Road Pricing with Multiple Policy Goals: The Effect on Car Ownership, Driving, and Commuting

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Tackling multiple negative externalities

(a) Plastic waste reduction

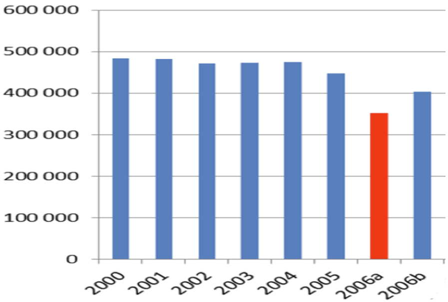
(b) Air pollution control

(c) Land degradation prevention

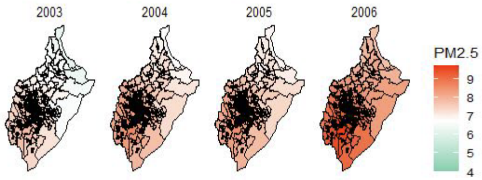
(d) Animal farming

Local air quality and traffic

Traffic volumes in Stockholm



Emission levels in Stockholm



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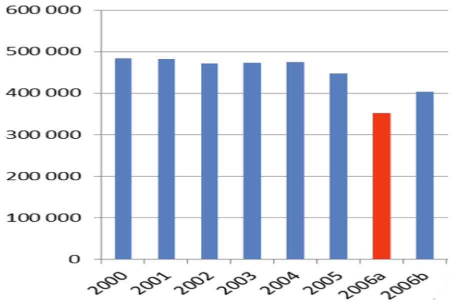

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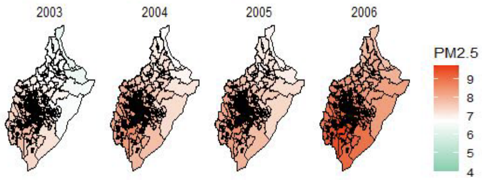

Purpose of Stockholm congestion trial in 2006 (*Stockholmsförsöket*):

> *"I syfte att minska trängseln, öka framkomligheten och förbättra miljön genomfördes det så kallade Stockholmsförsöket."*

> *"In order to reduce congestion, increase accessibility and improve the environment, the so-called Stockholm trial was carried out."*

Theory

Externalities:

- Emission externalities differ by vehicle type
- Congestion externalities differ by location
  - $\rightarrow$ Substitution across congestion and emission (*Imperfection I*)
  - $\rightarrow$ Substitution towards unpriced roads (*Imperfection II*)

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Behavioral responses to congestion zone (CZ):

1. **Fleet decomposition** (*Motive I*)**:**
   - → Sell internal combustion engine (ICE) car
   - → Adopt exempted alternative fuel (AF) car
2. **Number of trips** (*Motive II*)**:**
   - → Reduce number of trips in ICE cars
   - → Increase number of trips in AF cars
3. **Commuting distance** (*Motive III*)**:**
   - → Move into CZ or relocate to workplace outside CZ

Contributions

Primary contribution:

- We provide a theoretical and empirical framework for calculating congestion charges

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2. **Identification:**
   → We exploit variation in individuals' exposure to tolls on the road section between home and work
3. **Policy implication:**
   → We decompose congestion charges by motives and externalities

Preview of results

Empirical findings:

- Individuals exposed to congestion charges on their way to work:
  - $\rightarrow$ are .65 percentage points more likely to adopt an AF car
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Policy implications:

- Congestion charge equals €10.44 per crossing (€.6 per kilometer)
  - $\rightarrow$ Congestion externalities account for 89% (€9.3)

Literature review

This work speaks to three strands of literature:

1. Behaviorally-motivated taxes
   - → Taxation with behavioral agents (Farhi & Gabaix, 2020), internalities (Gerritsen, 2016; Allcott *et al.*, 2019), inattention (Chetty *et al.*, 2009, Koszegi & Seidl, 2013; Schwartzstein, 2014), self-control (Gruber & Koszegi, 2004; O'Donoghue & Rabin, 2006), social reputation (Benabou & Tirole, 2011)
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   → **Congestion zone charges** (Mun *et al.*, 2003; Verhoef, 2005)

2. Behavioral responses to road traffic policies
   → Reduced traffic volume in Singapore (Phang & Toh, 1997; Olsyewski & Xie, 2005), London (Santos *et al.*, 2004; Santos & Shaffer, 2004), Stockholm (Eliasson, 2009; Börjesson *et al.*, 2012), Gothenburg (Börjesson *et al.*, 2016), and Milan (Gibson & Carnovale, 2015; Beria, 2016), intertemporal substitution (Foreman, 2016), and substitution to unpriced roads (Leape, 2006; Tarduno, 2022)

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3. Adoption of environmentally friendly vehicles
   - → Vehicle subsidies (Muehlegger & Rapson, 2018; Clinton & Steinberg, 2019), charging infrastructure (Li *et al.*, 2017; Springel, 2021), and low emission zones (Wolff, 2014)

Model of urban travel

Consumer's problem (Anderson & Sallee, 2016)**:**

1. Number of EV and ICE cars (i.e., n_E, n_I)
2. Number of CZ and non-CZ trips in EV and ICE cars (i.e., t_E^c, t_E^o, t_I^c, t_I^o)
3. Commuting distance for CZ and non-CZ trips (i.e., v^c, v^o)

$$\begin{aligned}\max_{n_E,n_I,t_E^c,t_E^o,t_I^c,t_I^o,v^c,v^o} B = & \underbrace{\mu_E(n_E)[u_E^c(t_E^c)+u_E^o(t_E^o)]}_{\text{utility from EV trips}} - \underbrace{n_E(p^c+p_e e)v^c t_E^c - n_E(p^o+p_e e)v^o t_E^o}_{\text{utility cost of EV trips}} \\ & + \underbrace{\mu_I(n_I)[u_I^c(t_I^c)+u_I^o(t_I^o)]}_{\text{utility from ICE trips}} - \underbrace{n_I((p^c+p_g g)v^c+\tau)t_I^c - n_I(p^o+p_g g)v^o t_I^o}_{\text{utility cost of ICE trips}} \\ & - \underbrace{n_I c_I - n_E c_E}_{\text{cost of vehicles}} - \underbrace{r^c(v^c)-r^o(v^o)}_{\text{cost of location choice}} + y \qquad (1)\end{aligned}$$

