

Road Pricing under Heterogeneity

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• **TheUpshot**

27 Million Fewer Car Trips: Life After a Year of Congestion Pricing

By [Emily Badger](#), [Larry Buchanan](#), [Stefanos Chen](#), [Asmaa Elkeurti](#) and [Winnie Hu](#)

The authors commute to the Times office inside the congestion zone by foot, bus, bike, subway, ferry, tram, Amtrak and occasionally car.

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This Paper: What makes congestion pricing “work”?

- **Question:** How do [optimal] road prices drive welfare gains?

The answer depends on key primitives:

- Distribution of drivers' preferences (e.g. value of time)
- Distribution of drivers' trips through the road network
- Road capacity across the network + attractiveness of outside options
- Value [to consumers] of toll revenue collected

This Paper: What makes congestion pricing “work”?

Question: How do [optimal] road prices drive welfare gains?

Data: two-year panel from a usage-based pricing experiment in Israel

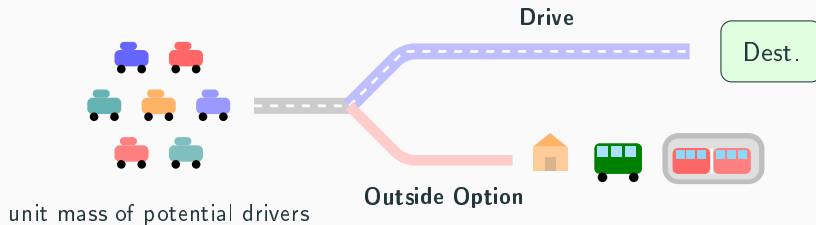
Reduced-form: Clear *intensive* and *extensive* margin responses to set prices w/ substantial heterogeneity in who does what

Model: Estimate **supply** (dynamic traffic flows along a real road network) & **demand** (driver sensitivity to travel time & price) and simulate **equilibrium driving** under different policies

Goal: Understand how primitives affect optimal policy design

► Literature

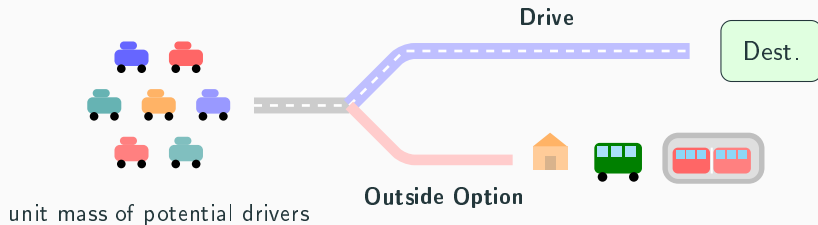
A Toy Model of Road Pricing



Driver i enters the road if:

$$u_i = \underbrace{V}_{\text{trip value}} - \underbrace{\alpha_i p}_{\text{toll cost}} - \underbrace{\gamma_i D(q)}_{\text{travel duration}} + \underbrace{\varepsilon_i}_{\text{logit shock}} > 0$$

A Toy Model of Road Pricing

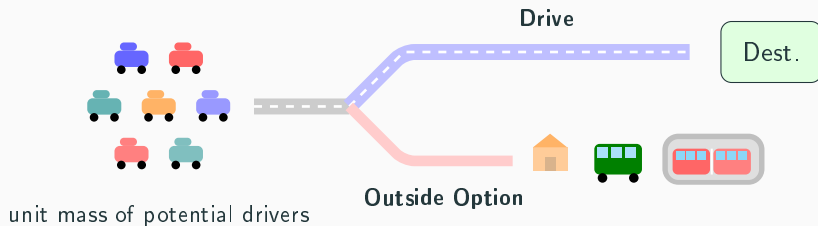


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- Entry probability $q_i = \sigma(V - \alpha_i p - \gamma_i D(q))$, $\sigma(z) = \frac{e^z}{1+e^z}$
- Total traffic $q = \sum_i q_i$
- Travel duration increases in traffic ($D'(q) > 0$)

A Toy Model of Road Pricing



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Nash Eqm. At the margin, each driver is indifferent b/w driving or not:

$$V - \gamma_i D(q) - \alpha_i p = \ln \frac{q_i(p)}{1 - q_i(p)}$$

The Welfare Objective

Money-metric welfare: consumer surplus + toll revenue

$$W_{\Lambda} = \sum_i \frac{1}{\alpha_i} \underbrace{\left[q_i (V - \alpha_i p - \gamma_i D(q)) + \mathcal{H}(q_i) \right]}_{\text{Expected value of driving}} + \Lambda \cdot p \cdot q$$

- $q = \sum_i q_i$: total traffic
- $\frac{1}{\alpha_i}$: money-metric weight (willingness to pay per util)
- $\Lambda \cdot p \cdot q$: toll revenue returned to drivers

When are congestion prices worth it?

- Welfare gain from a toll p^* :

► Sufficient Statistic Version

$$\Delta W_{\Lambda} = \underbrace{G(q^*) - G(q^0)}_{\text{congestion relief}} + \underbrace{S(q^*) - S(q^0)}_{\text{net sorting gain}} - \underbrace{(1-\Lambda)p^*q^*}_{\text{toll leakage}}$$

$\rightsquigarrow G(q)$: average surplus from making roads faster

$\rightsquigarrow S(q)$: surplus from *reallocating* trips to types w / higher values

$\rightsquigarrow \Lambda < 1$ means some revenue is lost (e.g. imperfect enforcement)

$\Delta W_{\Lambda} > 0 \iff \text{congestion relief} + \text{sorting gains} > \text{toll leakage}$

Toll revenues matter for optimal pricing

Suppose drivers have the **same** (α, γ, V) preferences.

Nash Eqm: $V - \gamma D(q) - \alpha p = \ln \frac{q(p)}{1 - q(p)}$

Case 1: $\Lambda = 1$

► Details

Optimal q^* solves:

$$V - \gamma D(q^*) - \underbrace{\gamma q^* D'(q^*)}_{\text{marg. externality}} = \ln \frac{q^*}{1 - q^*}$$

So the optimal price is:

$$p^* = \frac{\gamma}{\alpha} q^* D'(q^*) > 0$$

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Case 2: $\Lambda = 0$

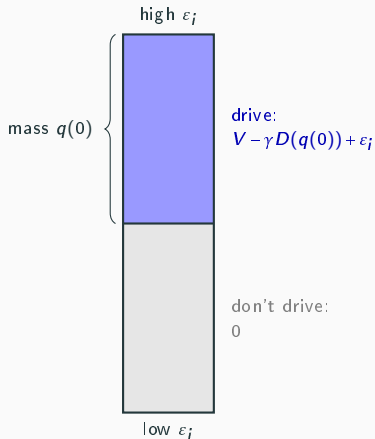
► Intuition

► Proof

The optimal price is zero:

$$p^* = 0$$

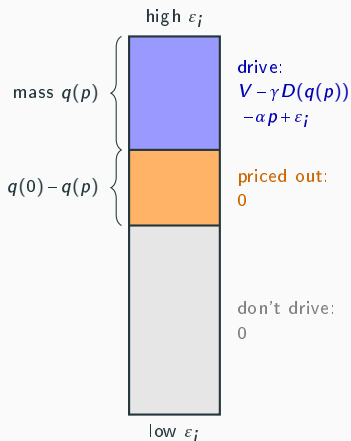
Intuition: $p^* = 0$ under $\Lambda = 0$ (Homogeneous Types)



- **No toll:** the top $q(0)$ of ε -draws drive; marginal driver is indifferent:

$$V - \gamma D(q(0)) = \ln \frac{q(0)}{1 - q(0)}$$

Intuition: $p^* = 0$ under $\Lambda = 0$ (Homogeneous Types)



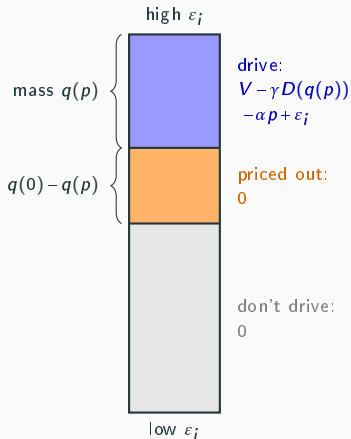
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⇒ The common value of driving **falls**:

$$\underbrace{V - \gamma D(q(p)) - \alpha p}_{= \ln \frac{q(p)}{1 - q(p)}} < \underbrace{V - \gamma D(q(0))}_{= \ln \frac{q(0)}{1 - q(0)}}$$

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Note: Congestion relief alone isn't enough to justify pricing

- How big each component is depends on the distribution of preferences...

When are congestion prices worth it?

