, the effects for adopting and utilizing alternative fuel vehicles increase, while the effects of fossil fuel utilization and adoption diminish (Table D10). This suggests that non-treated commuters in the congestion zone are less inclined to alter their vehicle adoption and usage but are more prone to relocate.

As our identification strategy exploits predetermined variation in whether the workplace is located within or outside the congestion zone, a potential identification threat arises if there are substantial differences between workplaces located close and far from the congestion. To address this concern, we re-run our main specifications, excluding workplaces that are far from the cordon boundary. We find that excluding workplaces more than three kilometers from the congestion zone does not affect the coefficients, implying that workplace differences do not generate our empirical findings (Table D11). In addition, we document that including workplace-location fixed effects has virtually no effect on the coefficient estimates (Table D12).

V Computing the optimal congestion charge

V.A Mapping empirical results to theory

To provide an estimate of the optimal congestion charge described in equation (3), we combine the empirical estimates on vehicle ownership, number of trips, and commuting distance from Section IV with estimates from the literature on vehicle emissions and congestion externalities. We rely on existing estimates of congestion externalities to assign social costs to congestion zone and periphery trips. These values are €.38 per kilometer for trips inside the congestion zone and €.13 per kilometer for trips outside the congestion zone, respectively (External Costs of Transport, 2011).[37] Emission externalities equal €.04 per kilometer in brown vehicles, and €0 for green vehicles, as per the European Environment Agency (2014, 2021).[38] All externalities are expressed in real 2021€. Table E2 summarizes key population statistics (Panel A), treatment effects on vehicle ownership, number of trips, and commuting distance estimated in Section IV(Panel B), and estimates on the costs of emission (Panel C) and congestion externalities (Panel D). Appendix E provides details on mapping our empirical results to the theory and computing the emission and congestion externalities.

Equation (9) shows how these statistics enter the theoretical formula of the congestion charge per crossing from equation (4):

[37]The estimates refer to marginal damages in congested peak hours, and our empirical estimates should be interpreted as peak-hour prices.

[38]Previous studies have shown that low emission zones, road tolls, and congestion charges can help improve urban air quality (Wolff, 2014; Gibson & Carnovale, 2015; Fu & Gu, 2017; Gehrsitz, 2017), with resulting health benefits such as lower asthma rates in children (Simeonova et al., 2021), lower infant mortality (Currie & Walker, 2011), and fewer hospital admissions related to chronic cardiovascular and respiratory diseases (Pestel & Wozny, 2019).

$$\tau = \underbrace{\Delta N_g(\widetilde{\phi}_g + \widetilde{\gamma}_g)}_{\triangle Green\ Cars} + \underbrace{\Delta N_b(\widetilde{\phi}_b + \widetilde{\gamma}_b)}_{\triangle Brown\ Cars} + \underbrace{\Delta T \cdot (\overline{\phi} + \overline{\gamma})}_{\triangle Trips} + \underbrace{\Delta V^c(\hat{\phi}^c + \hat{\gamma}^c)}_{\triangle Inside\ Driving} + \underbrace{\Delta V^o(\hat{\phi}^o + \hat{\gamma}^o)}_{\triangle Outside\ Driving}$$

$$\tau = -\text{€}.02 + \text{€}2.15 + \text{€}6.32 + \text{€}.97 + \text{€}.04 \approx \text{€}9.46 \tag{9}$$

Our baseline calculation of the optimal congestion charge for fossil fuel vehicles equals €9.46 per congestion zone crossing or €.54 per kilometer traveled using an average congestion trip length of 17.5 kilometers. Congestion-related terms – whether from changes in trips, fleet size, or trip length – account for around 89 percent (€8.39) of the total charge. Emissions-related terms account for the remaining 11 percent (€1.07). The benefits of reducing congestion outweigh the slight reduction in emissions caused by exempting green vehicles from the congestion charge, raising questions about the efficiency of such exemptions.

There are two ways that we can put this optimal charge into context. First, we can compare to the actual charge levied by the city. Second, we can compare our estimated optimal charge to the naive Pigouvian benchmark, where the toll price reflects the average emissions and congestion externalities associated with trips that use the cordon zone, but does not account for spillovers, moving decisions, or vehicle purchases. Our optimal toll estimate (€9.46) is above both Stockholm's congestion price (€4.78) as well as the naive Pigouvian benchmark (€7.35).

To better understand how the different responses to congestion pricing contribute to the optimal charge, Table II decomposes the optimal charge into the three components: fleet size, number of trips, and commuting distance (4). First, the "fleet composition" component accounts for €2.13 (23%) of the total optimal charge. This reflects the decrease in the brown vehicle fleet and its associated externalities (€2.15) and the increase in the green vehicle fleet and its associated externalities (€ − 0.02). In other words, a congestion charge levied only on brown vehicles will be higher than a charge that considers only the effect on vehicle trips. Second, the "number of trips" component accounts for €6.32 (62%) of the total congestion charge. This term largely reflects the impact of the zone on total brown trips inside and outside of the zone; increases in driving in green vehicles decreases this term by just €.03. As the brown fleet is substantially larger than the green fleet, a change in the number of brown trips has a much greater impact on externalities compared to an equivalent change in green trips. Third, €1.01 (11%) of the congestion charge reflects responses in commuting distances. This term is primarily driven by reductions in the commuting distance between the neighborhood and the workplace (€.97). As a result of relocating, the congestion charge also reduces the distance of non-congestion zone trips (€.04).

Table II: Congestion charge decomposition

	Per crossing (€)	Externality (€)	
		Congestion	Emission
Fleet Composition	**2.13**		
Effect on green vehicles $\Delta N_g(\widetilde{\phi_g} + \widetilde{\gamma_g})$	−.02	−0.02	0
Effect on brown vehicles $\Delta N_b(\widetilde{\phi_b} + \widetilde{\gamma_b})$	2.15	1.85	.3
Number of Trips	**6.32**		
Effect on green trips outside $\Delta T_g^o(\overline{\phi_g^o} + \overline{\gamma_g^o})$	−.00	−.00	0
Effect on green trips inside $\Delta T_g^c(\overline{\phi_g^c} + \overline{\gamma_g^c})$	−.03	−.03	0
Effect on brown trips inside $\Delta T_b^c(\overline{\phi_b^c} + \overline{\gamma_b^c})$	5.9	5.34	.56
Effect on brown trips outside $\Delta T_b^o(\overline{\phi_b^o} + \overline{\gamma_b^o})$	.45	.34	.11
Commuting Distance	**1.01**		
Effect on inside commute $\Delta V^c(\hat{\phi}^c + \hat{\gamma}^c)$	.97	.88	.09
Effect on outside commute $\Delta V^o(\hat{\phi}^o + \hat{\gamma}^o)$	.04	.03	.01
Congestion charge (€)	**9.46**	**8.39**	**1.07**

Notes: This table reports the congestion charge per crossing from equation (9) separated by each component (column 1). We split the congestion charge by congestion (column 2) and emission externalities (column 3). All charges and externalities are expressed in real 2021 €.

Figure V reports congestion charge results under several alternative assumptions, separated by emission and congestion externalities. As opposed to exempting green vehicles, we derive the optimal uniform congestion charge on all vehicles entering the congestion zone (Proposition 3). To identify the policy responses to the uniform charge, we exploit how commuters' vehicle adoption, usage, and commuting distances changed solely during the congestion trial in 2006 that charged all vehicles. The second bar reveals that the optimal uniform charge equals €9.5, which implies that the larger reduction in brown vehicle trips from the uniform charge roughly corresponds to the emission benefits from the green car exemption.

In our baseline specification, we use the average commuting distance among treated and non-treated commuters in Stockholm, which excludes nearby commuters (< 3 km). In contrast, if we include all individuals who commute to work and own at least one vehicle, the average commuting distance shrinks to 11.9 km and the optimal charge corresponds to €7.1. Therefore, longer commuting distances increase the size of the optimal congestion charge.

The fifth and sixth bars explore what happens to the congestion charge when the share of green vehicles increases. Before the introduction of the congestion charge, approximately 1% of vehicles were green, and 1.5% of vehicle kilometers were traveled in green vehicles. Instead, if we assume that 10%, and 25% of vehicles and trips are made with green vehicles, the congestion charge becomes €9.1 and €8.5. Hence, an increasing share of green vehicles implies a reduced congestion charge.

The following three bars report the congestion charge using the responses of low-, medium-, and high-income individuals from Section IV.B. Due to the limited responsiveness of low-income individuals to the policy with respect to the adoption of alternative fuel vehicles and the reduction in trips, the congestion charge amounts to €7.4. In contrast, middle-income individuals mainly respond by reducing their vehicular trips, thereby mitigating emissions and congestion-related externalities, leading to a corresponding congestion charge of €16.2. The adoption of alternative fuel vehicles and the shift towards utilizing these vehicles for trips contribute to a reduced congestion charge of €4.7 within the high-income group.

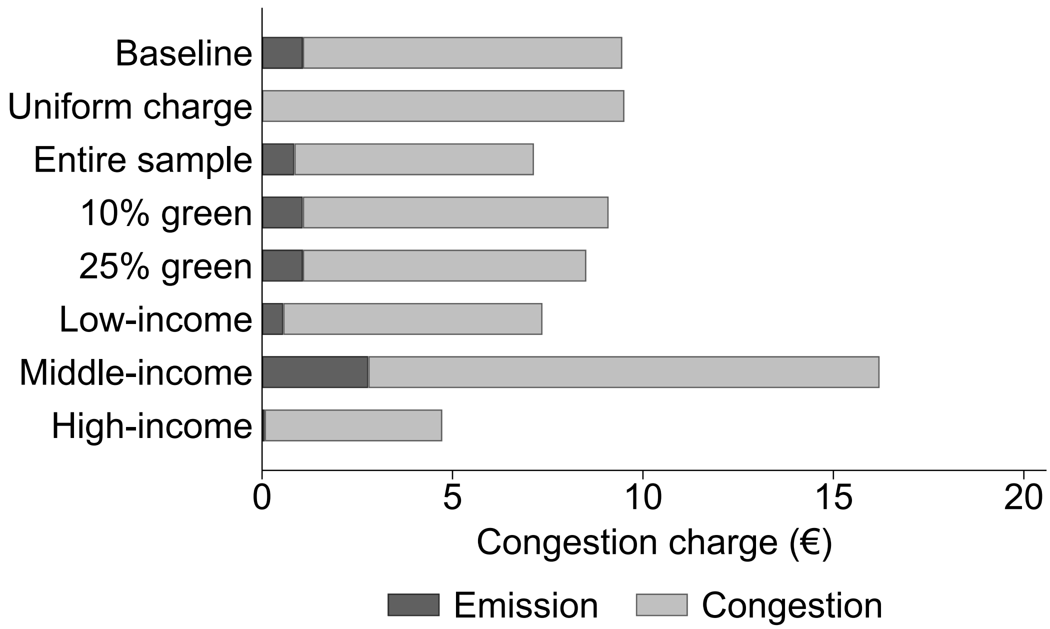


Figure V: Congestion charges under alternative assumptions

Notes: This figure reports the optimal brown vehicle congestion charge across a range of assumptions. The first bar reports our baseline calculations using equation (4), separated by emission-related (black) and congestion-related externalities (grey). The second bar shows the optimal uniform charge for all vehicle crossings according to equation (A24). The third bar reports the congestion charge for all commuters with vehicles. The fifth and sixth bars report the congestion charge, assuming that 10% and 25% of vehicles and trips are made with green vehicles. The seventh, eighth, and ninth bars report the congestion charge using the responses of low-, medium-, and high-income individuals. All charges and externalities are expressed in real 2021 €.

1. *Threshold for green vehicle exemptions to pass cost-benefit.* Exempting green vehicles in congestion pricing schemes trades off reductions in one externality (i.e., pollution) for another (i.e., congestion). As the share of green vehicles increases, this tradeoff becomes

less attractive. At the extreme, for example, there are no emissions benefits from exempting green vehicles if the fleet is 100 percent clean, but substantial costs in foregone reductions in congestion. Our estimated responses in trips taken and vehicle adoption allow us to quantify this tradeoff and calculate the break-even point in the share of green vehicles. Above this cutoff, the costs of exempting green vehicles outweigh the associated emissions benefits. Solving equation (5) for the number of green cars n_g^*, we can derive this cutoff as the marginal benefits of green cars divided by the induced marginal costs of green congestion zone trips:

$$n_g^* = \frac{.04\frac{€}{km} \cdot 15,202km \cdot .0064 - 1.138 \cdot 17.5km \cdot .38\frac{€}{km} \cdot .4}{17.5km \cdot .38\frac{€}{km} \cdot 5.9} = .022 \tag{10}$$

The numerator denotes the marginal emission benefits of replacing a brown car with a green car (€608) multiplied by the green car adoption in response to the congestion charge minus the costs of the foregone brown congestion trips of the exemption policy relative to the uniform charge. The denominator refers to the induced changes in green congestion zone trips from the congestion charge. This results in a cutoff for exempting green cars from the congestion charge of $n_g^* = .022$ assuming that the policy responses are linear along the green vehicle adoption curve. The optimal trajectory of congestion charges exempts green cars below this cutoff, while a uniform congestion charge without exemption applies to adoption levels above this cutoff. As the green fleet in Stockholm exceeded this cutoff in the exemption period ($n_g = .04$), the exemption policy costs more in foregone congestion than it reduces emissions.