- v^c, v^o : Vehicle kilometer traveled in CZ and outside CZ
- c_I, c_E : Cost of ICE and EV cars
- g, e : Vehicle fuel efficiency of ICE cars and EVs
- p_g, p_e : Cost of gasoline and electricity
- p^c, p^o : Kilometer costs of driving in CZ and outside CZ

Model of urban travel

Social planner's problem:

- Set congestion charge τ on ICE cars entering CZ

$$\max_{\tau} W = B^{-\tau} - \underbrace{n_I(v^c t_I^c + v^o t_I^o) g \phi_I}_{\text{emission from ICE trips}} - \underbrace{n_E(v^c t_E^c + v^o t_E^o) e \phi_E}_{\text{emission from EV trips}} - \underbrace{(n_I v^c t_I^c + n_E v^c t_E^c)\gamma^c}_{\text{congestion from inside trips}} - \underbrace{(n_I v^o t_I^o + n_E v^o t_E^o)\gamma^o}_{\text{congestion from outside trips}} \quad (2)$$

Externalities:

- Emission externalities differ by vehicle type (i.e., ϕ_E and ϕ_I)
- Congestion externalities differ by location (i.e., γ^c and γ^o)

Imperfections:

- Substitution towards unpriced roads
- Substitution across congestion and emission externalities

Expression for congestion charge

$$
\begin{aligned}
\tau \;=\; & \frac{1}{\frac{\partial t_I^c}{\partial \tau} n_I} \Bigg(\frac{\partial n_E}{\partial \tau} \Big((v^c t_E^c + v^o t_E^o) e\phi_E + v^c t_E^c \gamma^c + v^o t_E^o \gamma^o \Big) \\
& + \frac{\partial n_I}{\partial \tau} \Big((v^c t_I^c + v^o t_I^o) g\phi_I + v^c t_I^c \gamma^c + v^o t_I^o \gamma^o \Big) \\
& + \frac{\partial t_E^o}{\partial \tau} \Big(n_E v^o (e\phi_E + \gamma^o) \Big) + \frac{\partial t_E^c}{\partial \tau} \Big(n_E v^c (e\phi_E + \gamma^c) \Big) + \frac{\partial t_I^o}{\partial \tau} \Big(n_I v^o (g\phi_I + \gamma^o) \Big) \\
& + \frac{\partial v^c}{\partial \tau} \Big(n_I t_I^c g\phi_I + n_E t_E^c e\phi_E + (n_I t_I^c + n_E t_E^c) \gamma^c \Big) \\
& + \frac{\partial v^o}{\partial \tau} \Big(n_I t_I^o g\phi_I + n_E t_E^o e\phi_E + (n_I t_I^o + n_E t_E^o) \gamma^o \Big) \Bigg) + v^c (g\phi_I + \gamma^c)
\end{aligned}
\tag{3}
$$

Interpretation:

- Change in motives x (congestion + emission) ext. + externality of CZ trips in ICE cars

Intuition for congestion charge

For the purpose of building intuition, we rearrange equation (3) as follows:

$$\tau = \underbrace{\Delta N_E \cdot (\widetilde{\phi_E} + \widetilde{\gamma_E}) + \Delta N_I \cdot (\widetilde{\phi_I} + \widetilde{\gamma_I})}_{\triangle Fleet\ \ composition} + \underbrace{\Delta T \cdot (\overline{\phi} + \overline{\gamma})}_{\triangle Trips}$$
$$+ \underbrace{\Delta V^c \cdot (\hat{\phi}^c + \hat{\gamma}^c) + \Delta V^o \cdot (\hat{\phi}^o + \hat{\gamma}^o)}_{\triangle Commute\ \ Distances} + \underbrace{E^c}_{\triangle Externalities} \tag{4}$$

Motives:

- ΔN_E, ΔN_I: Changes in electric and ICE cars
- ΔT: Changes in the number of trips
- ΔV^c, ΔV^o: Changes in the commuting distance inside and outside

Externalities:

- $\widetilde{\phi} + \widetilde{\gamma}$: Emission and congestion externalities per car
- $\overline{\phi} + \overline{\gamma}$: Emission and congestion externalities per trip
- $\hat{\phi}^c + \hat{\gamma}^c$: Emission and congestion externalities per kilometer traveled

Interpreting the formula

Externality considerations:

- No congestion externality ($\gamma^c = \gamma^o = 0$)

$$\tau^{emission} = \Delta N_E \cdot \widetilde{\phi_E} + \Delta N_I \cdot \widetilde{\phi_I} + \Delta T \cdot \overline{\phi} + \Delta V^c \cdot \hat{\phi}^c + \Delta V^o \cdot \hat{\phi}^o + v^c g \phi_I \quad (5)$$

$\rightarrow$ Change in motives x emission damages + emission externality

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$$\tau^{congestion} = \Delta N_E \cdot \widetilde{\gamma_E} + \Delta N_I \cdot \widetilde{\gamma}_I + \Delta T \cdot \overline{\gamma} + \Delta V^c \cdot \hat{\gamma}^c + \Delta V^o \cdot \hat{\gamma}^o + v^c \gamma^c \tag{6}$$

$\rightarrow$ Change in motives x congestion damages + congestion externality

Interpreting the formula

Substitution to unpriced trips:

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

$$
\begin{aligned}
\tau^{leakage} = \frac{1}{\frac{\partial t_I}{\partial \tau} n_I} \Bigg(& \frac{\partial n_E}{\partial \tau} \Big((v^c t_E^c + v^o t_E^o) e\phi_E + v^c t_E^c \gamma^c + v^o t_E^o \gamma^o \Big) \\
& + \frac{\partial n_I}{\partial \tau} \Big((v^c t_I^c + v^o t_I^o) g\phi_I + v^c t_I^c \gamma^c + v^o t_I^o \gamma^o \Big) \\
& + \frac{\partial t_E^c}{\partial \tau} \Big(n_E v^c (e\phi_E + \gamma^c) \Big) \\
& + \frac{\partial v^c}{\partial \tau} \Big(n_I t_I^c g\phi_I + n_E t_E^c e\phi_E + (n_I t_I^c + n_E t_E^c)\gamma^c \Big) \\
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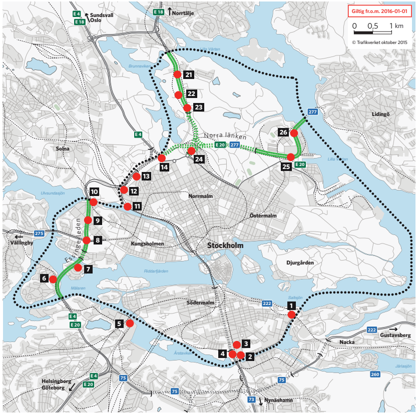
\end{aligned}
$$