- Welfare gain from a toll p^* :

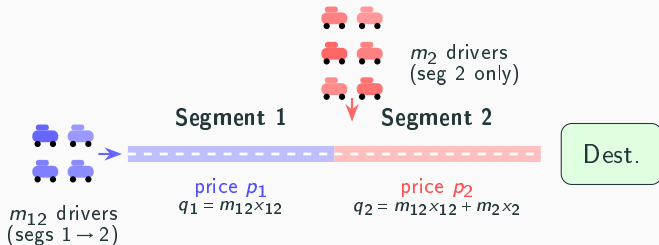
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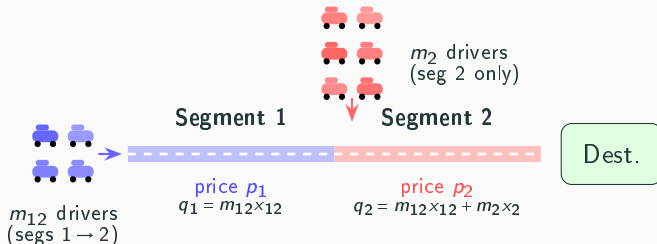
- How big each component is depends on the distribution of preferences... ...and on the structure of the road network

Network Heterogeneity: Two Sequential Segments



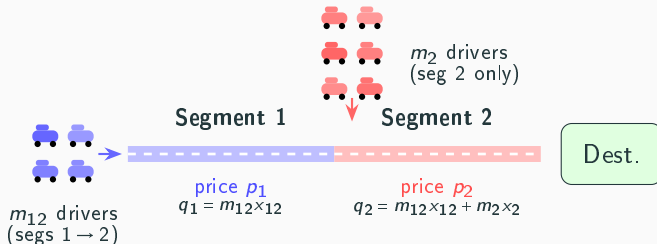
- Suppose drivers all have the same (α, γ, V) preferences

Network Heterogeneity: Two Sequential Segments



- Suppose drivers all have the same (α, γ, V) preferences
- The p_1 price adjusts the share of drivers on segment 2
 - $\Rightarrow p_1$ screens some of the m_{12} drivers off segment 2
 - $\Rightarrow$ Reduces congestion for all m_2 seg-2 entrants w/o charging them

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$\rightsquigarrow$ Efficient if gains for seg-2 entrants $>$ loss for seg-1 entrants

“Value Road”: A Usage-Based Pricing Experiment in Israel

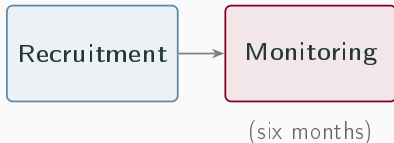
- Nationwide pilot run by the Highway Administration in Israel

Recruitment

- 10,000 drivers recruited between June 2019 and October 2020
 - ≈ 600 per month
 - Stratified by geographic region
 - Majority reside in the broader Tel Aviv commuting zone

“Value Road”: A Usage-Based Pricing Experiment in Israel

- Nationwide pilot run by the Highway Administration in Israel



- 10,000 drivers recruited between June 2019 and October 2020
- GPS device installed in each participant's car
 - Tamper-resistant — difficult to remove
 - six months with *no* communication and *no* pricing

“Value Road”: A Usage-Based Pricing Experiment in Israel

- Nationwide pilot run by the Highway Administration in Israel



- 10,000 drivers recruited between June 2019 and October 2020
- GPS device installed in each participant's car
- “Activate” usage-based congestion pricing for 12+ months
 - Annual budget of 4,500 NIS (~\$1,250)
 - Phone app to track budget + do trip planning
 - Subtract per-km fees based on location & time of day

“Value Road”: A Usage-Based Pricing Experiment in Israel

- Nationwide pilot run by the Highway Administration in Israel



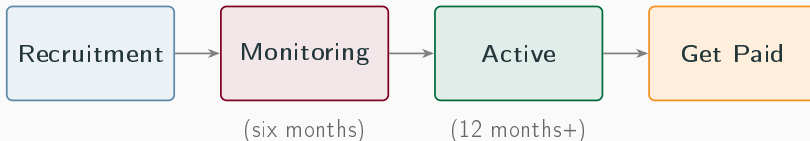
	Hours	Metro	Metro Fringe	Periphery
Weekdays				
Peak	6:45 – 9:30AM	1.5	0.3	0.0
	3:30 – 6:30PM	1.5	0.3	0.0
Off-peak	9:30AM – 3:30PM	0.1	0.0	0.0
	6:30 – 8PM	0.1	0.0	0.0
Leisure	8PM – 6:45AM	0	0	0
Weekends	All Hours	0	0	0

Price in NIS per kilometer traveled.

► [map](#)

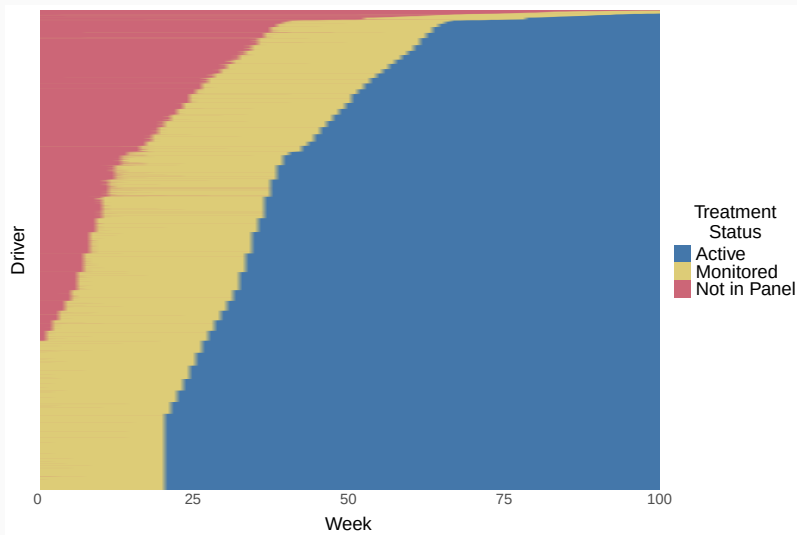
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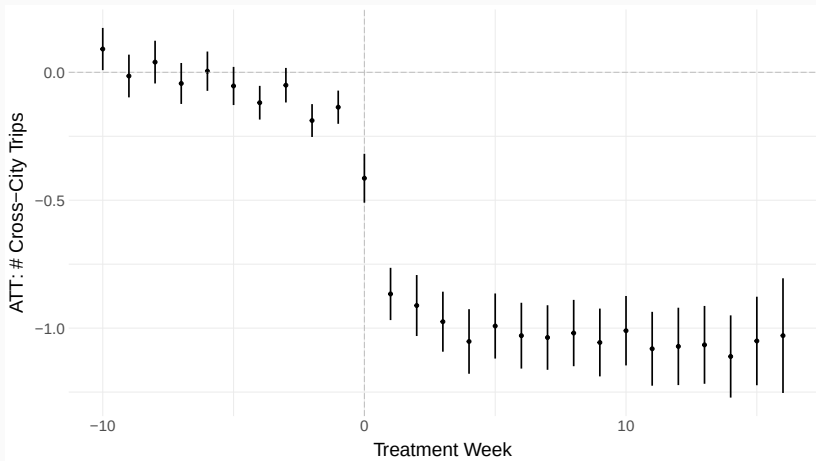


- 10,000 drivers recruited between June 2019 and October 2020
- GPS device installed in each participant's car
- “Activate” usage-based congestion pricing for 12+ months
- Remainder of the budget is paid out by bank transfer

Did Prices Change Behavior? Research Design



Dynamic Treatment Effects: Number of Cross-City Trips

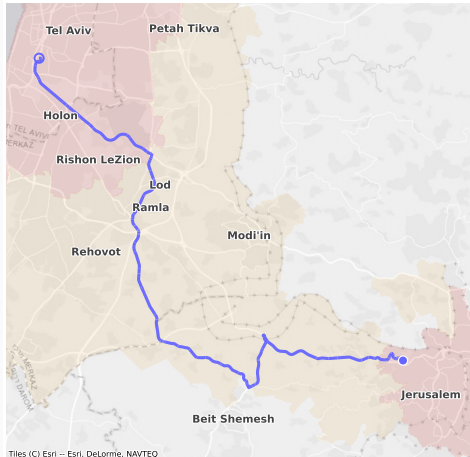


► Estimation Details

► Other Dynamic Effects

Model Overview

- **Demand:** Drivers taking different O-D trips choose *if* and *when* to drive as a function of travel time, price, and transit quality