2. *The cost of Stockholm's green vehicle exemption policy.* In addition to understanding whether green vehicle exemptions pass cost-benefit, policymakers may also be interested in the cost of inducing green vehicle adoption via congestion charge exemptions. This figure allows for comparisons between different available policy levers for encouraging green vehicle adoption. To calculate the cost of exempting green cars, we first derive the marginal costs incurred by leveraging the exemption policy aimed at a different objective (i.e., reducing emissions). Specifically, our framework measures the costs of promoting green car adoption as a function of foregone green and brown congestion zone trips. Mapping our empirical estimates and registry data into equation (5), the marginal annual costs of inducing .0064 exempted alternative fuel vehicles through the exemption policy equals 5.9 foregone green and .4 brown congestion zone trips times the external costs of congestion ($v^c\gamma^c$) for a given stock of .04 alternative fuel cars during the exemption period (n_g):

$$MC^{congestion}(.04) = \frac{5.9}{.0064}(.04 \cdot 17.5km \cdot .38\frac{€}{km}) + \frac{.4}{.0064}(1.138 \cdot 19km \cdot .38\frac{€}{km}) = €759 \tag{11}$$

The marginal congestion costs per additional green car equal €759 annually and €3,795 for the five-year exemption period of alternative fuel cars (August 2007 - August 2012). To put this number in context, during the same period, the Swedish government offered a 10,000 SEK vehicle rebate (converts to €1,212 in 2021). Assuming that 52% of adopters were inframarginal (i.e., who would have purchased a green car without incentives) (Fournel, 2023), the vehicle rebate cost the Swedish government €2,331 per additional green car, which is around €1,464 less than through the congestion charge exemptions.[39] This allows us to limit the subsidy required for one additional green car to €1,973 for the current green fleet by multiplying the marginal congestion costs with the share of inframarginal adopters.

V.B Distributional consequences

A common objection to congestion charges is that the benefits and costs are distributed unevenly across socioeconomic groups. Figure D5 demonstrates the distributional profile of the congestion charges in 2016, indicating that congestion charges fall disproportionately on low-income individuals. In Stockholm, the congestion charge accounts for approximately .68 percent of the annual salary for the lowest income decile and .16 percent for the highest income decile. Therefore, the congestion fees constitute a non-negligible portion of the income, approximately four times greater for low-income individuals. Similar regressive policy patterns remain even after applying the sample restrictions outlined in Section C.2. Consequently, the congestion charge is regressive for all Stockholm residents, not just those who own a vehicle and are subject to it on their way to work.

Three additional dimensions influence the distributional profile of the policy: substitution to other modes of transport, revenue recycling, and exemption of alternative fuel vehicles. First, we demonstrate systematic differences in how individuals adjust to the congestion fee in Section IV.A. Notably, we find that primarily middle-income individuals switch to other modes of transportation, whereas low-income individuals continue to use fossil fuel vehicles. This suggests that low-income individuals may be more reliant on existing commuting patterns, and substituting to alternative modes of transportation may be more challenging. Second, the net distributional effects of congestion fees depend on how the policy's proceeds are utilized. The congestion charge revenues were designated for a new bypass around Stockholm and road investments (Eliasson et al., 2014). However, as high-income individuals travel more by vehicle, road investments may again benefit higher-income groups disproportionately. Third, a charging system's distribution of costs and benefits depends on exemptions and discounts (Levinson, 2010; Ison & Rye, 2005). The social benefits of

[39] Put differently, if the share of inframarginal green car adopters exceeds 39%, the vehicle rebate is more effective in promoting green cars.

exempting alternative fuel vehicles in Stockholm are highly centered among high-income groups. The exemption makes the congestion charge's distributional profile even more regressive since primarily high-income individuals adopt alternative fuel vehicles in response to the policy.[40]

In contrast, low-income individuals tend to reside farther away from the congestion zone, which implies that they should be charged a lower fee in the ideal Pigouvian tax system for kilometers traveled. However, since the congestion fee charges a fixed amount regardless of the distance traveled, it is less regressive than the ideal Pigouvian tax system. Hence, the substitution pattern to other transportation modes, revenue recycling, and exemption of alternative fuel vehicles exacerbate the regressive effect of the policy, whereas the commuting distances reduce the regressive effect of the charge.

VI Conclusion

As the expansion of congestion pricing in the policy world coincides with a period of concern about environmental policy, many existing and proposed road pricing policies fold together multiple policy goals. This paper provides two main contributions to economists' thinking about tradeoffs and optimal prices in this setting.

First, we provide a framework for recovering optimal congestion charges that target emission and congestion externalities and include three responses to the policy — vehicle ownership, number of trips, and location choices — often missing from second-best congestion pricing models. The advantage of our approach is tractability. While our model incorporates these three responses to the congestion zone, recovering optimal prices requires only policy responses. By phrasing optimal prices in terms of responses, this approach highlights key policy tradeoffs in a way that quantitative spatial approaches may not. It also allows researchers to plug in estimates of these responses from other settings when data or natural experiments are unavailable.

Our second contribution is demonstrating the use of this framework to recover optimal congestion charges. Several of our empirical estimates from Stockholm's congestion zone are of interest as stand-alone results: We find evidence that the alternative fuel exemption induced individuals to switch vehicle types but left the total amount of vehicles roughly unchanged. We document that commuters take more trips with exempted alternative fuel

[40] In addition, the congestion charge is included in the "taxable benefit value" of company vehicles, which are either exempt or can deduce the charge from their gross income (West & Börjesson, 2020). Drivers can deduct charges incurred on commute trips if driving saves them more than an hour each way relative to transit and they travel five kilometers Börjesson et al. (2012). This reinforces the regressivity, as most company vehicle drivers belong to the highest income bracket.

vehicles or switch to alternative transport modes. Finally, the congestion charge induced individuals to sort across the zone to limit their pricing exposure between work and home, ultimately leading to marginally shorter commuting distances. Our findings are a new addition to the literature and can provide valuable insights for researchers or policymakers interested in these dimensions.

At the same time, the magnitude of these responses is small, meaning that a naive Pigouvian price applied to conventional fossil fuel vehicles within the congestion zone accounts for roughly 79 percent of the optimal charge. Overall, the second-best prices are above this Pigouvian benchmark because, on the margin, the induced reductions in fossil fuel vehicles and commuting distances outweigh the damages from substituting to other roads and increased usage of exempt vehicles. While these results are inherently setting-specific, the responses provide valuable priors for researchers interested in studying policies with similar attributes elsewhere.

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Appendix

Road Pricing with Green Vehicle Exemptions:
Theory and Evidence

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A Deriving the optimal congestion charge

This section shows the derivation of the optimal congestion charge. We begin by taking first-order conditions of the consumer's problem (see equation 1), and the planner's problem (see equation 2). Plugging in the consumer first-order conditions into the planner's problem and solving for τ yields the equation in Proposition 1.

A.1 Deriving first-order conditions

The consumer's first-order conditions are:

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

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

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

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:

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

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

A.2 Rearranging expression for optimal congestion charge

1. *Externality conversion.* First, we define the emission and congestion externalities per vehicle ($\widetilde{\phi}$ and $\widetilde{\gamma}$) 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 are:

$$\widetilde{\phi}_g = (v^c t_g^c + v^o t_g^o) l_g \phi_g \qquad \widetilde{\phi}_b = (v^c t_b^c + v^o t_b^o) l_b \phi_b \tag{A1}$$

$$\widetilde{\gamma}_g = v^c t_g^c \gamma^c + v^o t_g^o \gamma^o \qquad \widetilde{\gamma}_b = v^c t_b^c \gamma^c + v^o t_b^o \gamma^o \tag{A2}$$

Second, we define emission and congestion externalities per trip ($\overline{\phi}$ and $\overline{\gamma}$) 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:

$$\overline{\phi_g^c} = n_g v^c l_g \phi_g \qquad \overline{\phi_b^c} = n_b v^c l_b \phi_b \qquad \overline{\phi_g^o} = n_g v^o l_g \phi_g \qquad \overline{\phi_b^o} = n_b v^o l_b \phi_b \tag{A3}$$

$$\overline{\gamma_b^c} = n_b v^c \gamma^c \qquad \overline{\gamma_b^c} = n_b v^c \gamma^c \qquad \overline{\gamma_g^o} = n_g v^o \gamma^o \qquad \overline{\gamma_b^o} = n_b v^o \gamma^o \tag{A4}$$

Third, we define emission and congestion externalities per kilometer traveled ($\hat{\phi}$ and $\overline{\gamma}$) 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:

$$\hat{\phi}^c = n_b t_b^c l_b \phi_b + n_g t_g^c l_g \phi_g \qquad \hat{\phi}^o = n_b t_b^o l_b \phi_b + n_g t_g^o l_g \phi_g \tag{A5}$$

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

2. *Response conversion.* We discretize the derivatives of the fleet composition, the number of trips, and commuting distances with respect to the congestion charge and weigh them by the common denominator in equation (3) ($\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b$) as follows:

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

$$\Delta N_b = \frac{1}{(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b)} \frac{\partial n_b}{\partial \tau} = \frac{1}{(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b)} \frac{\Delta n_b}{\Delta \tau} = \frac{\Delta n_b}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \tag{A8}$$

$$\Delta T_g^o = \frac{1}{(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b)} \frac{\partial t_g^o}{\partial \tau} = \frac{1}{(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b)} \frac{\Delta t_g^o}{\Delta \tau} = \frac{\Delta t_g^o}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \tag{A9}$$

$$\Delta T_g^c = \frac{1}{(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b)} \frac{\partial t_g^c}{\partial \tau} = \frac{1}{(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b)} \frac{\Delta t_g^c}{\Delta \tau} = \frac{\Delta t_g^c}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \tag{A10}$$

$$\Delta T_b^o = \frac{1}{(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b)} \frac{\partial t_b^o}{\partial \tau} = \frac{1}{(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b)} \frac{\Delta t_b^o}{\Delta \tau} = \frac{\Delta t_b^o}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \tag{A11}$$

$$\Delta T_b^c = \frac{1}{(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b)} \frac{\partial t_b^c}{\partial \tau} = \frac{1}{(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b)} \frac{\Delta t_b^c}{\Delta \tau} = \frac{\Delta t_b^c}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \tag{A12}$$

$$\Delta V^c = \frac{1}{(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b)} \frac{\partial v^c}{\partial \tau} = \frac{1}{(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b)} \frac{\Delta v^c}{\Delta \tau} = \frac{\Delta v^c}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \tag{A13}$$

$$\Delta V^o = \frac{1}{(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b)} \frac{\partial v^o}{\partial \tau} = \frac{1}{(\frac{\Delta n_b}{\Delta \tau} t_b^c + \frac{\Delta t_b^c}{\Delta \tau} n_b)} \frac{\Delta v^o}{\Delta \tau} = \frac{\Delta v^o}{(\Delta n_b t_b^c + \Delta t_b^c n_b)} \tag{A14}$$

As 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, the congestion charge formula depends only on the responsiveness to taxes, not the magnitude of the tax change used to estimate these empirical objects. Inserting the converted externalities and discretized responses to the congestion charges allows us to rearrange equation (3) as equation (4).

A.3 Special cases

The congestion charge in equation (3) has several special cases that provide insight into how optimal congestion tolls reflect the consumer's different margins of response. We highlight three special cases of particular interest.