$\rightarrow$ Change in motives x CZ externalities + externalities

Design of the congestion charge

Exemptions:

1. *Essinge* bypass and *Lidingö* rule
2. Alternative fuel cars

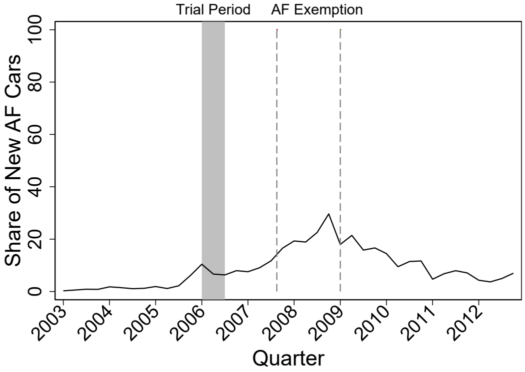


Fees Annual charges

Evolution of alternative fuel cars

Timeline:

1. Stockholm Congestion Trials (Jan 2006 - Jul 2006)
2. Permanent Implementation (Aug 2007 -)
   → AF car exemption (Aug 2007 - Dec 2008) - announcement in March 2007
   → Removal of AF car exemption (January 2012)



Split by fuel type

Data

We combine various Swedish administrative data sources (2003 to 2008):

1. Swedish vehicle register (*Fordonsregistret*)
2. Longitudinal integrated database for health insurance and labor market studies (*LISA*)
3. Geographic database (*Geografidatabasen)*
4. Occupational register (*Yrkesregistret*)
5. Swedish business register (*Företagsregister*)

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Sample restrictions:

- Employed, *treated/non-treated* commuters, commute between 3-50km, own 1-3 cars

Sample size

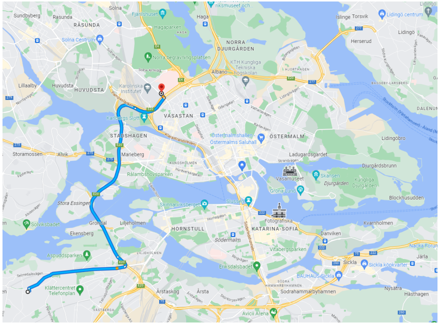
Empirical design

Intuition for identification:

- Both commuters resides outside CZ *(Hägersten)*

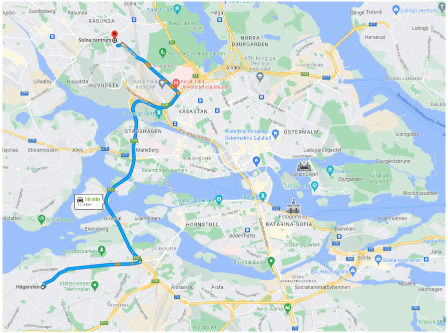
Treated commuters:

- Workplace is **inside** the CZ (*Vasastan*)



Non-treated commuters:

- Workplace is **outside** the CZ (*Solna* centrum)



Empirical design

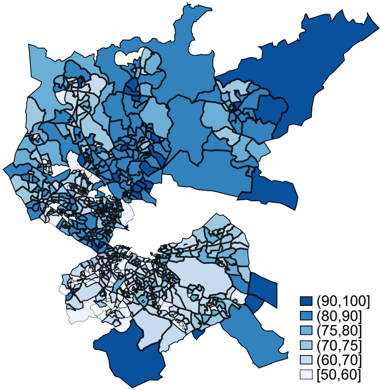
Definition of treatment and control group:

- *Treated*: Individuals who cross the CZ on their way to work
- *Non-treated*: Individuals who live and work outside the CZ and use the Essinge bypass or the Lidingö tunnel on their (time-minimizing) way to and from work

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

Treated commuters

Treated and non-treated commuters by area:



Estimating equation

Difference-in-Difference specification:

$$y_{it} = \beta post_t \times T_i + \theta T_i + \delta X_{it} + \lambda_t + \phi_n + \varepsilon_{it}, \tag{8}$$

- $y_{i,t}$: Outcome of interest
- $post_t$: Dummy variable equal to 1 after CZ implementation or the AF car exemption
- T_i : Dummy variable equal to 1 if the individual is classified as a *treated commuter*
- $X_{i,q}$: Individual demographic variables, work-route specific controls, and previous car attributes
- λ_t : Time-varying factors
- ϕ_n : Neighborhood fixed effects

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Coefficient of interest:

- β : Response to congestion charge

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Interpretation:

- Average treatment effect on the treated (ATT)

Dynamics

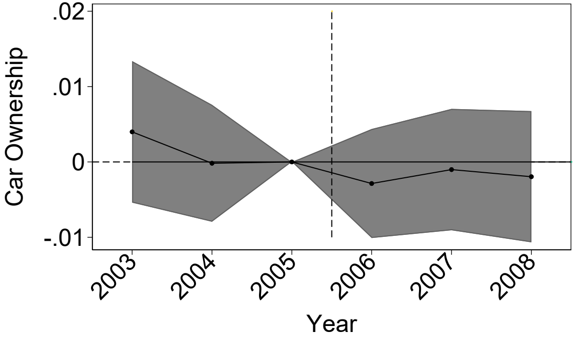
Dynamics effects:

$$y_{it} = \sum_{s\epsilon\{T|s\neq 2006]} \beta_t T_i \times 1[t=s] + \theta T_i + \delta X_{it} + \lambda_t + \phi_n + \varepsilon_{it}, \quad (9)$$

Assumption:

- No pre-trend in car ownership and driving behavior prior to CZ $\hat{\beta}_t \approx 0$

Car ownership and total vehicle kilometers traveled:



Fleet composition

Effect on fleet composition (*Motive I*)**:**

- Individuals exposed to congestion charges on their way to work are: Effects of Congestion Charges
  - → .65 percentage points more likely to adopt an AF car
  - → .69 percentage points less likely to adopt an ICE car
- 25% of AF car acquisition due to new vehicles Estimates on new cars
- No significant effect on vehicle characteristics Estimates on vehicle attributes

Number of trips

Effect on total number of trips: Effects of Congestion Charges

- *Estimation*: AF exemption period ($post_t \geq 2007$)
- Individuals exposed to congestion charges on their way to work: Effects on kilometers
  - → increase trips with AF cars by 6.8 (125 km)
  - → decrease trips with ICE cars by 16.1 (293 km)

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Effect on CZ trips (*Motive II*a)**:**

- *Estimation*: Removal of AF car exemption ($post_t \geq 2012$)
- Individuals exposed to congestion charges on their way to work:
  - → increase CZ trips with AF cars by 5.7 (99 km)
  - → decrease CZ trips with ICE cars by 14.6 (253 km)
- 78% of trips in AF cars & 87% in ICE cars were inside changes

Number of trips

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Effect on non-CZ trips (*Motive II*b)**:**

- *Estimation*: Residual of total and CZ trips
- Individuals exposed to congestion charges on their way to work:
  - → increase non-CZ trips with AF cars by 1.1 (26 km)
  - → decrease non-CZ trips with ICE cars by 1.5 (40 km)

Commuting distance

Effect on moving & relocating workplaces:

- Individuals exposed to congestion charges on their way to work are: Estimates on moving
  - → .2 percentage points more likely to move inside CZ
  - → 1.6 percentage points more likely to relocate to workplace outside CZ
    - 43 percent transfer to a new company
    - 57 percent relocate to a new office
    - Slight positive effects on salary Estimates on earnings

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Effect on commuting distance (*Motive III*):

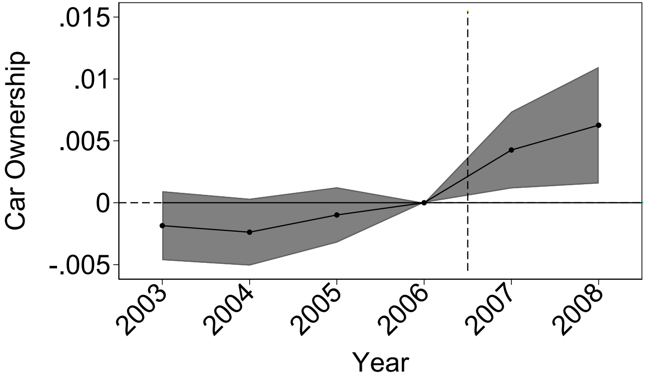
- Individuals exposed to congestion charges on their way to work: Effects of Congestion Charges
  - → decrease commute distance by .086 kilometers
  - → decrease outside commute distance by .014 kilometers

Dynamic estimates

Individuals exposed to congestion charges on their way to work:

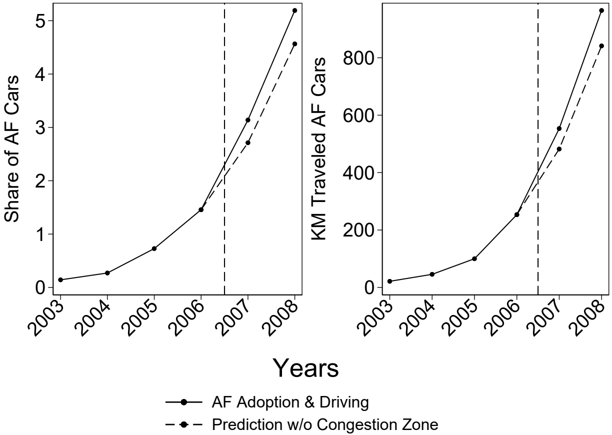
- are .65 percentage points more likely to adopt an AF car
- increase vehicle kilometers by 125.5 in AF cars

AF Car ownership and AF vehicle kilometers traveled:



Predictions

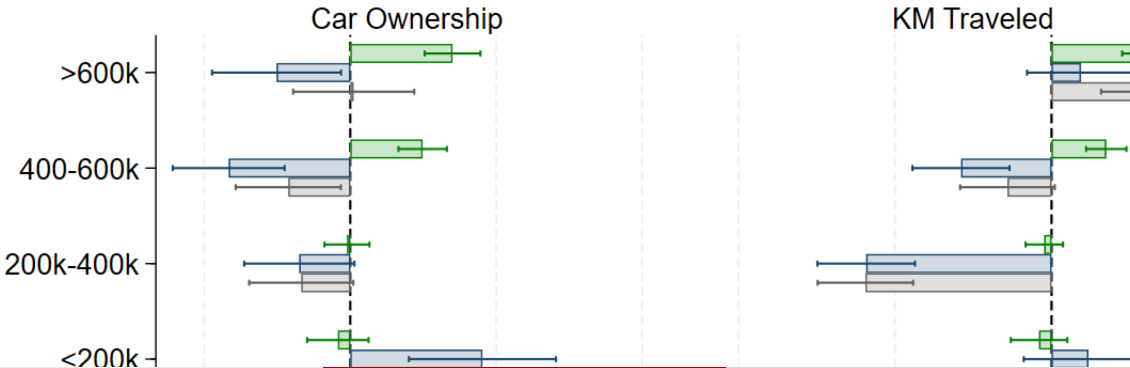
Congestion charge explains 20% of adoption and usage of AF cars



Heterogeneity

Heterogeneous responses to congestion charge:

- *Income*: High-income adopt AFs, middle-income reduce driving, low-income adopt ICE
- *Family status*: Couples shift to AF adoption and usage Family
- *Education*: AF take-up is increasing with education Education
- *Age*: Young people switch to AFs, old people reduce driving Age
- *Commuting*: No stark differences in commuting Commute



Robustness checks

Responses to the congestion charge remain robust along various dimensions:

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   → Individuals observed in all years (2003-2008) Balanced sample

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4. Placebo tests
   $\rightarrow$ No impact on AF adoption after exemption Placebo Years

Mapping empirical results to theory

Implement congestion formula using:

1. Registry data Registry data
2. Estimates of CZ effect Estimates
3. Emission and congestion externalities: Externalities
   - → ϕ_E, ϕ_I : €.033 per KM in ICE and €0 per KM in EV (European Environment Agency, 2014 & 2021)
   - → γ^c, γ^o: €.38 per KM inside and €.13 per KM outside CZ (External Costs of Transport Study, 2011)

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Congestion charge results: Congestion charge decomposition

- €10.44 per CZ crossing or €.6 per KM
- 89% of total charge is due to congestion (€9.3); 11% due to emission (€1.14)

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   - → Substitution towards unpriced roads (€.33)
   - → Increase in EV CZ trips (−€.03)

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3. Commuting distances are equal to €1.08
   - → Reduce distance between workplace and residence (€1)
   - → Reduce outside commute (€.08)

Congestion charge under alternative assumptions

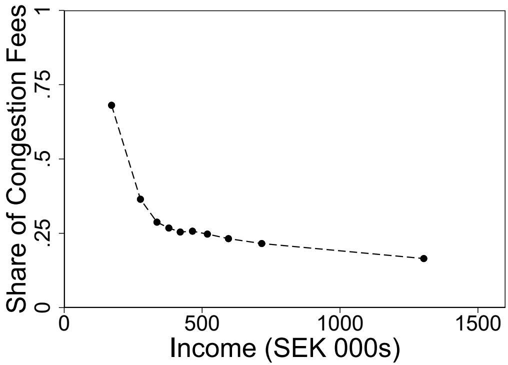
1. **Substitution towards unpriced road trips:**
   - → *No leakage (€9.84)*: All trip changes within CZ
   - → *25% leakage* (€11.77): One-quarter of trip changes within CZ
   - → *50% leakage* (€15.64.): One-half of trip changes within CZ
2. **Commute distance:**
   - → *Nearby commuters* (€7.79*):* Use average commuting distance of all commuters (11.9*km*)
3. **Share of EVs:**
   - → *10% EVs (€10.07)*: 10% of cars and trips are traveled with EVs
   - → *25% EVs (€9.48)*: 25% of cars and trips are traveled with EVs

Alternative Assumptions

Regressive effects

Distributional profile:

- Congestion charges falls disproportionately on low-income individuals



Distributional concerns

Three factors exacerbate regressive effects:

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3. **Exemption of AF cars:**
   → Exemptions and discounts skewed towards high-income groups (Levinsson, 2010; Ison & Rye, 2005)

Conclusion

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Empirical findings:

- Substantial effects on fleet composition, number of trips, and commuting
  - → Increase in take-up of AF cars
  - → Crowd out adoption of ICE cars
  - → Shift trips from ICE to AF cars or other transport modes
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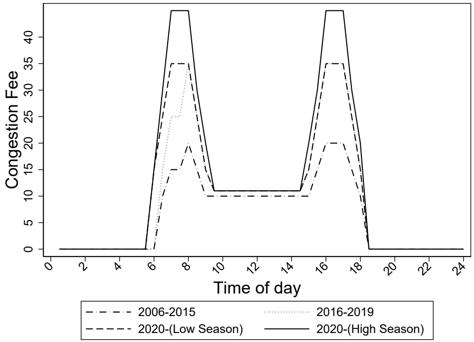
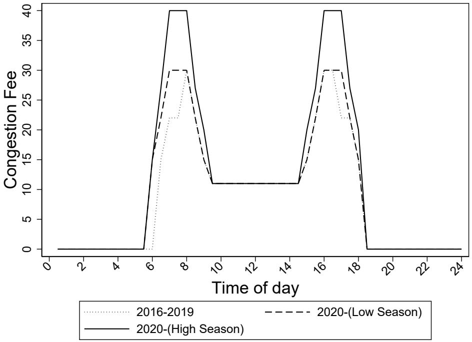
Policy implications:

- Congestion charge equals €10.44 per crossing (€.6 per KM)

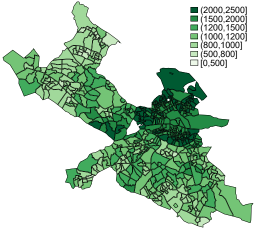
Congestion charges in Stockholm

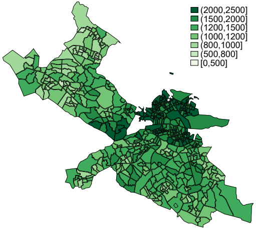


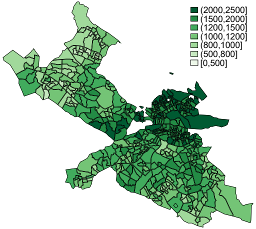


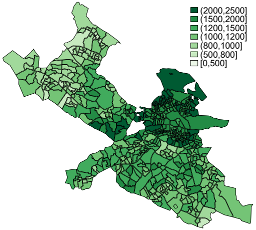
Design Charge

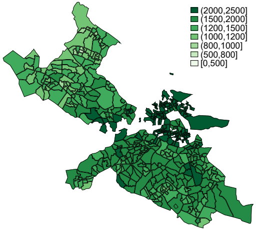
Annual congestion charges





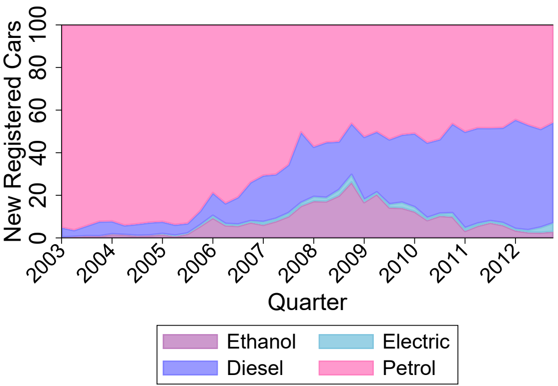


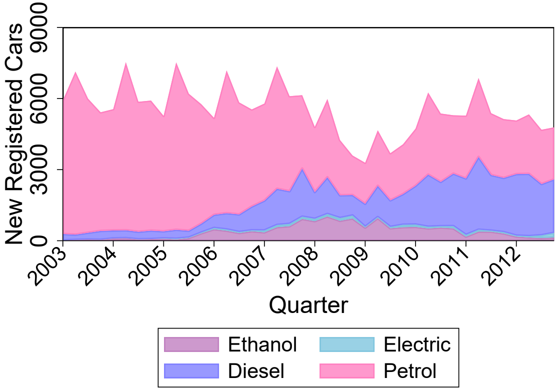




Design Charge

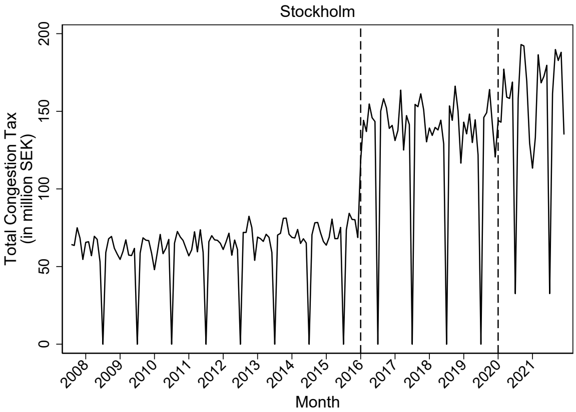
Share of newly registered cars in Stockholm