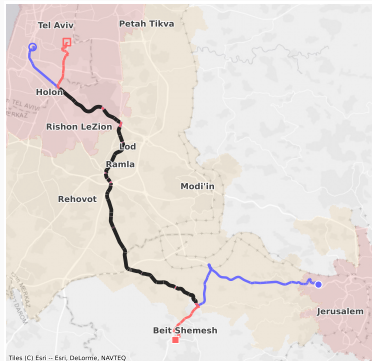
Model Overview

- **Demand:** Drivers taking different O-D trips choose *if* and *when* to drive as a function of travel time, price, and transit quality
- **Supply:** Drivers departing at different times and places overlap across the road network, creating congestion and slowdowns



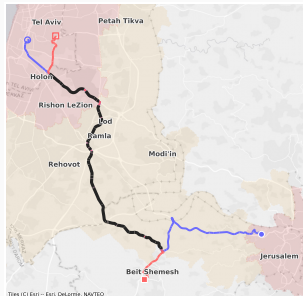
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- **Traffic Equilibrium:** In equilibrium, departure shares are consistent with travel times & prices determined by network propagation



Demand: “Regular Trips” and Mixed Logit

- (i) Panel of *trip opportunities* based on each driver’s regular trips
 - e.g., Person i generally drives from A to B Monday around 8 AM
 - ↪ Every Monday morning, i has an opportunity to drive $A \rightarrow B$
 - ↪ Consider potential departures $\pm$ one hour around 8 AM (or not at all)

Demand: “Regular Trips” and Mixed Logit

- (i) Panel of *trip opportunities* based on each driver’s regular trips
- Impute prices $\hat{P}_{i\ell jt}$, durations $\hat{D}_{i\ell jt}$ for each window t on day ℓ
 - Impute transit quality $\hat{R}_j$: avg ratio of driving vs best transit duration

Demand: “Regular Trips” and Mixed Logit

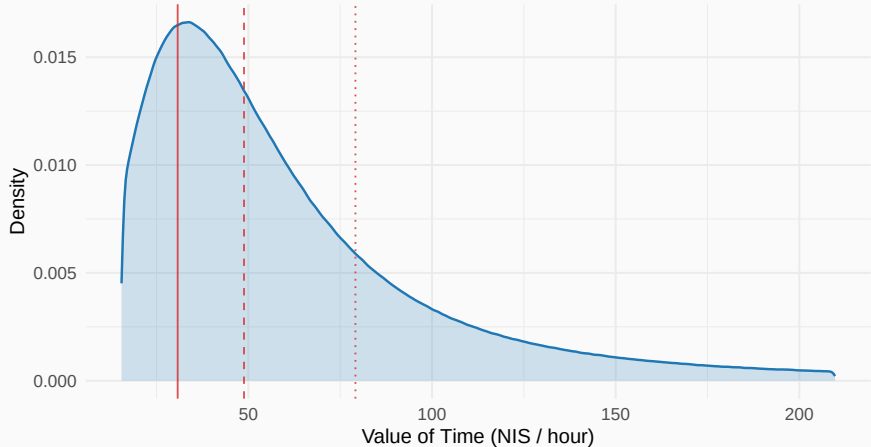
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- Impute prices $\hat{P}_{i\ell jt}$, durations $\hat{D}_{i\ell jt}$ for each window t on day ℓ
 - Impute transit quality $\hat{R}_i$: avg ratio of driving vs best transit duration
- (ii) At each potential departure time j , i chooses if & when to leave:

$$u_{ijt} = \xi_{jt} - \alpha_i \widehat{p}_{ijt} - \gamma_i \widehat{D}_{ijt} + \epsilon_{ijt}; \quad u_{i0t} = \rho_i \widehat{R}_i + \epsilon_{i0t}$$

$$\left. \begin{array}{l} \alpha_i : \text{price sensitivity} \\ \gamma_i : \text{travel time sensitivity} \\ \rho_i : \text{taste for transit} \end{array} \right\} (\alpha_i, \gamma_i, \rho_i) \sim N(\theta' X_i, \Sigma), \quad \epsilon_{ijt} \sim \text{TEV}(1)$$

- (iii) Estimate using Panel MLE + IV-GMM penalty (Grieco et al., 2025)
- α_i identified by driver responses to introduction of experiment prices
 - γ_i identified by duration variation from [weather IVs](#)
 - ρ_i identified by variation in transit access across drivers

Demand results: value of time distribution

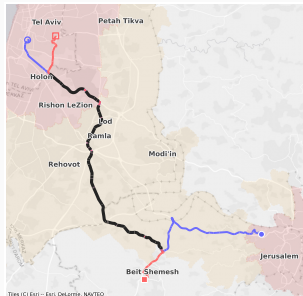


Quantile | 25% (31 NIS) | 50% (49 NIS) | 75% (79 NIS)

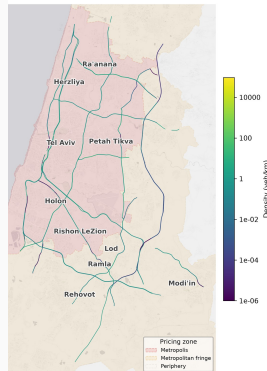
► Parameter estimates

Model Overview

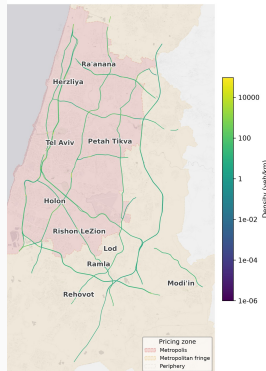
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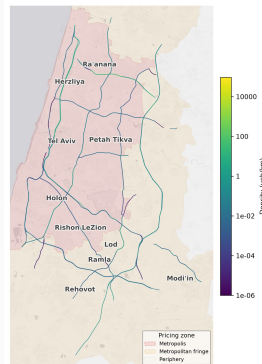
2:00 PM (t=1) — Off-peak



5:45 PM (t=16) — Peak

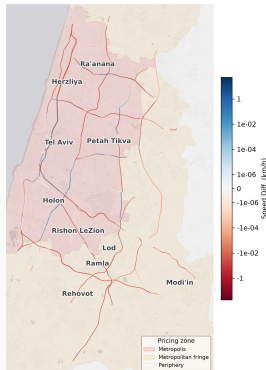


9:45 PM (t=32) — Unpriced

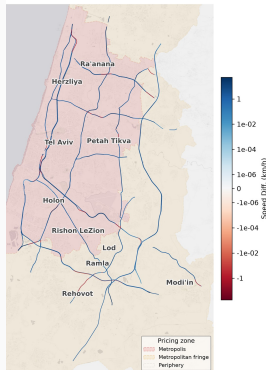


Compared to status quo, if everyone paid experiment prices

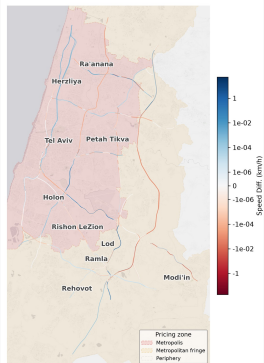
2:00 PM (t=1) — Off-peak



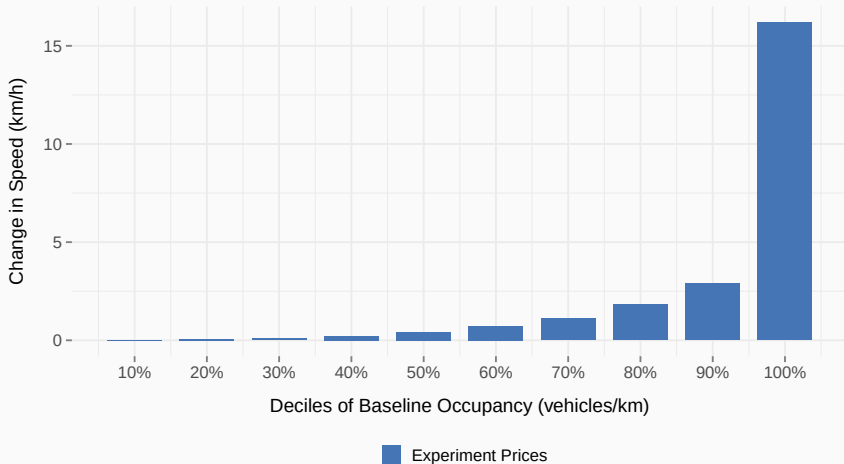
5:45 PM (t=16) — Peak



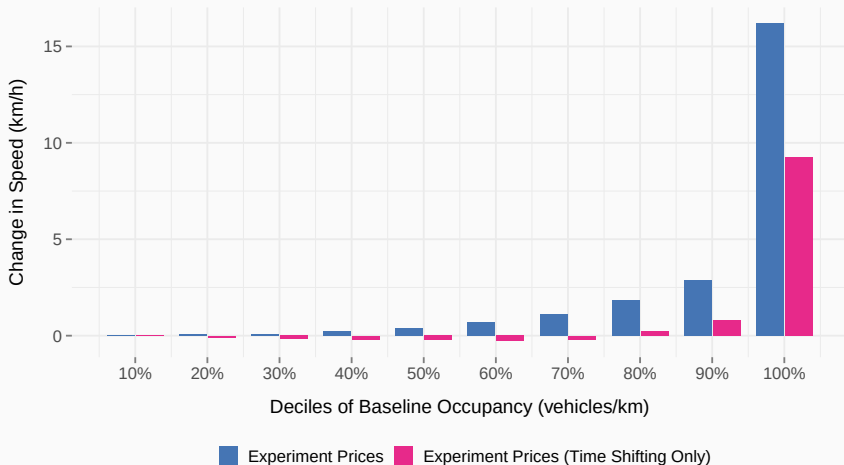
9:45 PM (t=32) — Unpriced



Compared to status quo, if everyone paid experiment prices



Compared to status quo, if everyone paid experiment prices



Compared to status quo, if everyone paid experiment prices

- Equilibrium trip probability ↓ **18%** (cf. ~11% in NYC)
- Average speeds for trips taken ↑ **17%** (cf. ~3–6% in NYC)
- Net welfare ↑ **1.85 NIS / trip-day** (if all revenues are redistributed)

Benchmark: What If We Built More Roads Instead?