1. *No congestion externality ($\gamma^c = \gamma^o = 0$).*

$$\tau^{emission} = \Delta N_g \cdot \widetilde{\phi}_g + \Delta N_b \cdot \widetilde{\phi}_b + \Delta T \cdot \overline{\phi} + \Delta V^c \cdot \hat{\phi}^c + \Delta V^o \cdot \hat{\phi}^o + \overline{\phi_b^c} \tag{A15}$$

2. *No emission externality ($\phi_g = \phi_b = 0$).*

$$\tau^{congestion} = \Delta N_g \cdot \widetilde{\gamma}_g + \Delta N_b \cdot \widetilde{\gamma}_b + \Delta T \cdot \overline{\gamma} + \Delta V^c \cdot \hat{\gamma}^c + \Delta V^o \cdot \hat{\gamma}^o + \overline{\gamma_I^c} \tag{A16}$$

3. *No leakage ($\frac{\partial t^o}{\partial \tau} = 0$).*

$$\begin{aligned}
\tau^{no\ leakage} = \frac{1}{(\frac{\partial n_b}{\partial \tau} t_b^c + \frac{\partial t_b^c}{\partial \tau} n_b)} \Bigg(& \frac{\partial n_g}{\partial \tau} \Big((v^c t_g^c + v^o t_g^o) l_g \phi_g + v^c t_g^c \gamma^c + v^o t_g^o \gamma^o \Big) \\
& + \frac{\partial n_b}{\partial \tau} \Big((v^c t_b^c + v^o t_b^o) l_b \phi_b + v^c t_b^c \gamma^c + v^o t_b^o \gamma^o \Big) \\
& + \frac{\partial t_g^c}{\partial \tau} \Big(n_g v^c (l_g \phi_g + \gamma^c) \Big) + \frac{\partial t_b^c}{\partial \tau} \Big(n_b v^c (l_b \phi_b + \gamma^c) \Big) \\
& + \frac{\partial v^c}{\partial \tau} \Big(n_b t_b^c l_b \phi_b + n_g t_g^c l_g \phi_g + (n_b t_b^c + n_g t_g^c) \gamma^c \Big) \\
& + \frac{\partial v^o}{\partial \tau} \Big(n_b t_b^o l_b \phi_b + n_g t_g^o l_g \phi_g + (n_b t_b^o + n_g t_g^o) \gamma^o \Big) \Bigg)
\end{aligned} \tag{A17}$$

A.4 Deriving the 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 give the congestion charge for green (τ_g) and brown vehicles (τ_b). The representative agent's problem is:

$$\begin{aligned} \underset{n_g,n_b,t_g^c,t_g^o,t_b^c,t_b^o,v^c,v^o}{max} B &= \underbrace{\mu_g(n_g)[u_g^c(t_g^c) + u_g^o(t_g^o)]}_{\text{utility from green trips}} - \underbrace{n_g((p^c + p_e l_e)v^c + \tau_g)t_g^c - n_g(p^o + p_e l_e)v^o t_g^o}_{\text{utility cost of green trips}} \\ &+ \underbrace{\mu_b(n_b)[u_b^c(t_b^c) + u_b^o(t_b^o)]}_{\text{utility from brown trips}} - \underbrace{n_b((p^c + p_b l_b)v^c + \tau_b)t_b^c - n_b(p^o + p_b l_b)v^o t_b^o}_{\text{utility cost of brown trips}} \\ &- \underbrace{n_b c_b - n_g c_g}_{\text{cost of vehicles}} - \underbrace{r^c(v^c) - r^o(v^o)}_{\text{cost of location choice}} + y. \end{aligned} \tag{A18}$$

The consumer's first-order conditions are:

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

The social planner's problem is to maximize consumer welfare $B^{-\tau}$ from equation (A18) by setting congestion charge for green (τ_g) and brown vehicles (τ_b) entering the congestion zone:

$$\max_{\tau_g,\tau_b} W = B^{-\tau} - \underbrace{n_b(v^c t_b^c + v^o t_b^o) l_b \phi_b}_{\text{emission from brown trips}} - \underbrace{n_g(v^c t_g^c + v^o t_g^o) l_g \phi_g}_{\text{emission from green trips}} - \underbrace{(n_b v^c t_b^c + n_g v^c t_g^c)\gamma^c}_{\text{congestion from inside trips}} - \underbrace{(n_b v^o t_b^o + n_g v^o t_g^o)\gamma^o}_{\text{congestion from outside trips}}. \tag{A19}$$

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

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

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

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

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:

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

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

Solving this system of two equations and unknowns gives the optimal congestion 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*

$$\tau_b = \frac{(c + da)}{(1 - db)} \tag{A20}$$

$$\tau_g = a + b\frac{(c + da)}{(1 - db)}, \tag{A21}$$

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:

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

$$b = -\frac{\frac{\partial n_b}{\partial \tau_g} t_b^c + \frac{\partial t_b^c}{\partial \tau_g} n_b}{\frac{\partial n_g}{\partial \tau_g} t_g^c + \frac{\partial t_g^c}{\partial \tau_g} n_g}$$

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

$$
d = - \frac{\frac{\partial t_g^c}{\partial \tau_b} n_g + \frac{\partial n_g}{\partial \tau_b} t_g^c}{\frac{\partial n_b}{\partial \tau_b} t_b^c + \frac{\partial t_b^c}{\partial \tau_b} n_b}.
$$

Recovering the two optimal vehicle type-specific taxes would require estimates of cross-price derivatives (e.g., how taxes on green vehicle trips impact brown vehicle adoption) that our setting does not allow us to recover. Still, 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 (A21) is greater than zero:

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

This allows us to rewrite the green tax as:

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

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, $|\frac{\partial t_g^o}{\partial \tau_g}\Big(n_g v^o l_g\phi_g + n_g v^o\gamma^o\Big)| < |\frac{\partial t_g^c}{\partial \tau_g}\Big(n_g v^c l_g\phi_g + n_g v^c\gamma^c\Big)|$) 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.

A.5 Deriving uniform congestion charge

This section shows the steps in solving for the uniform congestion charge for all vehicles (τ) entering the congestion zone without exemptions for green vehicles. The representative consumer's optimization problem is to pick the optimal fleet size (i.e., n), the optimal number inside and outside congestion zone trips (i.e., t^c, t^o), and the commuting distances (i.e., v^c, v^o) to maximize consumer welfare B give the congestion charge for vehicles (τ_b). The representative agent's problem can be stated as follows:

$$\begin{aligned} \underset{n,t^c,t^o,v^c,v^o}{max} B \; = \; & \underbrace{\mu(n)[u^c(t^c)+u^o(t^o)]}_{\text{utility from trips}} - \underbrace{n((p^c+pl)v^c+\tau)t^c - n(p^o+pl)v^o t^o}_{\text{utility cost of trips}} \\ & - \underbrace{nc}_{\text{cost of vehicles}} - \underbrace{r^c(v^c)-r^o(v^o)}_{\text{cost of location choice}} + y \end{aligned} \tag{A22}$$

The consumer's first-order conditions are:

$$\begin{aligned} \frac{\partial B}{\partial n} &= 0 = \mu'[u^c(t^c)+u^o(t^o)] - ((p^c+pl)v^c+\tau)t^c - (p^o+pl)t^o v^o - c \\ \frac{\partial B}{\partial t^c} &= 0 = \mu(n)[u'^c(t^c)] - n((p^c+pl)v^c+\tau) \\ \frac{\partial B}{\partial t^o} &= 0 = \mu(n)[u'^o(t^o)] - n(p^o+pl)v^o \\ \frac{\partial B}{\partial v^o} &= 0 = -n(p^o+pl)t^o - r'(v^c) \\ \frac{\partial B}{\partial v^c} &= 0 = -n(p^c+pl)t^c - r'(v^c). \end{aligned}$$

The social planner's problem is to maximize consumer welfare $B^{-\tau}$ from equation (A22) by setting congestion charges for vehicles (τ) entering the congestion zone:

$$\max_{\tau} W = B^{-\tau} - \underbrace{nv^c t^c \gamma^c}_{\text{congestion from inside trips}} - \underbrace{nv^o t^o \gamma^o}_{\text{congestion from outside trips}} \tag{A23}$$

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

$$\begin{aligned}
\frac{\partial W}{\partial \tau} = 0 = & \frac{\partial n}{\partial \tau}\bigg(\mu'[u^c(t^c) + u^o(t^o)] - (p^c + pl)v^c t^c - (p^o + pl)t^o v^o \\
& - c - v^c t^c \gamma^c - v^o t^o \gamma^o\bigg) \\
& + \frac{\partial t^o}{\partial \tau}\bigg(\mu(n)[u'^o] - n(p^o + pl)v^o - nv^o\gamma^o\bigg) \\
& + \frac{\partial t^c}{\partial \tau}\bigg(\mu(n)[u_g'^{\,c}] - n(p^c + pl)v^c - nv^c\gamma^c\bigg) \\
& + \frac{\partial v^c}{\partial \tau}\bigg(-n(p^c + pl)t^c - r'(v^c) - nt^c\gamma^c\bigg) \\
& + \frac{\partial v^o}{\partial \tau}\bigg(-n(p^o + pl)t^o - r'(v^o) - nt^o\gamma^o\bigg).
\end{aligned}$$

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

$$\begin{aligned}\frac{\partial W}{\partial \tau} = 0 = &\frac{\partial n}{\partial \tau}\left(\tau t^c - v^c t^c \gamma^c - v^o t^o \gamma^o\right) \\ &+ \frac{\partial t^o}{\partial \tau}\left(-n v^o \gamma^o\right) + \frac{\partial t^c}{\partial \tau}\left(n\tau - n v^c \gamma^c\right) \\ &+ \frac{\partial v^c}{\partial \tau}\left(-n t^c \gamma^c\right) + \frac{\partial v^o}{\partial \tau}\left(-n t^o \gamma^o\right)\end{aligned}$$

Proposition 3. *The second-best congestion charge τ on vehicles per crossing that addresses congestion externalities through changes in the fleet composition, the number of trips, and the commuting distance is given by*

$$\begin{aligned}\tau \ = \ &\frac{1}{(\frac{\partial n}{\partial \tau} t^c + \frac{\partial t^c}{\partial \tau} n)}\left(\frac{\partial n}{\partial \tau}\left(v^c t^c \gamma^c + v^o t^o \gamma^o\right)\right. \\ &+ \frac{\partial t^o}{\partial \tau}\left(n v^o \gamma^o\right) + \frac{\partial t^c}{\partial \tau}\left(n v^c \gamma^c\right) \\ &\left. + \frac{\partial v^c}{\partial \tau}\left(n t^c \gamma^c\right) + \frac{\partial v^o}{\partial \tau}\left(n t^o \gamma^o\right)\right) \qquad \text{(A24)}\end{aligned}$$

B Additional background on congestion pricing

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

B.1 Congestion charges

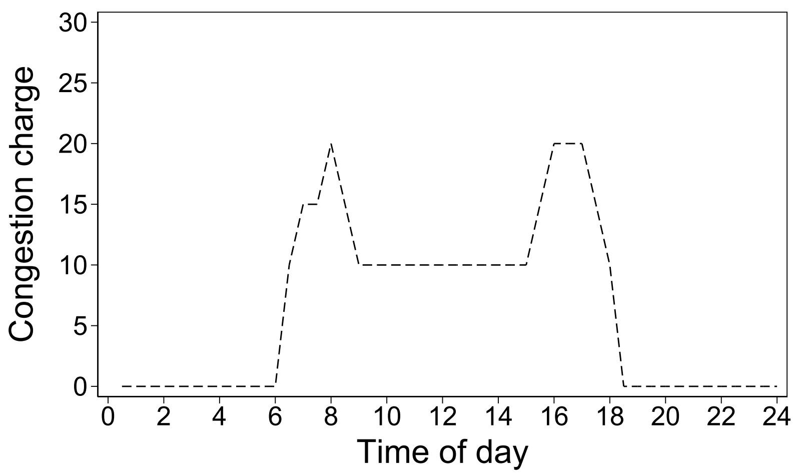


Figure B1: Congestion charges by time of the day in Stockholm

Notes: The figure shows congestion charges for Stockholm by the time of the day from 2006 to 2015.

Figure B2: Congestion charges at entry

Notes: The picture illustrates the Stockholm congestion charges at each entry point.

B.2 Vehicle market

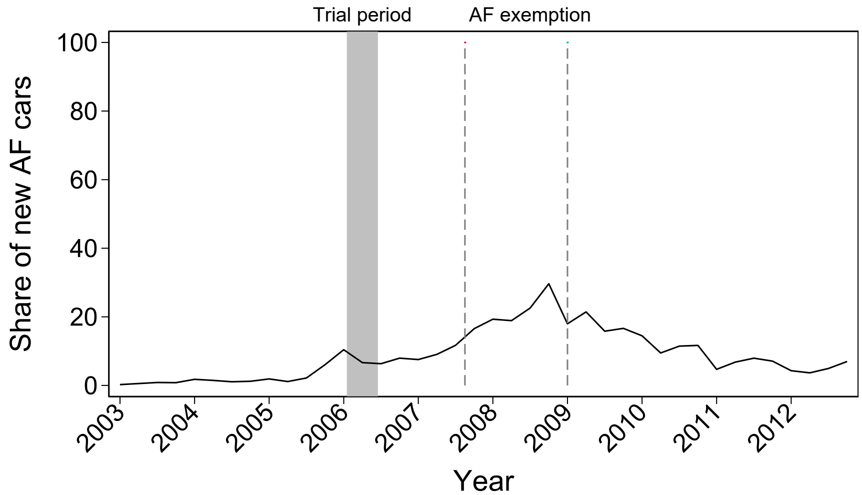


Figure B3: Share of new alternative fuel vehicles in Stockholm

Notes: The figure displays the share of quarterly new alternative fuel vehicles that private individuals registered in Stockholm between 2003 and 2012. The gray bar indicates the trial period between January 2006 and July 2006. The exemption period of alternative fuel vehicles for the congestion zone is indicated through the two dashed lines between August 2007 and December 2008.