Evolution AF cars

Total congestion fees



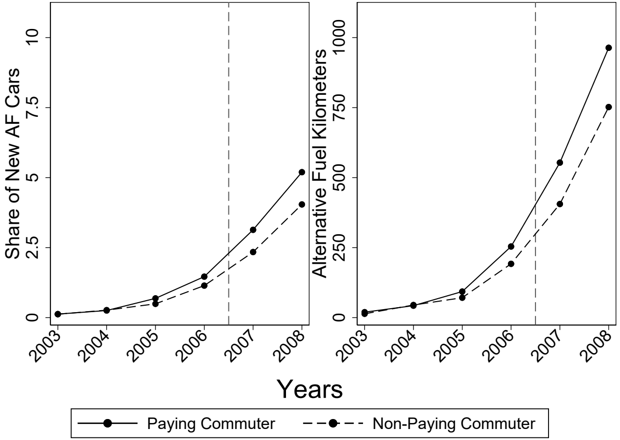
Exogenous Shocks

Sample selection

	Sample Selection Criteria							Balanced Sample
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	
Years								
2003	1,217,085	845,890	298,371	280,329	212,715	194,465	77,002	34,845
2004	1,236,578	859,827	301,500	283,150	209,222	188,195	75,721	34,845
2005	1,260,738	870,769	306,148	287,517	204,165	178,761	72,888	34,845
2006	1,293,780	903,686	315,007	295,840	192,484	157,645	66,594	34,845
2007	1,329,834	972,133	336,640	315,534	192,484	157,645	67,481	34,845
2008	1,366,838	993,526	345,715	324,067	192,484	157,645	68,181	34,845
Individuals	1,525,337	1,247,558	605,330	570,629	318,011	283,172	125,173	34,845
Total	7,704,853	5,445,831	1,903,381	1,786,437	1,203,553	1,034,356	427,867	209,070

Data sources

Vehicle ownership and driving



Prediction Performance

Effects of Congestion Charges

	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 (t-1)	.70	-2	-2.3
Mean Trips Outside	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

Fleet Composition Number of trips Commuting distance

Estimates on vehicle attributes

	Vehicle Attribute			
	(1) Fuel	(2) Carbon	(3) Weight	(4) Engine
A.Vehicle Ownership				
Post x Treated Commuters	-.0269	.0385	-.8850	-.0352
	(.0210)	(.3953)	(1.7292)	(.2366)
Mean Dep. Variable (2006)	4.2	200.6	1417.4	99.5
Observations	416256	182236	416256	416256

Fleet Composition

Estimates on new car adoption

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

Fleet Composition

Estimates 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

Number of trips

Estimates on moving

	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)