Suppose we added **one lane in each direction to every highway**

- Equilibrium trip probability ↑ **13%** (induced demand)
- Avg speeds for trips taken ↑ **10%** (cf. 17% under experiment prices)
- Net welfare ↑ **1.75 NIS / trip-day** (no revenues to redistribute)

↪ Experiment prices deliver **106%** of gains from new lanes

► Induced Demand

► Transit Benchmark

How Much Better Are Optimal Prices?

	Experiment Prices	Optimal Usage-Based
Rebated ΔCS	1.85	2.04

CS: NIS / trip-day; remainder: NIS / day per capita.

► Optimal usage prices

► Optimal cordon prices

How Much Better Are Optimal Prices?

	Experiment Prices	Optimal Usage-Based	Optimal Cordon
Rebated ΔCS	1.85	2.04	0.85

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How Much Better Are Optimal Prices?

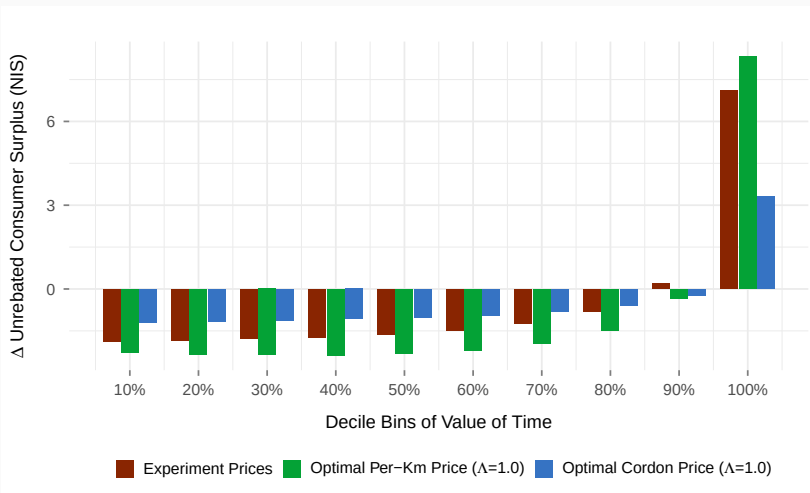
	Experiment Prices	Optimal Usage-Based	Optimal Cordon
Rebated ΔCS	1.85	2.04	0.85
Raw ΔCS (no toll revenue)	-0.51	-0.94	-0.49

CS: NIS / trip-day; remainder: NIS / day per capita.

► Optimal usage prices

► Optimal cordon prices

Raw ΔCS (no toll revenue) by Value of Time Bin



► By SES bin (appendix)

How Much Better Are Optimal Prices?

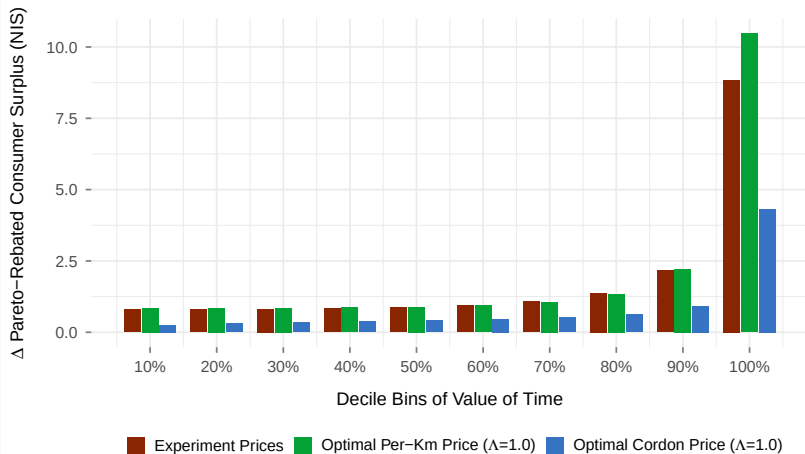
	Experiment Prices	Optimal Usage-Based	Optimal Cordon
Rebated ΔCS	1.85	2.04	0.85
Raw ΔCS (no toll revenue)	-0.51	-0.94	-0.49
Remainder after compensation	0.792	0.848	0.190

CS: NIS / trip-day; remainder: NIS / day per capita.

► Optimal usage prices

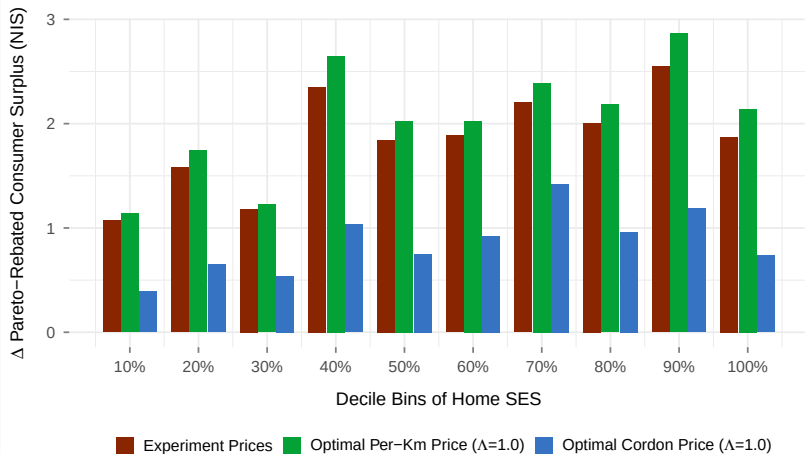
► Optimal cordon prices

Pareto-Rebated ΔCS by Value of Time Bin



► Uniform rebate (appendix)

Pareto-Rebated ΔCS by SES Bin



► Uniform rebate

How Much Revenue Do You Need?

What is the smallest revenue share Λ^* s.t. positive prices are optimal?

Preferences	Full network het.	
	Usage-based	Cordon
Estimated	0.00	0.05

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What is the smallest revenue share Λ^* s.t. positive prices are optimal?

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	Usage-based	Cordon
Estimated	0.00	0.05
Homogeneous	0.44	0.45

How Much Revenue Do You Need?

What is the smallest revenue share Λ^* s.t. positive prices are optimal?

Preferences	Full network het.		No network het.
	Usage-based	Cordon	
Estimated	0.00	0.05	0.10
Homogeneous	0.44	0.45	0.43

How Much Revenue Do You Need for a Pareto Improvement?

What is the smallest revenue share Λ^* s.t. positive prices are optimal and every driver is made weakly better off?