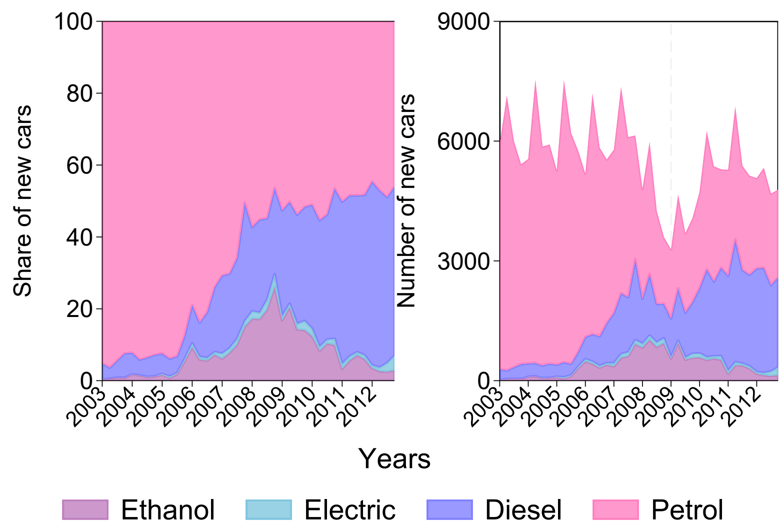


Figure B4: Newly registered cars in Stockholm

Notes: The figures display the share (Panel A) and the total number (Panel B) of quarterly new cars that private individuals registered in the Swedish vehicle market between 2003 and 2012.

B.3 Descriptive statistics on commuters in Stockholm

Table B1: Summary statistics by commuter group in 2005

	Treated		Non-Treated		Stockholm	
	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
A.Demographic Variables						
Age	45.27	9.84	44.59	9.71	40.63	13.05
Female	0.37	0.48	0.25	0.43	0.50	0.50
Gross Salary (in tho.)	515.91	501.51	474.28	291.09	303.43	311.61
Disposable Income (in tho.)	258.04	428.28	232.23	151.98	212.60	813.84
Unemployment Days	0.00	0.00	0.00	0.00	0.00	0.00
Self-Employmed	0.05	0.22	0.03	0.18	0.10	0.29
Married or Cohabitant	0.77	0.42	0.75	0.44	0.58	0.49
At Least 1 Child	0.38	0.48	0.31	0.46	0.45	0.50
Years of Education	13.32	2.48	12.74	2.43	12.59	2.47
B.Outcome Variables						
Alternative Fuel Cars	0.01	0.08	0.01	0.08	0.00	0.05
Fossil Fuel Cars	1.14	0.40	1.17	0.43	0.49	0.72
Total Cars	1.15	0.39	1.17	0.43	0.49	0.72
Alternative Fuel Kilometers	96.24	1287.11	79.73	1173.27	30.71	754.09
Fossil Fuel Kilometers	15004.70	8571.05	16293.30	8997.19	6753.97	13611.45
Vehicle Kilometers Traveled	15101.09	8522.75	16373.02	8964.44	6784.77	13631.37
Distance Commute (km)	16.86	9.75	19.43	8.87	24.22	75.94
N(Observation)	46.056		10.430		870.769	

Notes: The table shows summary statistics for socio-demographic characteristics (Panel A), and outcome variables (Panel B) for treated, non-treated commuters, and all people in Stockholm before the implementation of the congestion charge in 2005. Treated commuters are defined as individuals who cross the congestion 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 tunnel on the (time-minimizing) route between home and work.

B.4 Traffic volume

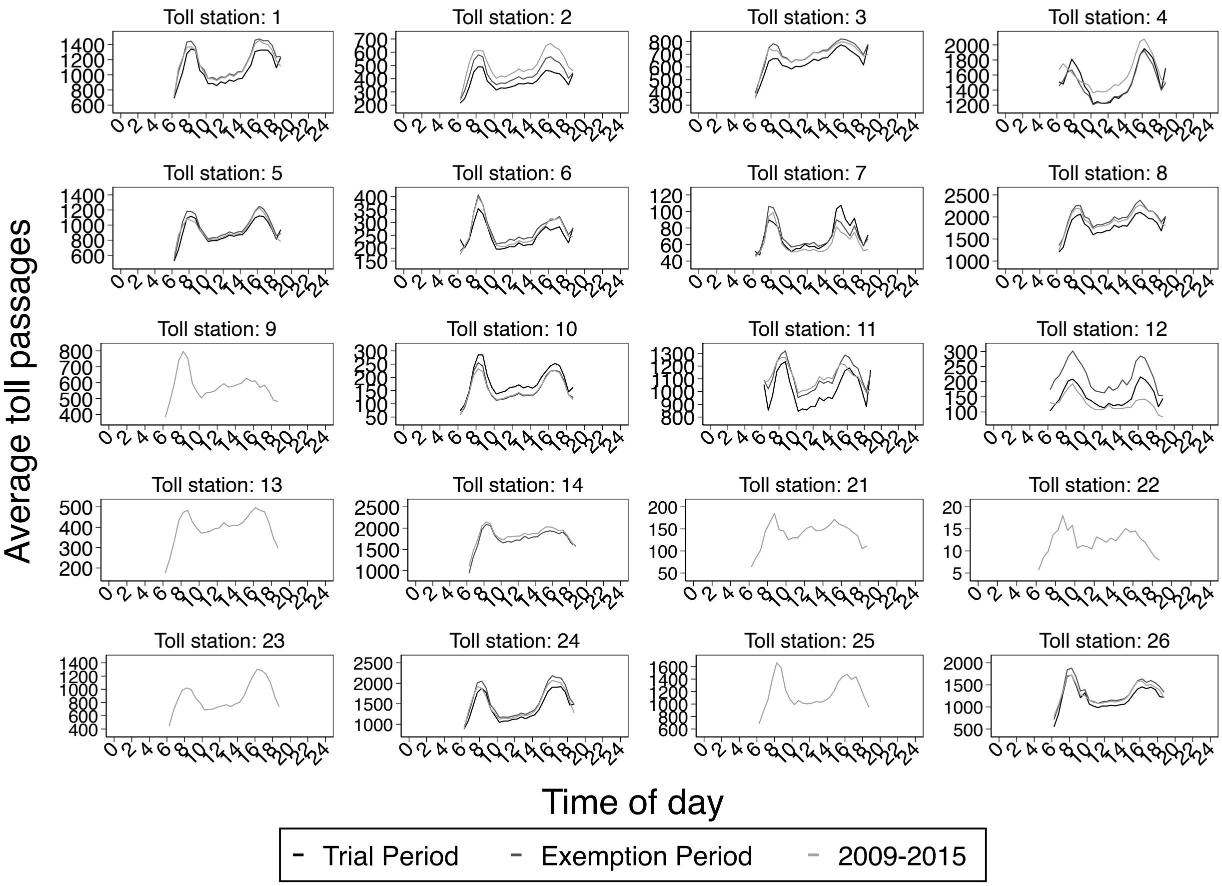


Figure B5: Toll station passages by time of day

Notes: The figure shows the average number of vehicles passing each toll cordon over a day based on 30-minute intervals. The corresponding toll station number can be found on the map in Figure I. The underlying data is sourced from the Swedish transport agency (*Transportstyrelsen*) and is based on sensor-level data. The data contains information on all vehicles passing the automated toll gates between 6 am and 7 pm on weekdays from 2006 to 2023, within a 30-minute resolution.

C Sample details

C.1 Definition of control and treatment group

Treated commuters are individuals who crossed the congestion 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. Table C1 summarizes the classification of treated- and non-treated commuters depending on the neighborhood and workplace location. *Non-treated commuters* are defined as individuals who live and work outside the congestion zone and use the Essinge bypass or the Lidingö tunnel 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 an increase in congestion charges. 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 commuters 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: Treatment and control group

		Workplace Location	
		Inside	Outside
Neighborhood Location	Inside	Excluded	*Treated commuters*
	Outside	*Treated commuters*	*Non-treated commuters* via Essinge/Lidingö

C.2 Sample selection

The database contains information at the individual-level restricted to persons above 18. Based on our definition of treated and non-treated commuters in Stockholm, we restrict our sample in the following way:

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.*
   - Remove people working and living inside Stockholm.
   - Remove individuals working and living outside of Stockholm 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.
6. Individuals must own at least one and up to 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 individuals to ensure these are not used for business purposes. We consider work distances below 3 kilometers as walking and cycling distances 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.[41] 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 D7). To estimate the effect on commuting distance, we restrict the sample to individuals outside the congestion zone (column 8).

[41] 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						Balanced Sample	Outside Zone
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Years								
2003	1,217,085	845,890	298,372	280,328	125,872	53,176	38,762	48,267
2004	1,236,578	859,827	301,486	283,134	139,182	59,138	38,762	53,597
2005	1,260,738	870,769	306,109	287,582	157,940	66,671	38,762	60,250
2006	1,293,780	903,686	315,005	295,839	192,485	77,653	38,762	69,590
2007	1,329,834	972,133	336,640	315,534	192,485	79,259	38,762	79,259
2008	1,366,838	993,526	345,715	324,067	192,485	80,348	38,762	80,348
Individuals	1,525,337	1,247,558	605,322	570,621	192,4845	97,298	38,762	95,644
Total	7,704,853	5,445,831	1,903,327	1,786,484	1,000,449	416,245	232,572	391,311

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 final sample. Column (7) corresponds to the balanced sample. Column (8) removes individuals that reside within the congestion zone.

C.3 Treated and non-treated commuters by area

Figure C1 displays neighborhoods within 50 kilometers of Stockholm by the share of treated commuters. Neighborhoods within the congestion zone have a share of treated commuters that equals 100 percent, as we only include commuters that cross the congestion zone on their way to work. The percentage of treated commuters is low near the Essinge bypass in the Southwest of Stockholm and close to the island of Lidingö in the east of Stockholm. Note that several neighborhoods close to the city centers are too small to be visible.

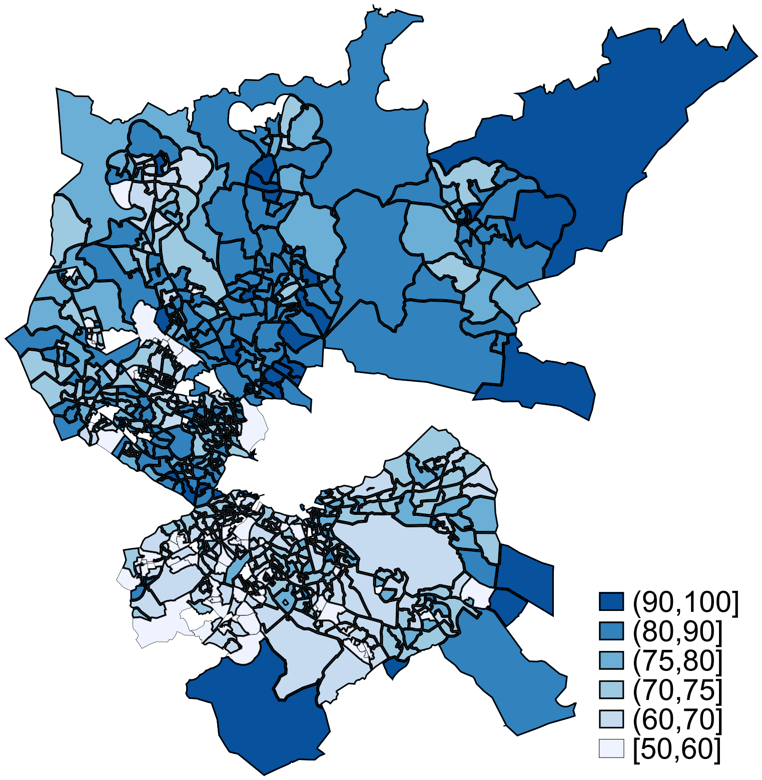


Figure C1: Share of treated commuters

Notes: The map displays the share of treated commuters in Stockholm by DeSO neighborhood in 2006. We exclude DeSO neighborhoods inside the congestion zone as the share of treated commuters equals 100 percent.