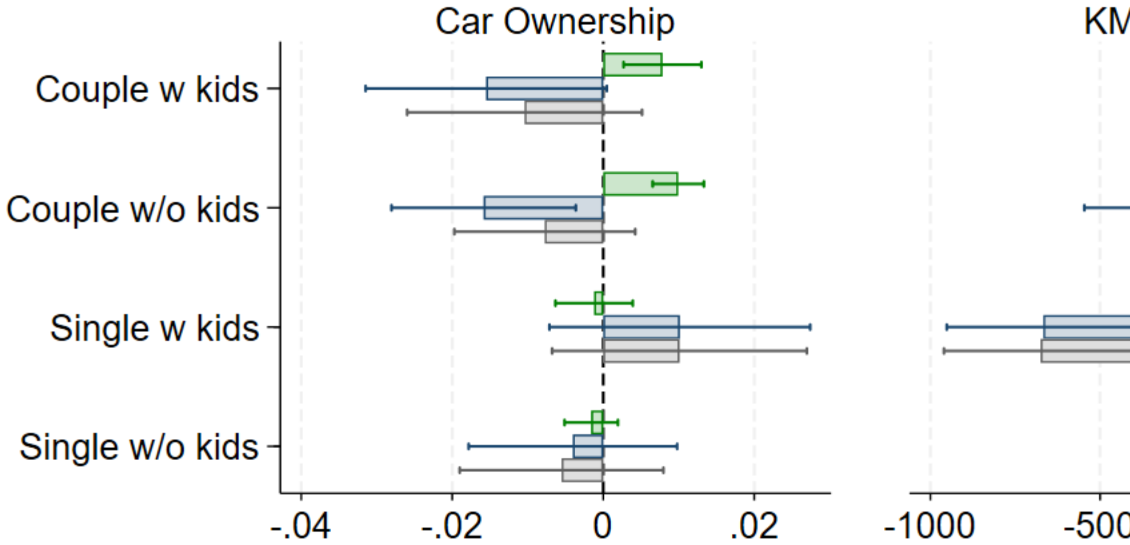
Commuting distance

Estimates on earnings

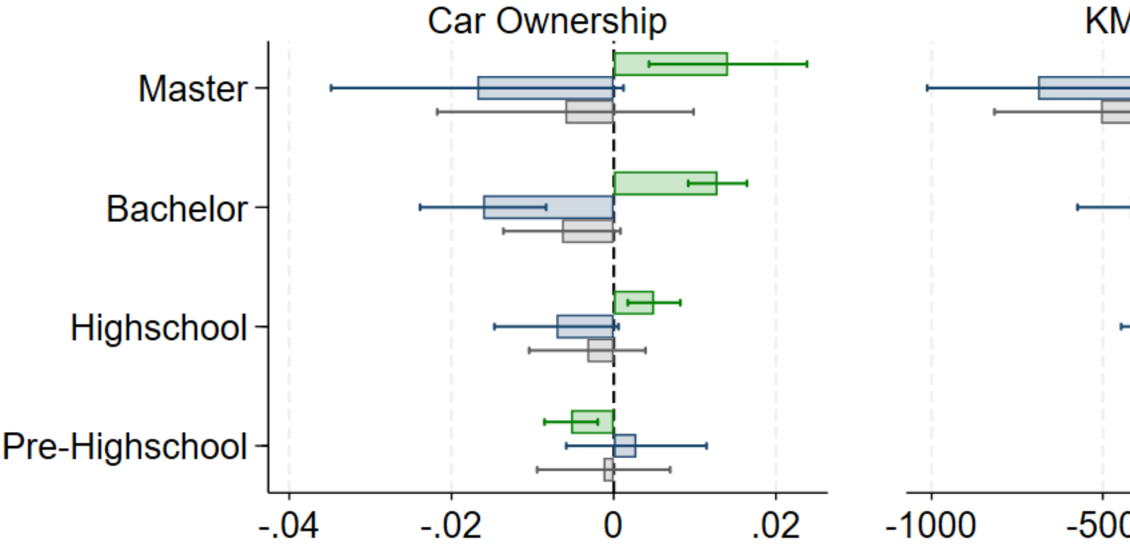
	Labor Market Effects	
	(1) Gross Salary	(2) Disposable Income
Post x Treated Commuters	2484.1*	1872.8
	(1475.6)	(1735.0)
Mean Dep. Variable	504373.1	268048.1

Commuting distance

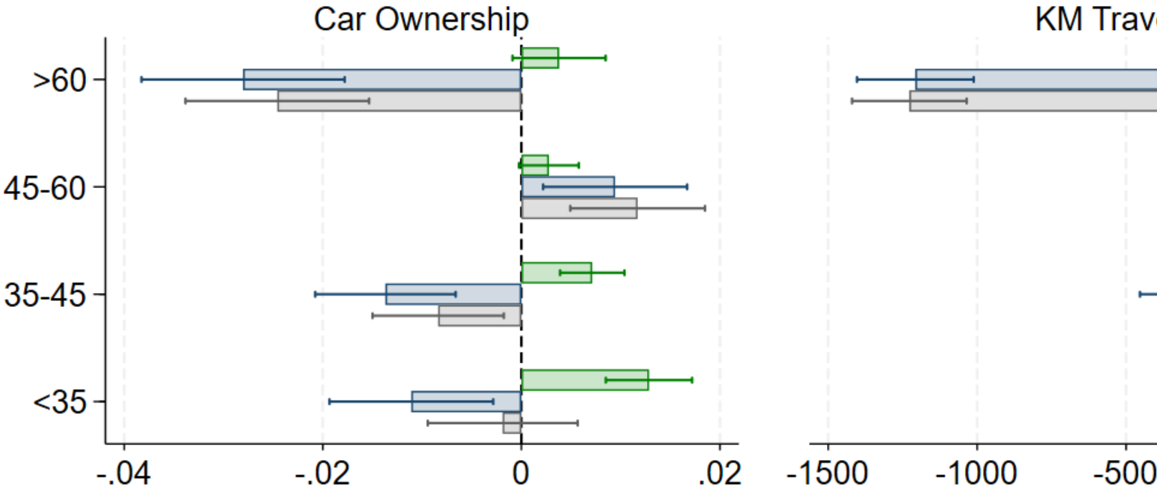
Heterogeneity - Family



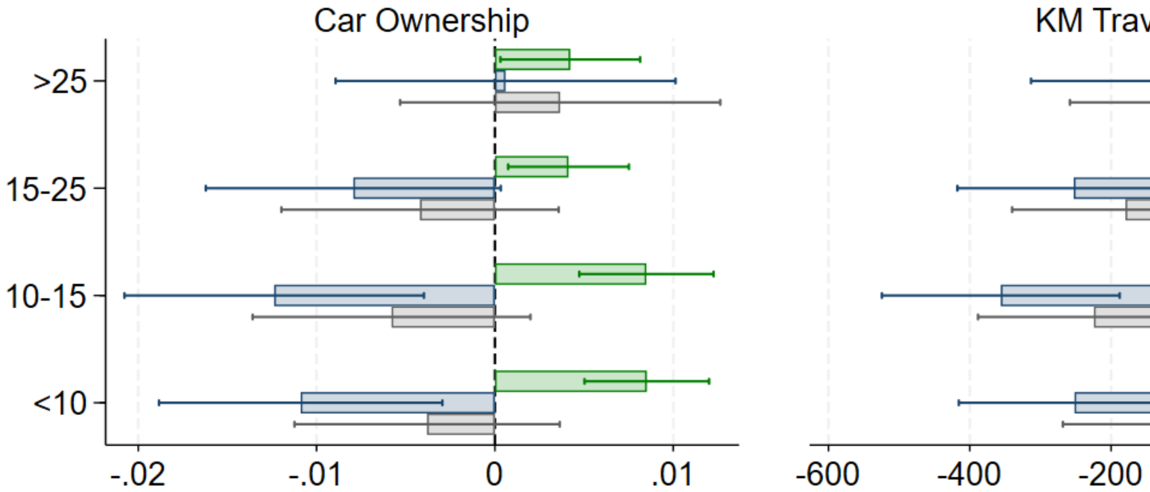
Heterogeneity - Education



Heterogeneity - Age



Heterogeneity - Commute



Balanced sample estimates

	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 (t-1)	0	-8.1	-8.6
Mean Trips Outside	7.1	446.1	449
C.Commuting Distance			

Outside congestion zone effects

	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 (t-1)	2	-2.6	-2.9
Mean Trips Outside	6.9	435.5	438.1
C.Commuting Distance			

Inside congestion zone effects

	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 (t-1)	-16.3	2.1	3.5
Mean Trips Outside	6.9	440.5	443.6
C.Commuting Distance			