Preferences	Full network het.		No network het.
	Usage-based	Cordon	
Estimated	0.48	0.53	0.35
Homogeneous	0.48	0.56	0.43

Thank You



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Appendix

References



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- **Congestion pricing and the costs of traffic:** Pigou, 1920; Knight, 1924; Walters, 1961; Vickrey, 1969; Henderson, 1974; Small, 1982; Richard Arnott, Andre De Palma, and Lindsey, 1993; Arnott, André De Palma, and Lindsey, 1994; Fosgerau and Palma, 2013; Berg and Verhoef, 2011; Hall, 2018; DiPasquale et al., 2026; Small, Winston, and Yan, 2005; Akbar and Duranton, 2017; Couture, Duranton, and Turner, 2018; Yang, Purevjav, and S. Li, 2020; Hall, 2021; Akbar, Couture, et al., 2023; Tarduno, 2024; Cook and P. Z. Li, 2025; Small, Verhoef, and Lindsey, 2024
- ⇒ Driver heterogeneity can support welfare gains w/o revenue recycling

Related Literatures

- **Congestion pricing and the costs of traffic:** Pigou, 1920; Knight, 1924; Walters, 1961; Vickrey, 1969; Henderson, 1974; Small, 1982; Richard Arnott, Andre De Palma, and Lindsey, 1993; Arnott, André De Palma, and Lindsey, 1994; Fosgerau and Palma, 2013; Berg and Verhoef, 2011; Hall, 2018; DiPasquale et al., 2026; Small, Winston, and Yan, 2005; Akbar and Duranton, 2017; Couture, Duranton, and Turner, 2018; Yang, Purevjav, and S. Li, 2020; Hall, 2021; Akbar, Couture, et al., 2023; Tarduno, 2024; Cook and P. Z. Li, 2025; Small, Verhoef, and Lindsey, 2024
- **Road-pricing experiments:** Martin and Thornton, 2017; Kreindler, 2024; Hintermann et al., 2026
 - ⇒ two-year panel of 10,000 drivers, mostly without rail alternatives

Related Literatures

- **Congestion pricing and the costs of traffic:** Pigou, 1920; Knight, 1924; Walters, 1961; Vickrey, 1969; Henderson, 1974; Small, 1982; Richard Arnott, Andre De Palma, and Lindsey, 1993; Arnott, André De Palma, and Lindsey, 1994; Fosgerau and Palma, 2013; Berg and Verhoef, 2011; Hall, 2018; DiPasquale et al., 2026; Small, Winston, and Yan, 2005; Akbar and Duranton, 2017; Couture, Duranton, and Turner, 2018; Yang, Purevjav, and S. Li, 2020; Hall, 2021; Akbar, Couture, et al., 2023; Tarduno, 2024; Cook and P. Z. Li, 2025; Small, Verhoef, and Lindsey, 2024
- **Road-pricing experiments:** Martin and Thornton, 2017; Kreindler, 2024; Hintermann et al., 2026
- **Structural models of congestion pricing:** Durrmeyer and Martínez, 2026; Almagro et al., 2026; Kreindler, 2024; Hall, 2021; Cook and P. Z. Li, 2025
⇒ Driver-level panel: time-shifting + extensive margin, granular traffic eqm

Related Literatures

- **Congestion pricing and the costs of traffic:** Pigou, 1920; Knight, 1924; Walters, 1961; Vickrey, 1969; Henderson, 1974; Small, 1982; Richard Arnott, Andre De Palma, and Lindsey, 1993; Arnott, André De Palma, and Lindsey, 1994; Fosgerau and Palma, 2013; Berg and Verhoef, 2011; Hall, 2018; DiPasquale et al., 2026; Small, Winston, and Yan, 2005; Akbar and Duranton, 2017; Couture, Duranton, and Turner, 2018; Yang, Purevjav, and S. Li, 2020; Hall, 2021; Akbar, Couture, et al., 2023; Tarduno, 2024; Cook and P. Z. Li, 2025; Small, Verhoef, and Lindsey, 2024
- **Road-pricing experiments:** Martin and Thornton, 2017; Kreindler, 2024; Hintermann et al., 2026
- **Structural models of congestion pricing:** Durrmeyer and Martínez, 2026; Almagro et al., 2026; Kreindler, 2024; Hall, 2021; Cook and P. Z. Li, 2025
- **Transportation infrastructure and spatial equilibrium:** Brinkman, 2016; Allen and Arkolakis, 2022; Herzog, 2024; Barwick et al., 2024; Hierons, 2025; Bordeu, 2025; Fogel, 1964; Duranton and Turner, 2011; Billings, 2011; Anderson, 2014; Donaldson, 2018; Fajgelbaum and Schaal, 2020; Tsivanidis, 2026; Severen, 2023; Donaldson, 2025; Allen, Fuchs, and Wong, 2025; Severen, 2026; Kreindler et al., 2026; Brancaccio, Kalouptsidi, and Papageorgiou, 2026
⇒ Compare congestion pricing w/ specific infrastructure investments, no GE

Demand Parameter Estimates

	Estimate	Std. Error	95% CI
<i>Mean Taste Coefficients</i>			
Price (α_0)	-0.1436***	(0.0097)	[-0.1626, -0.1245]
Duration (γ_0)	-5.0646***	(0.3138)	[-5.6797, -4.4495]
Transit Ratio (ρ_0)	-0.2643***	(0.0487)	[-0.3598, -0.1689]
<i>Interactions with Price</i>			
SES $\times$ Price	0.0321***	(0.0032)	[0.0258, 0.0384]
Population Density $\times$ Price	0.0070***	(0.0016)	[0.0038, 0.0102]
<i>Interactions with Duration</i>			
SES $\times$ Duration	-0.9579***	(0.1058)	[-1.1652, -0.7506]
Population Density $\times$ Duration	0.1955***	(0.0606)	[0.0767, 0.3142]
<i>Interactions with Transit Ratio</i>			
SES $\times$ Transit Ratio	-0.2020***	(0.0413)	[-0.2829, -0.1211]
Population Density $\times$ Transit Ratio	-0.0983***	(0.0249)	[-0.1471, -0.0496]
<i>Random Coefficient Covariance (Σ)</i>			
Var(Price) ($\Sigma_{p,p}$)	0.0022***	(0.0005)	[0.0012, 0.0031]
Cov(Duration, Price) ($\Sigma_{d,p}$)	-0.0401***	(0.0103)	[-0.0603, -0.0199]
Cov(Transit Ratio, Price) ($\Sigma_{tr,p}$)	0.0249***	(0.0057)	[0.0137, 0.0360]
Var(Duration) ($\Sigma_{d,d}$)	2.3808***	(0.3530)	[1.6891, 3.0726]
Cov(Transit Ratio, Duration) ($\Sigma_{tr,d}$)	-0.0586	(0.1277)	[-0.3088, 0.1916]
Var(Transit Ratio) ($\Sigma_{tr,tr}$)	0.3808***	(0.0745)	[0.2348, 0.5268]

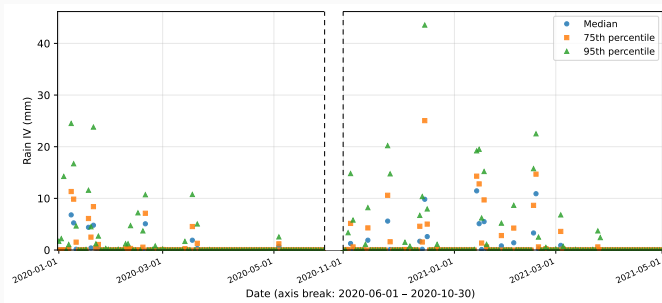
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*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$

Weather IVs: Construction

- Match each TAZ r on a route to the nearest station with rainfall data
- taz_rain_r : cumulative rain at r 's station from 1 PM to departure
- IV: average over route TAZs, weighted by distance w_r traveled in r

$$\text{trip_iv} = \frac{\sum_{r \in \text{route}} w_r \cdot \text{taz_rain}_r}{\sum_{r \in \text{route}} w_r}$$



Israel's traffic jams are back, and worse than ever



Traffic jam on Ayalon Highway in Tel Aviv credit: Tamar Matsafi

The Role of Preference Heterogeneity

Welfare effect of marginal toll increase at $p = 0$:

$$\left. \frac{dW_{\Lambda}}{dp} \right|_{p=0} = \underbrace{-\dot{D}(0)q^*(0)\bar{\phi}}_{\text{average congestion relief}} + \underbrace{-\dot{D}(0)\text{Cov}(q_i^*(0), \phi_i)}_{\text{sorting gain}} - \underbrace{(1-\Lambda)q^*(0)}_{\text{revenue leakage}}.$$

- $\phi_i := \gamma_i/\alpha_i$: value of time; $\bar{\phi} = \mathbb{E}[\phi_i]$: population average
- $\dot{D}(0) = dD(q^*(p))/dp|_{p=0} < 0$: duration response to marginal toll $\uparrow$

The Role of Preference Heterogeneity

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- $\phi_i := \gamma_i/\alpha_i$: value of time; $\bar{\phi} = \mathbb{E}[\phi_i]$: population average
- $\dot{D}(0) = dD(q^*(p))/dp|_{p=0} < 0$: duration response to marginal toll $\uparrow$
- A marginal toll $\uparrow$ improves welfare when

$$\underbrace{|\dot{D}(0)| \left[\bar{\phi} + \text{Cov}\left(\frac{q_i^*(0)}{q^*(0)}, \phi_i\right) \right]}_{\text{value of time saved, weighted by relative driving prob.}} > 1 - \Lambda.$$

Optimal Pricing under Homogeneous Types & Rebates

Nash Equilibrium

$$V - \underbrace{\gamma D(q(p))}_{\text{private cost}} - \alpha p = \ln \frac{q(p)}{1 - q(p)}$$