D Supporting results and robustness checks

D.1 Main effects

Table D1: The impact of congestion pricing on new vehicle adoption

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.New Vehicle Adoption			
Post x Treated Commuters	.0017***	-.0037**	-.0022
	(.0007)	(.0018)	(.0019)
Mean New Car Adoption (t-1)	.005	.063	.066

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on new vehicle adoption (Panel A). The dependent variables in Panel A are indicators for whether an individual adopts a new alternative fuel vehicle (column 1), a new fossil fuel vehicle (column 2), or any new vehicle (column 3). The mean dependent variables of the previous year are reported below the coefficients. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. 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 vehicle kilometers traveled

	Vehicle Kilometers Traveled		
	(1) Alternative	(2) Fossil	(3) Total
A.Alternative Fuel Exemption			
Post x Treated Commuters	121.39***	-253.05***	-149.78**
	(26.79)	(70.97)	(69.44)
Mean Vehicle Kilometers (t-1)	242.7	15202.4	15299
B.Removal of Alternative Exemption			
Post x Treated Commuters	-103.50**	206.29**	102.79
	(50.88)	(87.48)	(82.69)
Mean Vehicle Kilometers (t-1)	1885.1	12168.6	14053.7

Notes: This table displays the coefficients from a DiD specification (equation 6) 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 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. 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 D3: The impact of congestion pricing on the decisions of family members

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.Vehicle Ownership			
Post x Treated Commuters	.0004	.0008	.0011
	(.0003)	(.0020)	(.0021)
B.Kilometers Traveled			
Post x Treated Commuters	10.0*	-8.7	-.1
	(5.6)	(28.9)	(29.3)

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on the vehicle ownership (Panel A) and driving behavior (Panel B) of the family members of treated commuters. The dependent variables in Panel A are indicators for whether family members of treated commuters own an alternative fuel vehicle (column 1), a fossil fuel vehicle (column 2), or any vehicle (column 3). The dependent variables in Panel B are the vehicle kilometers traveled by family members in alternative fuel vehicles (column 1), fossil fuel vehicles (column 2), and all vehicles (column 3). The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D4: 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	-.005***	-.006***	.002***
	(.002)	(.002)	(.000)
Mean Dep. Variable	.059	.056	.003
B.Workplace Relocation			
Post x Treated Commuters	.005**	.016***	-.010***
	(.002)	(.001)	(.002)
Mean Dep. Variable	.094	.025	.069
New Employer	-.007***	.007***	-.014***
	(.002)	(.001)	(.001)
Old Employer	.012***	.008***	.004***
	(.001)	(.001)	(.001)

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on where individuals live and work. The first column displays estimates on 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). The mean dependent variables of the previous year are reported below the coefficients. 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.

D.2 Dynamic effects

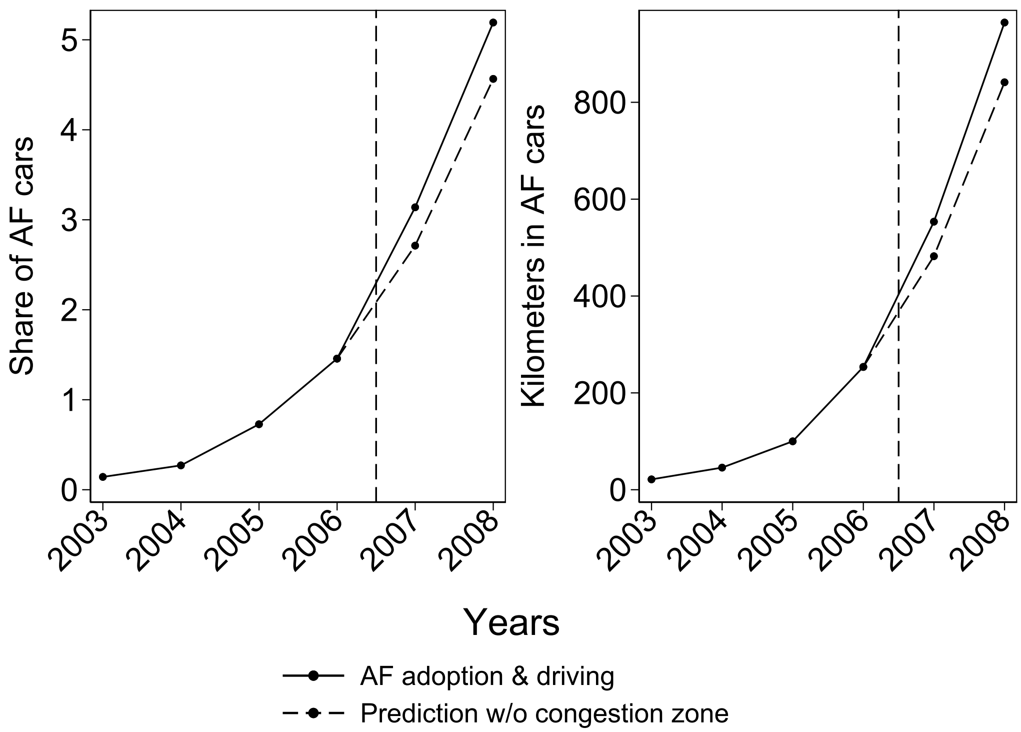


Figure D1: Predicted vehicle ownership and driving behavior

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 that 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 IV. The vertical distance between the two lines is the estimated annual treatment effect of the congestion pricing policy on the share and kilometers traveled of alternative fuel cars. The vertical dashed line denotes the implementation of the exemption policy (2007).

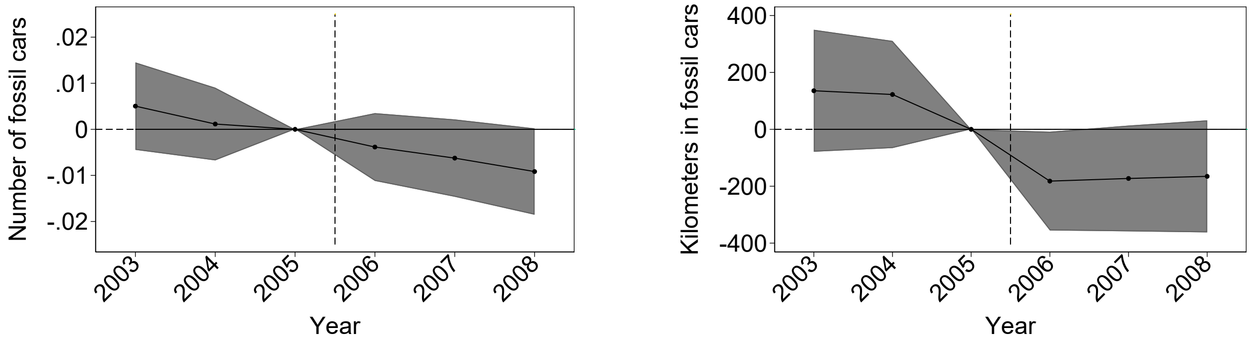


Figure D2: The impact of congestion pricing on fossil fuel vehicles

Notes: These figures plot the coefficients from a dynamic DiD specification (equation 7), where β_{2005} is normalized to zero. Panel A shows the annual treatment effect on the probability of owning a fossil fuel vehicle. Panel B shows the annual treatment effect on kilometers traveled with fossil fuel vehicles. The sample is restricted to 2003-2008, where 2006-2008 is the post-period. Standard errors are clustered at the neighborhood level. The vertical dashed line denotes the imposition of the Stockholm Congestion Trial (2006).

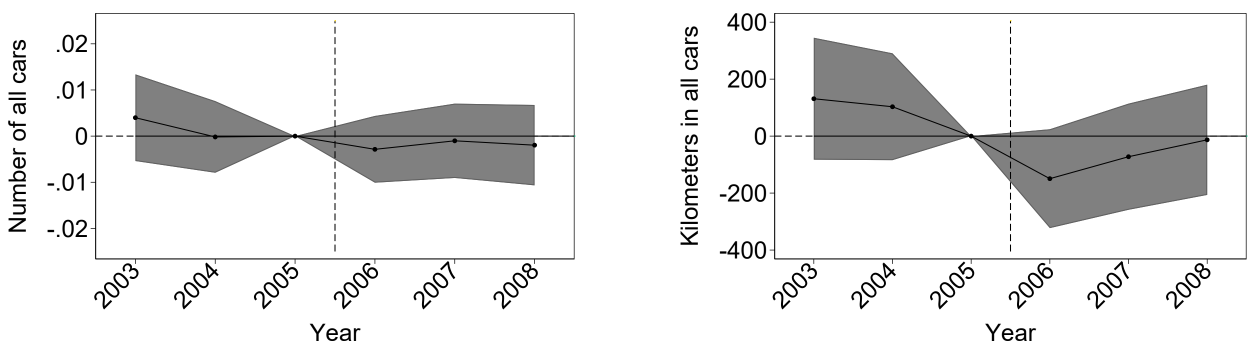
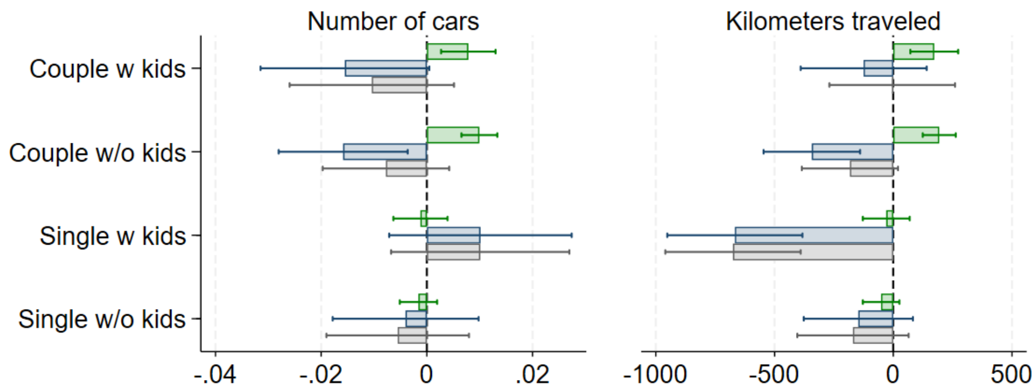


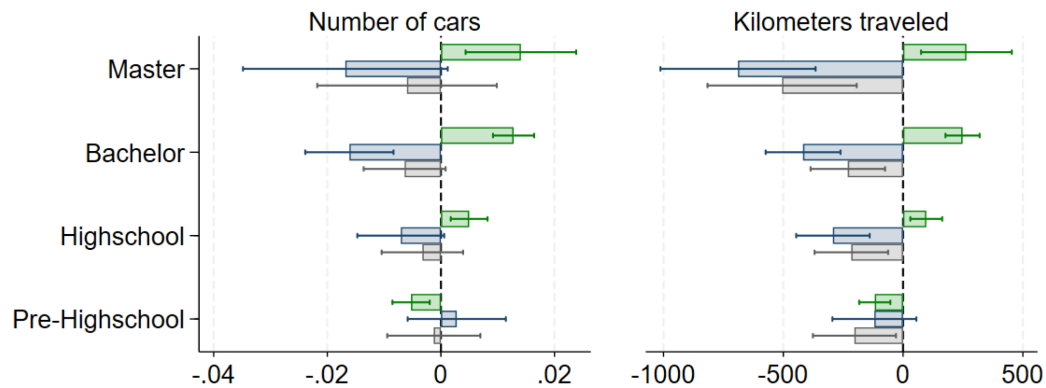
Figure D3: The impact of congestion pricing on any vehicle

Notes: These figures plot the coefficients from a dynamic DiD specification (equation 7), where β_{2005} is normalized to zero. Panel A shows the annual treatment effect on the probability of owning any vehicle. Panel B shows the annual treatment effect on total vehicle kilometers traveled. The sample is restricted to 2003-2008, where 2006-2008 is the post-period for fossil fuel vehicles. Standard errors are clustered at the neighborhood level. The vertical dashed line denotes the imposition of the Stockholm Congestion Trial (2006).

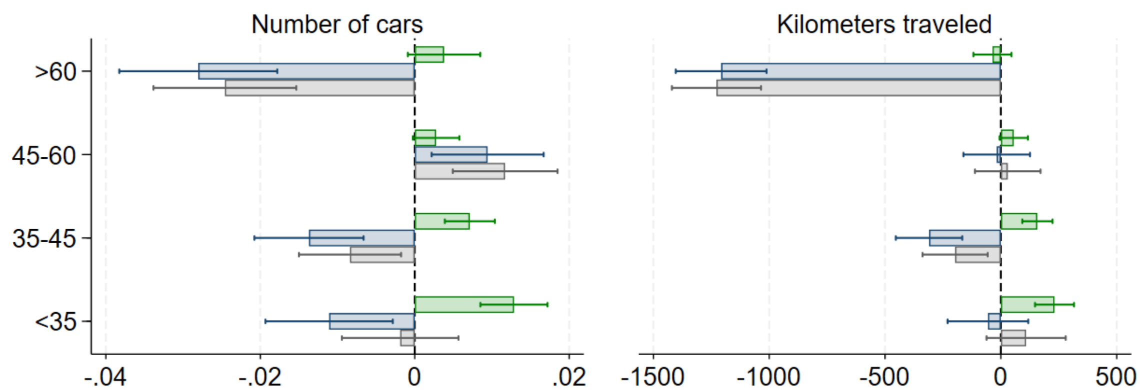
D.3 Heterogeneous effects



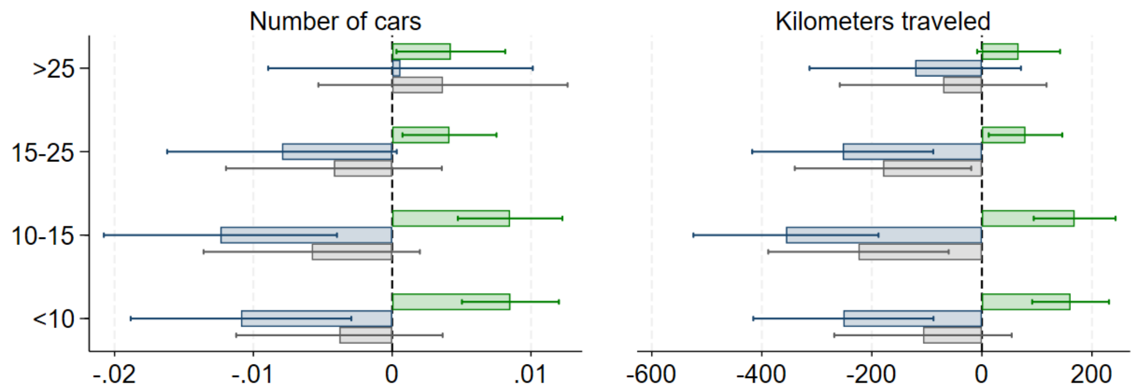
(a) Family status



(b) Years of education



(c) Age



(d) Commuting distance

Figure D4: The impact of congestion pricing on different socio-economic groups

Notes: The figures plot the coefficients β_k on vehicle ownership and driving behavior for alternative (green), fossil fuel (blue), and any vehicle (gray) for four socio-economic characteristics: family status (Panel A), education (Panel B), age (Panel C), and commuting distance (Panel D). 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. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles and 2006-2008 is the post-period for fossil fuel vehicles. 95%-confidence intervals are indicated through whiskers and reflect robust standard errors clustered by neighborhoods.