Estimates with firm characteristics

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.Vehicle Ownership			
Post x Treated Commuters	.0067***	-.0084**	-.0030
	(.0014)	(.0036)	(.0035)
Mean Car Ownership (t-1)	.014	1.138	1.145
B.Number of Trips			
Post x Treated Commuters	6.5***	-15.9***	-10.6***
	(1.5)	(4.0)	(3.9)
Inside Congestion Trips	6.1**	-5.0	1.0
	(2.9)	(5.0)	(4.7)
Mean Trips Inside (t-1)	6.4	399.1	401.7
Change Trips Outside (t-1)	.4	-10.9	-11.6
Mean Trips Outside	6.9	432.1	434.8

Robustness Checks

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 (t-1)	.7	-.9	-.8
Mean Trips Outside	6.4	429.7	432.3
C.Commuting Distance			

Placebo year estimates

	Type of Car		
	(1) Alternative	(2) Fossil	(3) Total
A.Vehicle Ownership			
Post x Treated Commuters	.0032	-.0054	-.0023
	(.0025)	(.0046)	(.0041)
Mean Car Ownership (t-1)	.	.	.
B.Number of Trips			
Post x Treated Commuters	.7	-.6	.1
	(2.7)	(4.7)	(4.6)
C.Commuting Distance			
Post x Treated Commuters			.070***
			(.018)
Mean Commute Distance (t-1)			17.5
Changes in Outside Distance			-.142
Mean Outside Distance (t-1)			10

Congestion charge decomposition

	Per-crossing (€)	Externality (€)	
		Congestion	Emission
Fleet Composition	**1.77**		
Effect on electric cars $\Delta N_E(\widetilde{\phi_E} + \widetilde{\gamma_E})$	$-.02$	-0.02	0
Effect on ICE cars $\Delta N_I(\widetilde{\phi_I} + \widetilde{\gamma_I})$	1.79	1.54	.25
Number of Trips	**7.59**		
Effect on electric trips outside $\Delta T_E^o(\overline{\phi_E^o} + \overline{\gamma_E^o})$	$-.00$	$-.00$	0
Effect on electric trips inside $\Delta T_E^c(\overline{\phi_E^c} + \overline{\gamma_E^c})$	$-.03$	$-.03$	0
Effect on ICE trips outside $\Delta T_I^o(\overline{\phi_I^o} + \overline{\gamma_I^o})$	.33	.25	.08
ICE trips inside $v^c(g\phi_I + \gamma^c)$	7.29	6.6	.69
Commuting Distance	**1.08**		
Effect on inside commute $\Delta V^c(\hat{\phi}^c + \hat{\gamma}^c)$	1	.9	.1
Effect on outside commute $\Delta V^o(\hat{\phi}^o + \hat{\gamma}^o)$	.08	.06	.02
Congestion charge (€)	**10.44**	**9.3**	**1.14**

Mapping

Alternative Assumptions

		Externality (€)	
	Per-crossing (€)	Congestion	Emission
Baseline	10.44	9.3	1.14
No leakage	9.84	8.81	1.03
25% leakage	11.77	10.38	1.39
50% leakage	15.64	13.53	2.11
Nearby commuters	7.79	6.91	.88
10% EVs	10.07	8.93	1.14
25% EVs	9.48	8.34	1.14

Alternative Assumption

Emission externalities

Coefficient	Descriptions	Value
ΔPM	Emission of particulate matter $[\frac{g}{kg\ fuel}]$	.25
ΔCO_2	Emission from carbon dioxide $[\frac{g}{kg\ fuel}]$	3162
ΔNH_3	Emission from ammonia $[\frac{g}{kg\ fuel}]$	9.11
ΔSO_2	Emission from sulfur dioxide $[\frac{g}{kg\ fuel}]$	6.69
$MC_{PM_{2.5}}$	Costs of fine particulate matter $[\frac{€}{kg}]$	23.2
$MC_{PM_{10}}$	Costs of particulate matter $[\frac{€}{kg}]$	15.01
MC_{CO_2}	Costs of carbon dioxide $[\frac{€}{kg}]$	0.105
MC_{NH_3}	Costs of ammonia $[\frac{€}{kg}]$	12.15
MC_{SO_2}	Costs of sulfur dioxide $[\frac{€}{kg}]$	15.44

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Registry data for congestion charge

Coefficient	Descriptions	Value
Panel A: Registry Data		
n_E	Number of electric cars per person	.014
n_I	Number of ICE cars per person	1.145
t_E^c	Number of congestion-trips with electric cars	6.3
t_I^c	Number of congestion-trips with ICE cars	403.8
t_E^o	Number of non-congestion-trips with electric cars	6.7
t_I^o	Number of non-congestion-trips with ICE cars	433.2
v^c	Average kilometers traveled on congestion zone trips	17.4km
v^o	Average kilometers traveled on non-congestion zone trips	19km

Mapping CZ formula

Estimates of congestion charge

Coefficient	Descriptions	Value
Panel B: Empirical estimates		
$\frac{\partial n_E}{\partial \tau}$	Effect of congestion charge τ on number of electric cars n_E	.0065
$\frac{\partial n_I}{\partial \tau}$	Effect of congestion charge τ on number of ICE cars n_I	$-.0069$
$\frac{\partial t_E^o}{\partial \tau}$	Effect of congestion charge τ on number of outside congestion trips in electric cars t_E^o	1.1
$\frac{\partial t_E^o}{\partial \tau}$	Effect of congestion charge τ on number of congestion trips in electric cars t_E^c	5.7
$\frac{\partial t_I^o}{\partial \tau}$	Effect of congestion charge τ on number of outside congestion trips in ICE cars t_I^o	-14.6
$\frac{\partial t_I^c}{\partial \tau}$	Effect of congestion charge τ on number of congestion trips in ICE cars t_I^c	-1.5
$\frac{\partial v^c}{\partial \tau}$	Effect of congestion charge τ on average kilometers on congestion trips v^c	$-.086$
$\frac{\partial v^o}{\partial \tau}$	Effect of congestion charge τ on average kilometers	$-.015$

Externalities for congestion charge

Coefficient	Descriptions	Value
Panel C: Emission externalities $[\frac{€}{km}]$		
$\phi_I \cdot g$	Emission externalities for ICE cars	.04
$\phi_E \cdot e$	Emission externalities for electric cars	0
Panel D: Congestion externalities $[\frac{€}{km}]$		
γ^c	Congestion externalities for inside cordon driving	.38
γ^o	Congestion externalities for outside cordon driving	.13

Mapping CZ formula