At the margin, each driver is indifferent b/w driving and not

► Derivation

► Picture

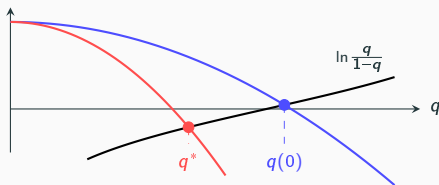
Optimal Allocation ($\Lambda = 1$)

$$V - \gamma [D(q^*) + \underbrace{q^* D'(q^*)}_{\text{marg. externality}}] = \ln \frac{q^*}{1 - q^*}$$

FOC of W_Λ internalizes externality

Pigouvian tax:

$$p^* = \frac{\gamma}{\alpha} q^* D'(q^*)$$



◀ Back

Proof: $p^* = 0$ under $\Lambda = 0$ (Homogeneous Types)

- Suppose a toll $p > 0$ improved welfare relative to $p = 0$.
 - $\rightsquigarrow$ Then $q^*(p) < q^*(0)$ (otherwise congestion is weakly worse while everyone pays a toll)

► Intuition

◀ Back

Proof: $p^* = 0$ under $\Lambda = 0$ (Homogeneous Types)

- Suppose a toll $p > 0$ improved welfare relative to $p = 0$.
 - $\rightsquigarrow$ Then $q^*(p) < q^*(0)$ (otherwise congestion is weakly worse while everyone pays a toll)
 - $\rightsquigarrow$ But $F^{-1}(q) = \ln \frac{q}{1-q}$ is increasing so $F^{-1}(q^*(p)) < F^{-1}(q^*(0))$

► Intuition

◀ Back

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 - $\rightsquigarrow$ In equilibrium, $V - \gamma D(q^*(p)) - \alpha p = F^{-1}(q^*(p))$ so...

► Intuition

◀ Back

Proof: $p^* = 0$ under $\Lambda = 0$ (Homogeneous Types)

- Suppose a toll $p > 0$ improved welfare relative to $p = 0$.
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 - $\rightsquigarrow$ But $F^{-1}(q) = \ln \frac{q}{1-q}$ is increasing so $F^{-1}(q^*(p)) < F^{-1}(q^*(0))$
 - $\rightsquigarrow$ In equilibrium, $V - \gamma D(q^*(p)) - \alpha p = F^{-1}(q^*(p))$ so...

$$\underbrace{\gamma [D(q^*(0)) - D(q^*(p))]}_{\text{congestion relief}} = \alpha p - \underbrace{[F^{-1}(q^*(0)) - F^{-1}(q^*(p))]}_{\text{selectivity tightening} > 0} < \alpha p.$$

Deriving the Indifference Condition

- Driver enters if $u = V - \alpha p - \gamma D(q) + \varepsilon > 0$, where $\varepsilon \sim \text{Type I EV}$
- Equilibrium traffic (homogeneous, $M = 1$):

$$q = \sigma(V - \alpha p - \gamma D(q)) = \frac{e^{V - \alpha p - \gamma D(q)}}{1 + e^{V - \alpha p - \gamma D(q)}}$$

- Inverting the logistic:

$$\frac{q}{1 - q} = e^{V - \alpha p - \gamma D(q)}$$

- Taking logs:

$$\ln \frac{q}{1 - q} = V - \alpha p - \gamma D(q)$$

- At Nash equilibrium with $p = 0$:

$$V - \gamma D(q_0) = \ln \frac{q_0}{1 - q_0}$$

$\Rightarrow$ the marginal value of driving equals the log-odds of entry.

Deriving the Optimal Allocation & Pigouvian Tax

- With $\Lambda = 1$ and homogeneous types, welfare reduces to:

$$W_1(q) = \frac{1}{\alpha} \left[q(V - \gamma D(q)) + \mathcal{H}(q) \right]$$

- Take the FOC $\frac{dW_1}{dq} = 0$:

$$\frac{1}{\alpha} \left[V - \gamma D(q) - \gamma q D'(q) + \mathcal{H}'(q) \right] = 0$$

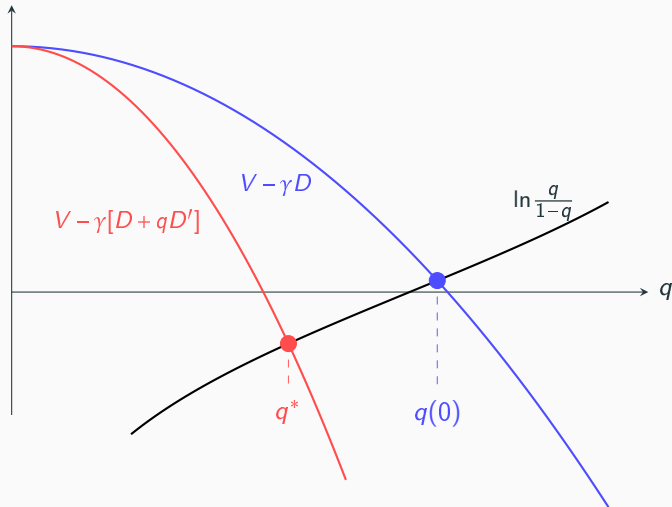
- Since $\mathcal{H}'(q) = -\ln q + \ln(1-q) = -\ln \frac{q}{1-q}$:

$$V - \gamma [D(q^*) + q^* D'(q^*)] = \ln \frac{q^*}{1-q^*}$$

- Compare to the equilibrium condition $V - \alpha p - \gamma D(q) = \ln \frac{q}{1-q}$:

$$\alpha p^* = \gamma q^* D'(q^*) \quad \Rightarrow \quad \boxed{p^* = \frac{\gamma}{\alpha} q^* D'(q^*)}$$

Equilibrium vs. Optimum



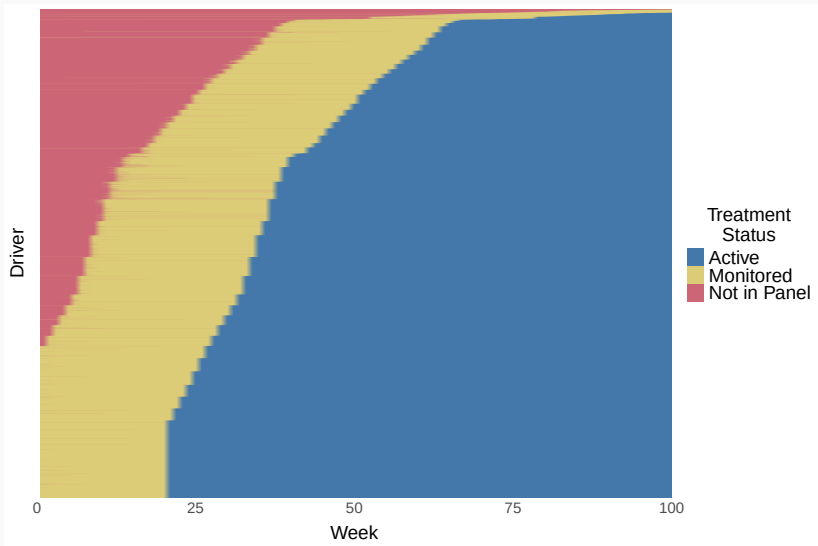
Money-Metric Welfare

- **Money-metric welfare:** consumer surplus *after* paying the toll

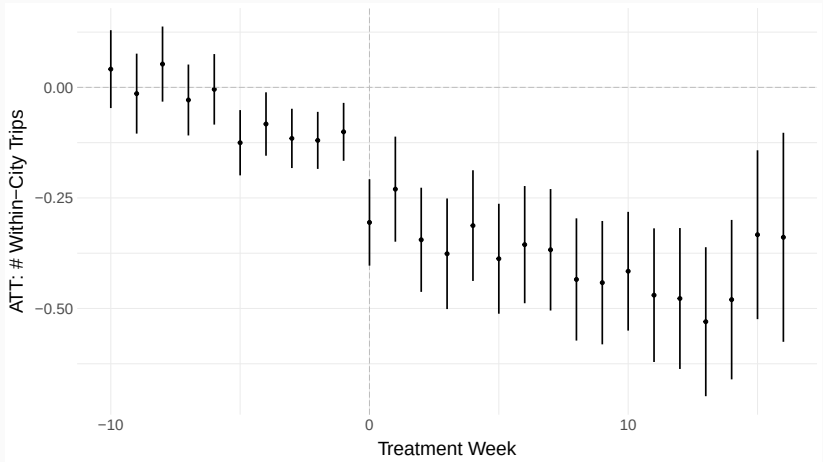
$$W_{\Lambda} = \sum_i \frac{1}{\alpha_i} \left[\underbrace{q_i(V - \alpha_i p - \gamma_i D(q))}_{\text{(deterministic) value of driving}} + \underbrace{\mathcal{H}(q_i)}_{\text{option value}} \right] + \underbrace{\Lambda \cdot p \cdot q}_{\text{toll rebate}}$$