Table D5: The heterogeneous effects of congestion pricing on commuting distances

	Commuting Distance			
	(1)	(2)	(3)	(4)
Panel A. Income				
Post x Paying Commuters	-.0050	.0025	-.0426	-.0396
	(.0430)	(.0323)	(.0316)	(.0311)
Panel B. Family Status				
Post x Paying Commuters	-.0868**	-.0614	-.0238	.0776*
	(.0419)	(.0420)	(.0302)	(.0426)
Panel C. Education				
Post x Paying Commuters	-.0347	-.0582*	-.0118	.0207
	(.0333)	(.0308)	(.0307)	(.0513)
Panel D. Age				
Post x Paying Commuters	.0032	-.0701**	-.0318	.0787**
	(.0505)	(.0318)	(.0285)	(.0354)
Panel E. Commute Distance				
Post x Paying Commuters	-.1632***	.0271	.0206	-.0309
	(.0464)	(.0329)	(.0324)	(.0362)

Notes: This table displays the results from the DiD specification (equation 6) 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 (1)-(4) correspond to the socio-economic subgroups defined in Figure D4. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

D.4 Robustness checks

Table D6: Same post period estimates

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.Vehicle Ownership			
Post x Treated Commuters	.0052***	-.0083**	-.0030
	(.0011)	(.0035)	(.0033)
Mean Car Ownership (t-1)	.007	1.138	1.145
B.Number of Trips			
Post x Treated Commuters	5.6***	-13.8***	-8.2**
	(1.2)	(3.9)	(3.8)
Inside Congestion Trips	5.9**	-11.8**	-5.9
	(2.9)	(5.0)	(4.7)
Mean Trips Inside (t-1)	2.5	399.1	401.7
Change Trips Outside	-.3	-2	-2.3
Mean Trips Outside (t-1)	2.7	432.1	434.8
C.Commuting Distance			
Post x Treated Commuters			-.086***
			(.030)
Mean Commute Distance (t-1)			17.5
Changes in Outside Distance			-.007
Mean Outside Distance (t-1)			19

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), number of trips (Panel B), and commuting distance (Panel C), using the same post period specification for both alternative fuel and fossil fuel vehicles. 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 number of trips 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). The mean dependent variables of the previous year are reported below the coefficients. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Appendix E.2 details the conversion from vehicle kilometers traveled to the number of trips by fuel type and the change in commute distances. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D7: Estimates using a balanced panel

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.Vehicle Ownership			
Post x Treated Commuters	.0049***	-.0060	-.0018
	(.0019)	(.0048)	(.0046)
Mean Car Ownership (t-1)	.015	1.164	1.171
B.Number of Trips			
Post x Treated Commuters	4.5**	-14.6***	-10.6**
	(2.1)	(4.9)	(4.8)
Inside Congestion Trips	4.5	-6.5	-2.0
	(3.3)	(6.1)	(5.6)
Mean Trips Inside (t-1)	6.4	404.3	406.9
Change Trips Outside	0	-8.1	-8.6
Mean Trips Outside (t-1)	7.1	446.1	449
C.Commuting Distance			
Post x Treated Commuters			-.028
Mean Commute Distance (t-1)			17.9
Changes in Outside Distance			.007
Mean Outside Distance (t-1)			19

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), number of trips (Panel B), and commuting distance (Panel C), using the balanced sample from column (8) 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 number of trips 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). The mean dependent variables of the previous year are reported below the coefficients. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Appendix E.2 details the conversion from vehicle kilometers traveled to the number of trips by fuel type and the change in commute distances. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D8: 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	.0037***	-.0036	-.0025
	(.0013)	(.0035)	(.0034)
Mean Car Ownership (t-1)	.014	1.145	1.152
B.Number of Trips			
Post x Treated Commuters	3.8***	-11.4***	-9.9**
	(1.4)	(3.9)	(3.9)
Inside Congestion Trips	1.9	-8.8*	-6.9
	(2.9)	(5.0)	(4.8)
Mean Trips Inside (t-1)	6.4	402.3	404.7
Change Trips Outside	2	-2.6	-2.9
Mean Trips Outside (t-1)	6.9	435.5	438.1
C.Commuting Distance			
Post x Treated Commuters			-.086***
			(.030)
Mean Commute Distance (t-1)			17.5
Changes in Outside Distance			-.008
Mean Outside Distance (t-1)			19

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), number of trips (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 number of trips 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). The mean dependent variables of the previous year are reported below the coefficients. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Appendix E.2 details the conversion from vehicle kilometers traveled to the number of trips by fuel type and the change in commute distances. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D9: 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	.0174***	-.0422***	-.0078*
	(.0017)	(.0050)	(.0043)
Mean Car Ownership (t-1)	.014	1.13	1.139
B.Number of Trips			
Post x Treated Commuters	17.6***	-31.8***	3.4
	(1.8)	(5.6)	(5.3)
Inside Congestion Trips	33.9***	-33.9***	-.1
	(4.0)	(6.5)	(6.1)
Mean Trips Inside (t-1)	6.4	406.9	409.8
Change Trips Outside	-16.3	2.1	3.5
Mean Trips Outside (t-1)	6.9	440.5	443.6
C.Commuting Distance			
Post x Treated Commuters			-.186***
			(.048)
Mean Commute Distance (t-1)			17.5
Changes in Outside Distance			-.005
Mean Outside Distance (t-1)			19

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), number of trips (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 number of trips 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). The mean dependent variables of the previous year are reported below the coefficients. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Appendix E.2 details the conversion from vehicle kilometers traveled to the number of trips by fuel type and the change in commute distances. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D10: Effects including inside-inside commuters

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.Vehicle Ownership			
Post x Treated Commuters	.0081***	-.0114***	-.0044
	(.0014)	(.0035)	(.0033)
Mean Car Ownership (t-1)	.015	1.132	1.139
B.Number of Trips			
Post x Treated Commuters	8.6***	-15.7***	-8.1**
	(1.5)	(3.9)	(3.8)
Inside Congestion Trips	7.9***	-13.8***	-5.9
	(3.1)	(5.2)	(4.9)
Mean Trips Inside (t-1)	7.1	416.1	418.8
Change Trips Outside	.7	-1.9	-2.2
Mean Trips Outside (t-1)	7.3	426.1	428.9
C.Commuting Distance			
Post x Treated Commuters			-.064**
			(.030)
Mean Commute Distance (t-1)			16.6
Changes in Outside Distance			-.012
Mean Outside Distance (t-1)			19

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), number of trips (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 number of trips 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). The mean dependent variables of the previous year are reported below the coefficients. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Appendix E.2 details the conversion from vehicle kilometers traveled to the number of trips by fuel type and the change in commute distances. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D11: Estimates with workplaces near congestion zone

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.Vehicle Ownership			
Post x Treated Commuters	.0044***	-.0110**	-.0078*
	(.0016)	(.0045)	(.0043)
Mean Car Ownership (t-1)	.013	1.139	1.146
B.Number of Trips			
Post x Treated Commuters	4.5**	-16.0***	-12.2**
	(1.8)	(5.0)	(4.9)
Inside Congestion Trips	3.7	-15.1**	-11.4*
	(3.8)	(6.4)	(5.9)
Mean Trips Inside (t-1)	6.1	410.2	412.7
Change Trips Outside	.7	-.9	-.8
Mean Trips Outside (t-1)	6.4	429.7	432.3
C.Commuting Distance			
Post x Treated Commuters			-.147***
			(.030)
Mean Commute Distance (t-1)			17
Changes in Outside Distance			-.027
Mean Outside Distance (t-1)			19

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), number of trips (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 number of trips 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). The mean dependent variables of the previous year are reported below the coefficients. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Appendix E.2 details the conversion from vehicle kilometers traveled to the number of trips by fuel type and the change in commute distances. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D12: Estimates with workplace-location fixed effects

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.Vehicle Ownership			
Post x Treated Commuters	.0074***	-.0063*	-.0004
	(.0014)	(.0035)	(.0034)
Mean Car Ownership (t-1)	.014	1.138	1.145
B.Number of Trips			
Post x Treated Commuters	7.4***	-12.5***	-6.4
	(1.5)	(4.0)	(3.9)
Inside Congestion Trips	5.9**	-9.0*	-3.1
	(3.0)	(5.0)	(4.7)
Mean Trips Inside (t-1)	6.4	399.1	401.7
Change Trips Outside	1.5	-3.6	-3.3
Mean Trips Outside (t-1)	6.9	432.1	434.8
C.Commuting Distance			
Post x Treated Commuters			-.086***
			(.030)
Mean Commute Distance (t-1)			17.5
Changes in Outside Distance			-.007
Mean Outside Distance (t-1)			19

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), number of trips (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 number of trips 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). The mean dependent variables of the previous year are reported below the coefficients. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Appendix E.2 details the conversion from vehicle kilometers traveled to the number of trips by fuel type and the change in commute distances. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

D.5 Responses by income groups

Table D13: Estimates for low-income groups

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.Vehicle Ownership			
Post x Treated Commuters	-.0020	.0082*	.0076*
	(.0017)	(.0043)	(.0040)
Mean Car Ownership (t-1)	.011	1.112	1.117
B.Number of Trips			
Post x Treated Commuters	-2.8	-13.0***	-13.7***
	(1.9)	(4.8)	(4.8)
Inside Congestion Trips	4.9	-13.7*	-8.8
	(3.9)	(7.1)	(6.7)
Mean Trips Inside (t-1)	5.2	368.1	370.1
Change Trips Outside	-7.7	.7	-4.9
Mean Trips Outside (t-1)	5.7	401.6	403.8
C.Commuting Distance			
Post x Treated Commuters			-.070*
			(.036)
Mean Commute Distance (t-1)			17.7
Changes in Outside Distance			-.008
Mean Outside Distance (t-1)			19

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), number of trips (Panel B), and commuting distance (Panel C), for individuals with an annual income of less than 350k 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 number of trips 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). The mean dependent variables of the previous year are reported below the coefficients. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Appendix E.2 details the conversion from vehicle kilometers traveled to the number of trips by fuel type and the change in commute distances. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D14: Estimates for medium-income groups

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.Vehicle Ownership			
Post x Treated Commuters	.0063***	-.0142***	-.0089**
	(.0015)	(.0037)	(.0035)
Mean Car Ownership (t-1)	.014	1.122	1.13
B.Number of Trips			
Post x Treated Commuters	5.7***	-22.4***	-17.4***
	(1.6)	(4.0)	(3.9)
Inside Congestion Trips	3.5	-3.7	-.2
	(4.2)	(7.4)	(6.9)
Mean Trips Inside (t-1)	6.2	387.9	390.8
Change Trips Outside	2.2	-18.7	-17.2
Mean Trips Outside (t-1)	6.8	424.9	428.1
C.Commuting Distance			
Post x Treated Commuters			-.000
			(.018)
Mean Commute Distance (t-1)			17.7
Changes in Outside Distance			.023
Mean Outside Distance (t-1)			19

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), number of trips (Panel B), and commuting distance (Panel C), for individuals with an annual income of between 350k to 500k 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 number of trips 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). The mean dependent variables of the previous year are reported below the coefficients. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Appendix E.2 details the conversion from vehicle kilometers traveled to the number of trips by fuel type and the change in commute distances. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

Table D15: Estimates for high-income groups

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.Vehicle Ownership			
Post x Treated Commuters	.0138***	-.0098**	.0005
	(.0019)	(.0045)	(.0042)
Mean Car Ownership (t-1)	.017	1.205	1.212
B.Number of Trips			
Post x Treated Commuters	16.6***	4.9	17.5***
	(2.2)	(4.9)	(4.7)
Inside Congestion Trips	11.6**	-46.4***	-34.8***
	(4.9)	(8.9)	(8.3)
Mean Trips Inside (t-1)	8	460.6	462.7
Change Trips Outside	5	51.3	52.3
Mean Trips Outside (t-1)	8.3	480.7	482.9
C.Commuting Distance			
Post x Treated Commuters			-.110***
			(.032)
Mean Commute Distance (t-1)			16.9
Changes in Outside Distance			-.187
Mean Outside Distance (t-1)			19

Notes: This table displays the coefficients from a DiD specification (equation 6) that estimates the impact of Stockholm's congestion pricing policy on vehicle ownership (Panel A), number of trips (Panel B), and commuting distance (Panel C), for individuals with an annual income of over 500k 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 number of trips 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). The mean dependent variables of the previous year are reported below the coefficients. The sample is restricted to 2003-2008, where 2007-2008 is the post-period for alternative fuel vehicles, and 2006-2008 is the post-period for fossil fuel vehicles. Appendix E.2 details the conversion from vehicle kilometers traveled to the number of trips by fuel type and the change in commute distances. Standard errors are clustered at the neighborhood level. *, **, ***: statistically significant with 90%, 95%, and 99% confidence, respectively.