- $\frac{1}{\alpha_i}$: money-metric weight (willingness to pay per util)
- $\mathcal{H}(q_i) = -q_i \ln q_i - (1 - q_i) \ln(1 - q_i)$: logit option value
- $\Lambda \in [0, 1]$: share of toll revenue rebated to consumers

Did Prices Change Behavior? Experimental Design



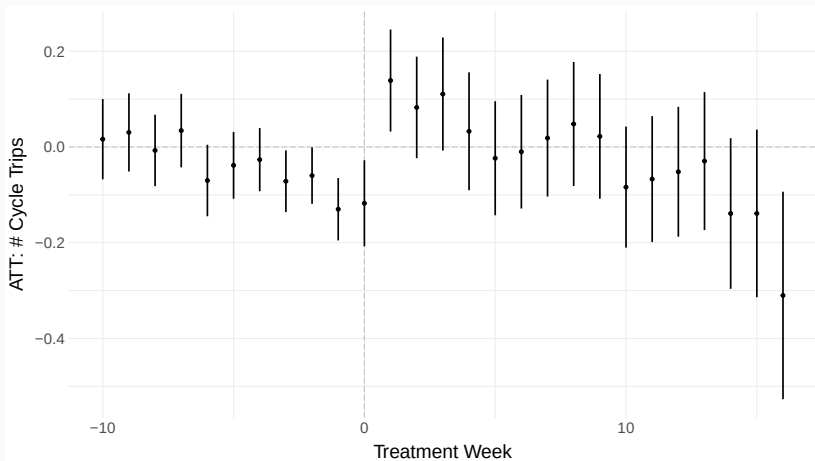
Dynamic Treatment Effects: Number of Within-City Trips



► Estimation Details

◀ Back

Dynamic Treatment Effects: Number of Loop Trips



► Estimation Details

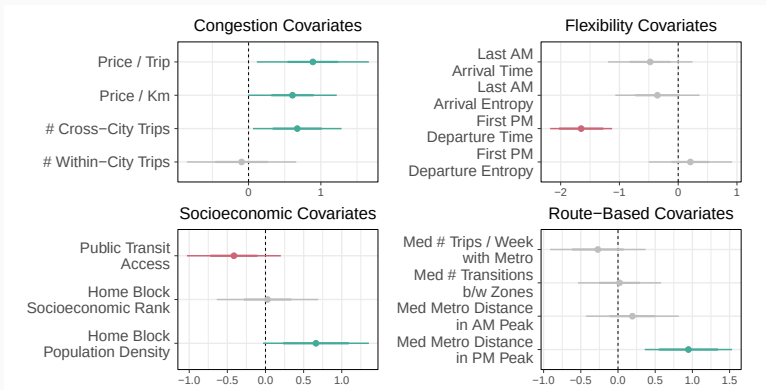
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Who Changed Their Behavior? Estimation Strategy

“Sorted Effects Method” (Chernozhukov, Fernández-Val, and Luo, 2018)

1. Impute individual ATTs from control outcome model
2. Project individual ATTs onto driver characteristics
3. Rank predicted individual treatment effects by effect size
4. Compare the average of each characteristic among the top and bottom 20% of the TE distribution
5. Construct confidence intervals corrected for *FWER* per plot via Bayesian Bootstrap
 - ⇒ reject zeros using step-down procedure in Romano and Wolf, 2005

Who Shifts Their First PM Departure More?

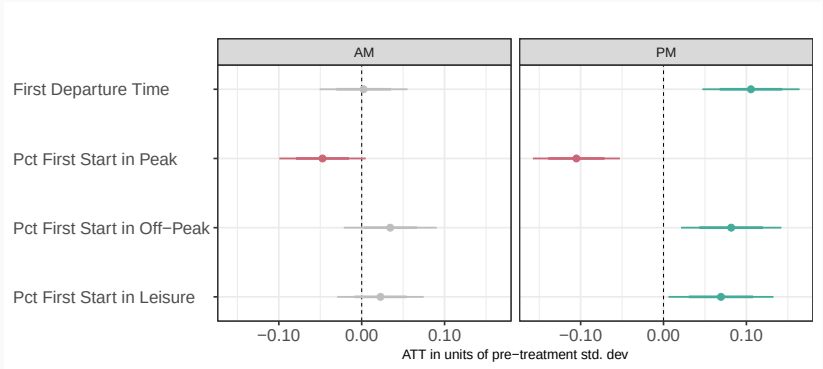


Δ avg. covariate (in std. devs.) of top vs. bottom 20% of first PM departure-time CATEs
across drivers

► Estimation Details

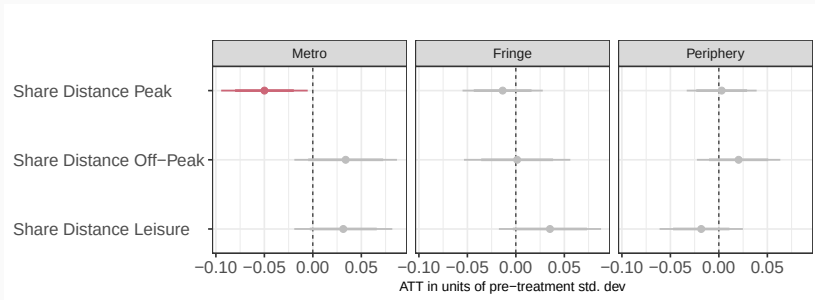
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Average Treatment Effects on Departure Times



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Trip Distance Shares by Price Bucket for PM Cross-City Trips



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Usage-Based Optimal Prices ($\Lambda = 1$)

	Peak	Off-peak
Metropolis	1.78	0.73
Metro Fringe	0.30	0.01
Periphery	0.37	0.55

► Experiment prices

◀ Back

Cordon-Based Optimal Prices ($\Lambda = 1$)

	Peak	Off-peak
Metropolis → Metro Fringe	12.30	6.64
Metro Fringe → Metropolis	0.00	2.80
Metro Fringe → Periphery	0.00	0.00
Periphery → Metro Fringe	7.64	5.33

[► Experiment prices](#)[◀ Back](#)

Congestion Pricing Schedule

	Hours	Metro	Metro Fringe	Periphery
Weekdays				
Peak	6:45 – 9:30AM	1.5	0.3	0.0
	3:30 – 6:30PM	1.5	0.3	0.0
Off-peak	9:30AM – 3:30PM	0.1	0.0	0.0
	6:30 – 8PM	0.1	0.0	0.0
Leisure	8PM – 6:45AM	0	0	0
Weekends	All Hours	0	0	0

Price in NIS per kilometer traveled.

► Map

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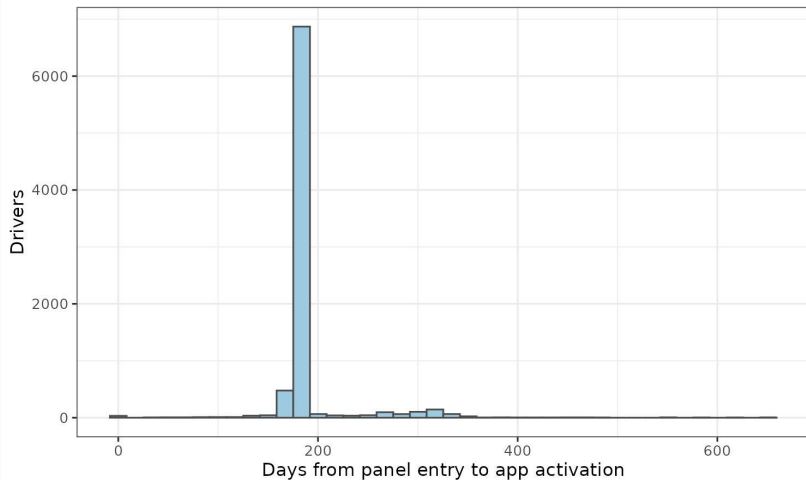
Pricing Map



► Pricing table

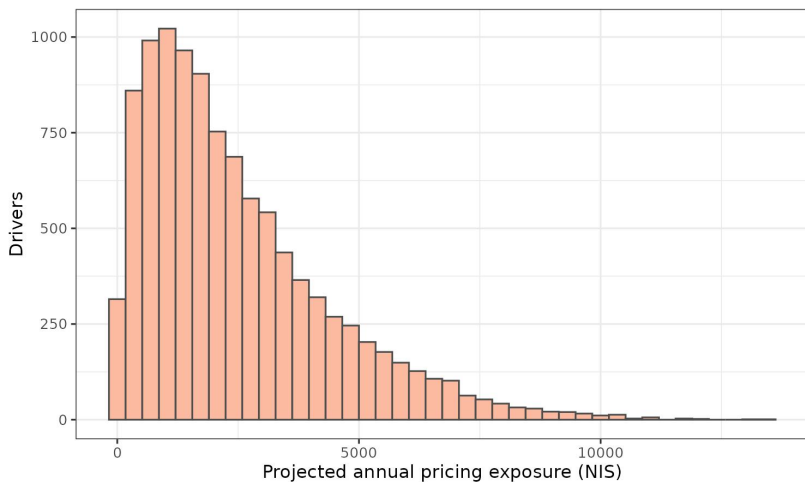
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Distribution of App Download Times