D.6 Distributional effects

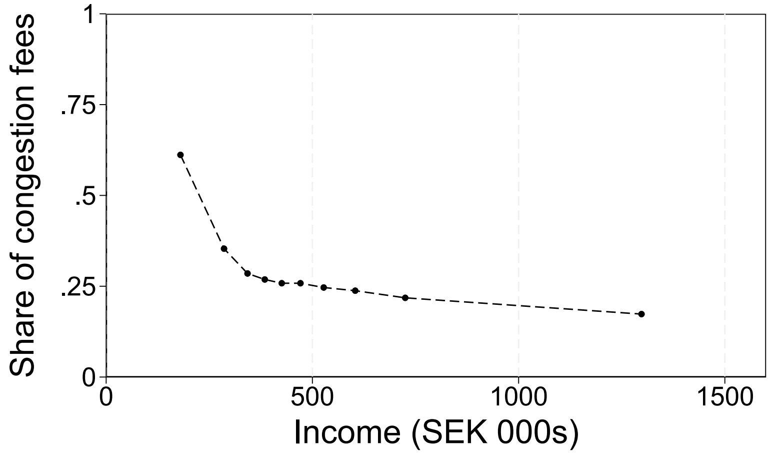


Figure D5: Congestion charges by share of salary

Notes: This figure illustrates the Stockholm congestion charges as a share of income for each income decile in 2016.

E Details of calculating the optimal congestion charge

In this section, we implement our congestion charge formula from equation (3) using our empirical estimates and supplementing it with costs of emissions and congestion from the literature.

E.1 Registry data

1. *Number of trips.* The individual-level vehicle kilometers traveled by green and brown vehicles are equal to the sum of the number and length of congestion crossings and non-congestion zone crossings:

$$KM_g = v^c \cdot t_g^c + v^o \cdot t_g^o \tag{E1}$$

$$KM_b = v^c \cdot t_b^c + v^o \cdot t_b^o \tag{E2}$$

We observe the individual-level vehicle kilometers traveled for both fuel types (Panel A of Table D2) 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 on the number of congestion and non-congestion zone trips ($t^c,\ t^o$), we use the fact that 46 percent of kilometer-weighted trips are business-related (The Swedish National Travel Survey, 2007). We calculate the number of trips in the congestion zone for green and brown vehicles as follows:

$$\begin{aligned} .46 \cdot KM_g &= v^c \cdot t_g^c \\ t_g^c &= \frac{.46 \cdot KM_g}{v^c} \\ t_g^c &= \frac{.46 \cdot 242.7km}{17.5km} \approx 6.4 \end{aligned} \tag{E3}$$

$$\begin{aligned} .46 \cdot KM_b &= v^c \cdot t_b^c \\ t_b^c &= \frac{.46 \cdot KM_b}{v^c} \\ t_b^c &= \frac{.46 \cdot 15,202.4km}{17.5km} \approx 399.1 \end{aligned} \tag{E4}$$

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

$$\begin{aligned} .54 \ \cdot \ KM_g \ &= v^o \cdot t_g^o \\ t_g^o \ &= \ \frac{.54 \ \cdot \ KM_g}{v^o} \\ t_g^o \ &= \ \frac{.54 \ \cdot \ 242.7km}{19km} \ \approx \ 6.9 \end{aligned} \tag{E5}$$

$$\begin{aligned} .54 \ \cdot \ KM_b \ &= v^o \cdot t_b^o \\ t_b^o \ &= \ \frac{.54 \ \cdot \ KM_b}{v^o} \\ t_b^o \ &= \ \frac{.54 \ \cdot \ 15,202.4km}{19km} \ \approx \ 432.1 \end{aligned} \tag{E6}$$

E.2 Deriving changes in trips by vehicle type and outside commuting distance

The congestion charge formula from equation (9) 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.

1. *Changes in number of congestion trips by vehicle type.* To convert the estimates on vehicle kilometers traveled for green and brown vehicles into changes in the number of congestion trips by vehicle type, we exploit that the exemption of alternative fuel vehicles of 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 the kilometers traveled in green and brown vehicles after 2012 equals the effect on kilometers traveled inside the congestion zone after the implementation of the congestion charge:

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

We use the effect of removing the alternative fuel vehicle exemption on the kilometer traveled (Table D2) scaled by the average congestion distance v^c to calculate the change in congestion zone trips with green vehicles as follows:

$$\begin{aligned} \frac{\partial t_g^c}{\partial \tau_g} &= -\frac{\partial KM_g}{\partial \tau_{-g}} \cdot \frac{1}{v^c} \\ \frac{\partial t_g}{\partial \tau_g} &= \frac{103.5km}{17.5km} = 5.9 \end{aligned} \tag{E8}$$

We derive the change in the number of non-congestion zone trips in green vehicles as the difference between the change of all green congestion zone trips (Table I, Panel B) less the change in green trips from equation (E8):

$$\begin{aligned} \frac{\partial t_g^o}{\partial \tau} &= \frac{\partial t_g}{\partial \tau} - \frac{\partial t_g^c}{\partial \tau} \\ \frac{\partial t_g^o}{\partial \tau} &= 6.6 - 5.9 = .7 \end{aligned} \tag{E9}$$

Similarly, we use the effect of removing the alternative fuel vehicle exemption on the kilometer traveled (Table D2) scaled by the average congestion distance v^c to calculate the change in congestion zone trips with brown vehicles as follows:

$$\begin{aligned} \frac{\partial t_b^c}{\partial \tau} &= -\frac{\partial KM_b}{\partial \tau_{-g}} \cdot \frac{1}{v^c} \\ \frac{\partial t_b^c}{\partial \tau^c} &= -\frac{206.3km}{17.5km} = -11.8 \end{aligned} \tag{E10}$$

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

$$\begin{aligned} \frac{\partial t_g^o}{\partial \tau} &= \frac{\partial t_g}{\partial \tau} - \frac{\partial t_g^c}{\partial \tau} \\ \frac{\partial t_g^o}{\partial \tau} &= -13.8 + 11.8 - = -2 \end{aligned} \tag{E11}$$

2. *Changes in outside commuting distance.* The total outside vehicle kilometers traveled is equal to the product of the number of trips and the average commuting distance outside the congestion zone. Inserting the total vehicle kilometers traveled (Table I) and the average outside commuting distance v^o from the Swedish National Travel Survey (2007), we

calculate the number of outside trips as:

$$
\begin{aligned}
KM^o &= v^o \cdot t^o \\
t^o &= \frac{.54 \cdot 15,299km}{19km} \approx 434.1
\end{aligned} \tag{E12}
$$

We then estimate the change in vehicle kilometers traveled outside the congestion zone with respect to the congestion charge, which is equal to the change in total vehicle kilometers traveled (Panel A, Table D2) less the change in kilometers traveled inside the congestion zone (Panel B, Table D2):

$$
\begin{aligned}
\frac{\partial KM}{\partial \tau} &= \frac{\partial KM^c}{\partial \tau} + \frac{\partial KM^o}{\partial \tau} \\
\frac{\partial KM^o}{\partial \tau} &= -149.8km + 102.8km \approx -47km
\end{aligned} \tag{E13}
$$

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

$$
\begin{aligned}
\frac{\partial KM^o}{\partial \tau} &= \frac{\partial v^o}{\partial \tau} \cdot t^o + \frac{\partial t^o}{\partial \tau} \cdot v^o \\
\frac{\partial v^o}{\partial \tau} &= \frac{\frac{\partial KM^o}{\partial \tau} - \frac{\partial t^o}{\partial \tau} \cdot v^o}{t^o} \\
\frac{\partial v^o}{\partial \tau} &= \frac{-47 + 2.3 \cdot 19km}{434.8} \approx -.007km
\end{aligned} \tag{E14}
$$

In calculating the change in outside trip distances, we insert 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 D2).

E.3 Emission externalities

1. *Emission rates for brown vehicles.* We assume that the emission externalities consist of "global" pollutants, which contribute to climate change, and "local" pollutants, which negatively impact the health of nearby residents (Anderson, 2020; Currie & Walker, 2011).[42] To quantify the social costs of emission externalities, we combine our empirical estimates

[42] A growing literature has documented various channels through which air pollution has adverse effects on societal outcomes, such as low birth weight (Currie & Walker, 2011), respiratory diseases (Jans et al., 2018), lower productivity in physical and high-skilled work (Zivin & Neidell, 2012; Chang et al., 2016; Ebenstein et al., 2016; Archsmith et al., 2018), criminal activity (Bondy et al., 2020).

with vehicle emission factors – the amount of a particular pollutant that a vehicle emits while traveling a kilometer – and the social costs of the pollutant from the literature. Table E2 summarizes the vehicle emission estimates and costs of pollutants.

First, we rely on a recent report by the European Environment Agency (2021) that provides emission factors by vehicle type for the main pollutants in Sweden.[43] The main local air pollutants are ammonia (NH_3), particulate matter (PM) and sulfur oxides (SO_2), and the global pollutant is carbon dioxide (CO_2). These pollution externalities have been shown to make up most of kilometer-weighted average emissions factors (Tarduno, 2022). 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 use the fleet composition of Swedish vehicles in 2006 to quantify the average local emissions rates per kilometer traveled.

Second, 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. 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 given pollutant in a given location. The price year used is 2005.

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. Table E1 summarizes the emission externalities that are derived from the European Environment Agency (2014, 2021). We assume that emission externalities are equal inside and outside the congestion zone. To quantify the monetary equivalent of the emission externalities, we then multiply the average vehicle emission factor by the social cost for each pollutant:[44]

[43] Although vehicle emission factors depend on several variables, including the type of fuel consumed, fuel economy, vehicle age, and vehicle speed, we assume a constant emission factor for each vehicle.

[44] We convert kilogram into liter by assuming that one kilogram of petrol is equal to .72 liter (https://coolconversion.com/density-volume-mass/–1–liter–of–petrol%2C-natural–in–kg).

$$\begin{aligned}
\phi_b &= \Big(\Delta PM \cdot (MC_{PM_{2.5}} + MC_{PM_{10}}) + \Delta CO_2 \cdot MC_{CO_2} + \Delta CNH_3 \cdot MC_{NH_3} \\
&\quad + \Delta SO_2 \cdot MC_{SO_2}\Big) \cdot .72 \frac{kg}{l} \\
\phi_b &= \Big(.25 \frac{g\ PM}{kg\ fuel} \cdot (23.2 \frac{€}{kg\ PM} + 15.01 \frac{€}{kg\ PM}) + 3162 \frac{g\ CO_2}{kg\ fuel} \cdot .105 \frac{€}{kg\ CO_2} \\
&\quad + 9.11 \frac{g\ NH_3}{kg\ fuel} \cdot 12.15 \frac{€}{kg\ NH_3} + 6.69 \frac{g\ SO_2}{kg\ fuel} \cdot 15.44 \frac{€}{kg\ SO_2}\Big) \cdot .72 \frac{kg}{l} \\
\phi_b &= (.009 + .33 + .11 + .103) \frac{€}{kg\ fuel} \cdot .72 \frac{kg}{l} \ = \ .397 \frac{€}{l} \qquad \text{(E15)}
\end{aligned}$$

Equation (E15) states that the marginal emission externality equals €.397 (≈ 3.7 SEK) per liter fuel for brown vehicles. Relative to the average petrol price of 11.4 SEK in Sweden in 2006,[45] the emission externalities correspond to around 32.8 percent of the average petrol price. We convert the emission externalities into real 2021 € using the Consumer Price Index from Statistics Sweden. If we multiply this with the average vehicle fuel efficiency for fossil fuel vehicles (l_b) , we obtain the emission externality for brown vehicles per kilometer:

$$\phi_b \cdot l_b \ = \ .397 \frac{€}{l} \cdot 8.37 \frac{l}{100km} \ \cdot 1.22393 = \ .04 \frac{€}{km} \qquad \text{(E16)}$$

[45]We use historical data on fuel prices from *bensinstation.nu* (https://www.bensinstation.nu/historiska-br%C3%A4nslepriser/).

Table E1: Emission externalities

Coefficient	Descriptions	Value	Source
ΔPM	Emission of particulate matter $[\frac{g}{kg\ fuel}]$	.25	European Environment Agency (2021), Table A1-0-28
ΔCO_2	Emission from carbon dioxide $[\frac{g}{kg\ fuel}]$	3162	European Environment Agency (2021), Table A1-0-28
ΔNH_3	Emission from ammonia $[\frac{g}{kg\ fuel}]$	9.11	European Environment Agency (2021), Table A1-0-28
ΔSO_2	Emission from sulfur dioxide $[\frac{g}{kg\ fuel}]$	6.69	European Environment Agency (2021), Table A1-0-28
$MC_{PM_{2.5}}$	Costs of fine particulate matter $[\frac{€}{kg}]$	23.2	European Environment Agency (2014)
$MC_{PM_{10}}$	Costs of particulate matter $[\frac{€}{kg}]$	15.01	European Environment Agency (2014)
MC_{CO_2}	Costs of carbon dioxide $[\frac{€}{kg}]$	0.105	
MC_{NH_3}	Costs of ammonia $[\frac{€}{kg}]$	12.15	European Environment Agency (2014)
MC_{SO_2}	Costs of sulfur dioxide $[\frac{€}{kg}]$	15.44	European Environment Agency (2014)

2. *Emissions rates for green vehicles.* Although electric vehicles produce little to no exhaust when in use, they charge from the electrical grid, which may generate emissions depending on the marginal fuel source (Holland et al., 2016). In this Appendix, we describe how we estimate emissions factors for electric vehicles in Sweden.

We use Revision of emission factors for electricity generation and district heating (2016), commissioned by the Swedish Environmental Protection Agency for emissions rates for local and global air pollutants. This report uses data from fossil fuel generation in Sweden to suggest emissions factors for use in emissions inventory analyses.
The emissions rates by fuel type are as follows:

Coal: $100g/GJ\ SO_2$; $80g/GJ\ NO_x$; $2g/GJ\ NH_3$; $16.6g/GJ\ PM_{2.5}$
Natural Gas: $50g/GJ\ NO_x$; $.4g/GJ\ PM_{2.5}$[46]

[46]Note that there is no entry for $PM_{2.5}$ emissions for Natural Gas in 2015, we instead use the then forward-looking estimate for a 2020 emissions factor.

Residual Fuel Oil: $60g/GJ\ NO_x$; $8.3g/GJ\ PM_{2.5}$

Following the European Environment Ageny (2014), we use the following costs (converted into €2021) for the damages of emitting one ton of each pollutant in Sweden:[47]

$PM_{2.5}$: €21761.94
NO_x: €5540.60
SO_2: €14556.14
NH_3: €11399.15

We multiply the emissions rates by damages and convert units, assuming 3 kWh per kilometer:

$$\underbrace{\frac{[g]}{[GJ]}}_{emissions\ factor} \cdot \frac{[tons]}{[g]} \cdot \frac{[GJ]}{[kWh]} \cdot \underbrace{\frac{[€]}{[ton]}}_{damages} \cdot \frac{[kWh]}{[km]} = \frac{[€]}{[km]}$$

The result is damages per kilometer driven if the marginal kilometer is charged at a time when any of the above fuels are the marginal emissions source.

Coal: $.003\ \frac{€}{km}$
Natural Gas: $.0004\ \frac{€}{km}$
Residual Fuel Oil: $.0007\ \frac{€}{km}$

$$\begin{aligned} \phi_g \cdot l_g =&\ \Delta Coal + \Delta Gas + \Delta Oil \\ \phi_g \cdot l_g =&\ (.003 + .0004 + .0007)\frac{€}{km} \ = \ .0041\frac{€}{km} \end{aligned} \tag{E17}$$

E.4 Congestion externalities

Marginal costs of road congestion vary in space and time. The transportation economics literature canonically presents congestion externalities as a function of traffic density, measured in vehicles per lane-mile (Small & Verhoef, 2007). 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, and the occupancy of vehicles in terms of passengers and

[47] The European Environment Agency reports a "high" and "low" value for each pollutant. We take the mean of these two values.

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 for rural areas the congestion externalities outside the congestion zone. We convert the congestion externalities into real 2021 € using the Consumer Price Index from Statistics Sweden.

The congestion costs in small and medium urban areas arrive ($< 2,000,000$ citizens) at a value for passenger vehicles of around €.38 per kilometer and €.13 per kilometer in rural areas.[48] Based on an average congestion and non-congestion zone journey length of 17.4km and 19km, respectively, we estimate a congestion externality of approximately €6.57 and €2.47 per trip, which exceeds the peak-hour congestion pricing in Stockholm.

E.5 Calculating total externalities per vehicle, trip, and kilometer

Here, we show how we combine each of our data sources to estimate the parameters described in Appendix A. These parameters are themselves inputs into the optimal fax formula shown in Proposition 1.

First, the emission and congestion externalities per brown and green vehicle ($\widetilde{\phi}$ and $\widetilde{\gamma}$) are:

$$\begin{aligned}
\widetilde{\phi}_g + \widetilde{\gamma}_g &= (v^c t_g^c + v^o t_g^o) l_g \phi_g + v^c t_g^c \gamma^c + v^o t_g^o \gamma^o \\
\widetilde{\phi}_g + \widetilde{\gamma}_g &= 0 \frac{€}{km} + 17.5km \cdot 6.4 \cdot .38 \frac{€}{km} + 19km \cdot 6.9 \cdot .13 \frac{€}{km} \\
\widetilde{\phi}_g + \widetilde{\gamma}_g &\approx 59.6€ \qquad \text{(E18)}
\end{aligned}$$

$$\begin{aligned}
\widetilde{\phi}_b + \widetilde{\gamma}_b &= (v^c t_b^c + v^o t_b^o) l_b \phi_I + v^c t_b^c \gamma^c + v^o t_b^o \gamma^o \\
\widetilde{\phi}_b + \widetilde{\gamma}_b &= (17.5km \cdot 399.1 + 19km \cdot 432.1) \cdot .04 \frac{€}{km} + 17.5km \cdot 399.1 \cdot .38 \frac{€}{km} + 19km \cdot 432.1 \cdot .13 \frac{€}{km} \\
\widetilde{\phi}_b + \widetilde{\gamma}_b &\approx 4329.1€ \qquad \text{(E19)}
\end{aligned}$$

Second, the emission and congestion externalities for brown and green vehicles per trip ($\overline{\phi}$ and $\overline{\gamma}$) inside and outside the congestion zone are:

[48] Marginal congestion costs rise with the size of agglomeration areas because large urban areas attract traffic from surrounding towns, and a shift to outside roads is often impossible.

$$\begin{aligned}
\overline{\phi_g^c} + \overline{\gamma_g^c} &= n_g v^c (l_g \phi_g + \gamma^c) \\
\overline{\phi_g^c} + \overline{\gamma_g^c} &= .014 \cdot 17.5km \cdot (0\frac{€}{km} + \cdot .38\frac{€}{km}) \\
\overline{\phi_g^c} + \overline{\gamma_g^c} &\approx .09€
\end{aligned} \tag{E20}$$

$$\begin{aligned}
\overline{\phi_g^o} + \overline{\gamma_g^o} &= n_g v^o \cdot (l_g \phi_g + \gamma^o) \\
\overline{\phi_g^o} + \overline{\gamma_g^o} &= .014 \cdot 19km \cdot (0\frac{€}{km} + .13\frac{€}{km}) \\
\overline{\phi_g^o} + \overline{\gamma_g^o} &\approx .03€
\end{aligned} \tag{E21}$$

$$\begin{aligned}
\overline{\phi_b^c} + \overline{\gamma_b^c} &= n_b v^c (l_b \phi_b + \gamma^c) \\
\overline{\phi_b^c} + \overline{\gamma_b^c} &= 1.138 \cdot 17.5km \cdot (.04\frac{€}{km} + \cdot .38\frac{€}{km}) \\
\overline{\phi_b^c} + \overline{\gamma_b^c} &\approx 8.36€
\end{aligned} \tag{E22}$$

$$\begin{aligned}
\overline{\phi_b^o} + \overline{\gamma_b^o} &= n_b v^o (l_b \phi_b + \gamma^o) \\
\overline{\phi_b^o} + \overline{\gamma_b^o} &= 1.138 \cdot 19km \cdot (.04\frac{€}{km} + .13\frac{€}{km}) \\
\overline{\phi_b^o} + \overline{\gamma_b^o} &\approx 3.68€
\end{aligned} \tag{E23}$$

Third, the emission and congestion externalities inside and outside the congestion zone per kilometer traveled ($\hat{\phi}$ and $\overline{\gamma}$) are:

$$\begin{aligned}
\hat{\phi}^c + \hat{\gamma}^c &= n_b t_b^c l_b \phi_b + n_g t_g^c l_g \phi_g + (n_b t_b^c + n_g t_g^c)\gamma^c \\
\hat{\phi}^c + \hat{\gamma}^c &= 1.138 \cdot 399.1 \cdot .04\frac{€}{km} + 0\frac{€}{km} + (1.138 \cdot 399.1 + .014 \cdot 6.4) \cdot .38\frac{€}{km} \\
\hat{\phi}^c + \hat{\gamma}^c &\approx 190.79\frac{€}{km}
\end{aligned} \tag{E24}$$

$$\begin{aligned}
\hat{\phi}^o + \hat{\gamma}^o &= n_b t_b^o l_b \phi_b + n_g t_g^o l_g \phi_g + (n_b t_b^o + n_g t_g^o)\gamma^o \\
\hat{\phi}^o + \hat{\gamma}^o &= 1.138 \cdot 432.1 \cdot .04\frac{€}{km} + 0\frac{€}{km} + (1.138 \cdot 432.1 + .014 \cdot 6.9) \cdot .13\frac{€}{km} \\
\hat{\phi}^o + \hat{\gamma}^o &\approx 83.6\frac{€}{km}
\end{aligned} \tag{E25}$$

Table E2: Parameter estimates used for congestion charge

Coefficient	Descriptions	Value	Source
Panel A: Registry Data			
n_g	Number of green vehicles per person	.014	Table I, Panel A
n_b	Number of brown vehicles per person	1.138	Table I, Panel A
t_g^c	Number of congestion-trips with green vehicles	6.4	Table I, Panel B, equation (E3)
t_b^c	Number of congestion-trips with brown vehicles	399.1	Table I, Panel B, equation (E4)
t_g^o	Number of non-congestion-trips with green vehicles	6.9	Table I, Panel B, equation (E5)
t_b^o	Number of non-congestion-trips with brown vehicles	432.1	Table I, Panel B, equation (E6)
v^c	Average kilometers traveled on congestion zone trips	17.5	Table I, Panel C
v^o	Average kilometers traveled on non-congestion zone trips	19	Table I, Panel B, Swedish National Travel Survey (2007)
Panel B: Empirical estimates			
$\frac{\partial n_g}{\partial \tau}$	Effect of congestion charge τ on number of green vehicles n_g	.0064	Table I, Panel A
$\frac{\partial n_b}{\partial \tau}$	Effect of congestion charge τ on number of brown vehicles n_b	$-.0083$	Table I, Panel A
$\frac{\partial t_g^o}{\partial \tau}$	Effect of congestion charge τ on number of outside congestion trips in green vehicles t_g^o	.7	Table D2, Panel B, equation (E9)
$\frac{\partial t_g^o}{\partial \tau}$	Effect of congestion charge τ on number of congestion trips in green vehicles t_g^c	5.9	Table D2, Panel B, equation (E8)
$\frac{\partial t_b^o}{\partial \tau}$	Effect of congestion charge τ on number of outside congestion trips in brown vehicles t_b^o	-11.8	Table D2, Panel B, equation (E10)
$\frac{\partial t_b^o}{\partial \tau}$	Effect of congestion charge τ on number of congestion trips in brown vehicles t_b^c	-2	Table D2, Panel B, equation (E11)
$\frac{\partial v^c}{\partial \tau}$	Effect of congestion charge τ on average kilometers on congestion trips v^c	$-.086$	Table D4, Panel C
$\frac{\partial v^o}{\partial \tau}$	Effect of congestion charge τ on average kilometers on non-congestion trips v^o	$-.007$	Table D4, Panel C, equation (E14)
Panel C: Emission externalities [$\frac{€}{km}$]			
$\phi_b \cdot l_b$	Emission externalities for brown vehicles	.04	Equation (E16)
$\phi_g \cdot l_g$	Emission externalities for green vehicles	0	Equation (E17)
Panel D: Congestion externalities [$\frac{€}{km}$]			
γ^c	Congestion externalities for inside cordon driving	.38	External Costs of Transport (2011), Table 38
γ^o	Congestion externalities for outside cordon driving	.13	External Costs of Transport (2011), Table 38

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