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Distribution of Driver Payments



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Did Prices Change Behavior? Estimation Strategy

- Event study assuming parallel trends on control potential outcomes

$$\Longleftrightarrow \mathbb{E}[Y_{i,t}(0) - Y_{i,t-1}(0) \mid C_i] = \beta_t - \beta_{t-1}$$

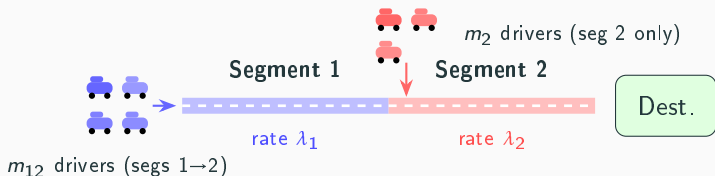
$$\Longleftrightarrow Y_{i,t}(0) = \alpha_i + \beta_t + \varepsilon_{i,t}$$

- Estimand is Average Treatment Effect on Treated (ATT):

$$\tau_e = \sum_c \sum_t \mathbb{1}\{t - c = e\} \mathbb{E}[(Y_{i,t}(c) - Y_{i,t}(0)) \mathbb{1}\{C_i = c\}]$$

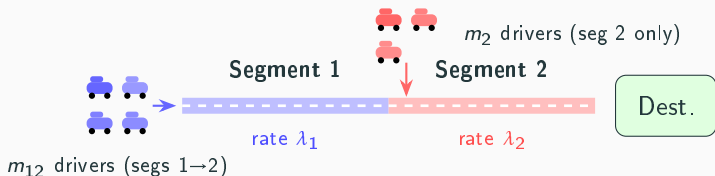
- Model-based imputation for unobserved post-treatment control potential outcomes (Borusyak, Jaravel, and Spiess, 2024)
- Confidence intervals corrected for *FWER* via Bayesian Bootstrap (Romano, Shaikh, and Wolf, 2010)
 - $\Rightarrow$ reject zeros using step-down procedure (Romano and Wolf, 2005)

Supply: Accounting for Vehicle “Overlap” in Space and Time



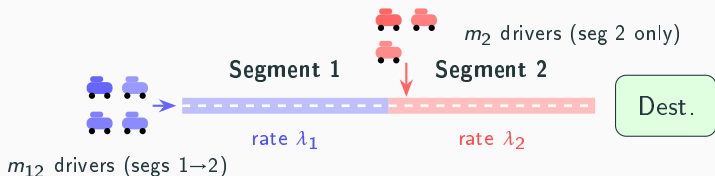
- The m_{12} drivers **overlap** with m_2 drivers on segment 2—but *when*?
 - ⇒ Depends on how long each driver spends on segment 1
 - ⇒ Congestion on segment 1 delays their arrival onto segment 2

Supply: Accounting for Vehicle “Overlap” in Space and Time



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 - Transition from segment k to $k+1$ at rate $\lambda_{k:(k+1)}(q(\tau))$

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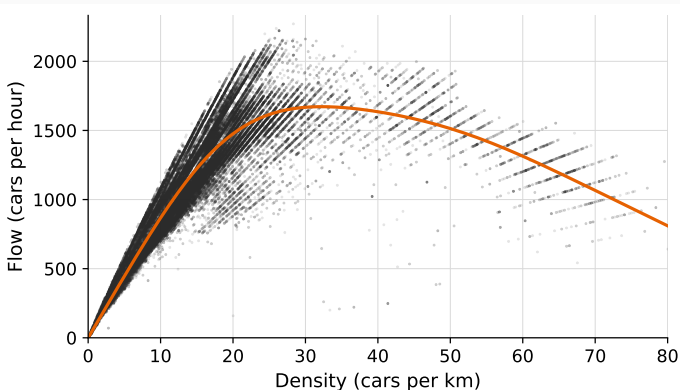
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- Time-varying traffic **eqbm** ⇒ solve ODE system:

$$\underbrace{\frac{d}{d\tau} q_2(\tau)}_{\Delta \text{ mass on segment 2}} = \underbrace{\lambda_{1:2}(q(\tau)) q_1(\tau)}_{\text{inflow from segment 1}} - \underbrace{\lambda_2(q_2(\tau)) q_2(\tau)}_{\text{outflow from segment 2}} + \underbrace{m_2 x_2(\tau; q)}_{m_2 \text{ drivers leaving at } \tau}$$

Supply: Estimating Congestion Technology $\lambda(q)$

► Why Highways?

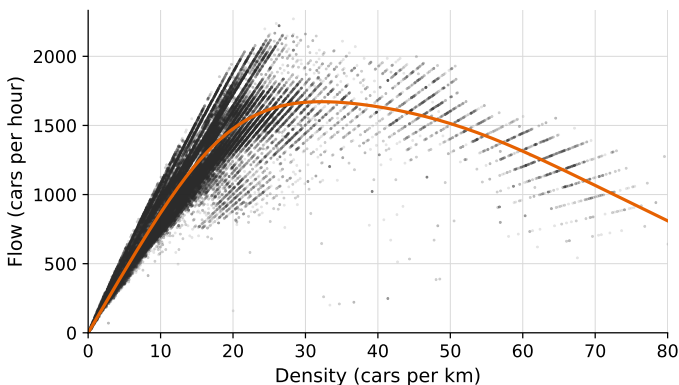
- ↪ Use real-time speeds and road occupancy from highway sensors
- ↪ Model volume as nonparametric, concave function of vehicle density (Daganzo, 1994; Daganzo, 1995; Lebacque, 1996)



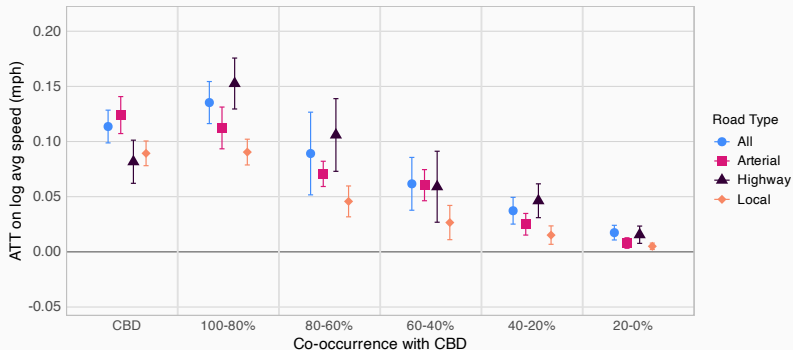
Supply: Estimating Congestion Technology $\lambda(q)$

► Why Highways?

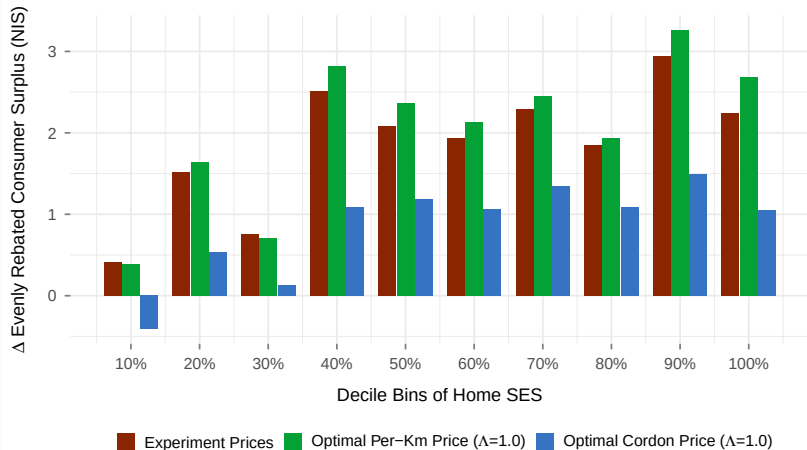
- ↪ Use real-time speeds and road occupancy from highway sensors
- ↪ Model volume as nonparametric, concave function of vehicle density (Daganzo, 1994; Daganzo, 1995; Lebacque, 1996)
- ↪ Calibrate pop.-weights to make trip counts match sensor volumes



Cook, Kreidieh, Vasserman et al (2026)



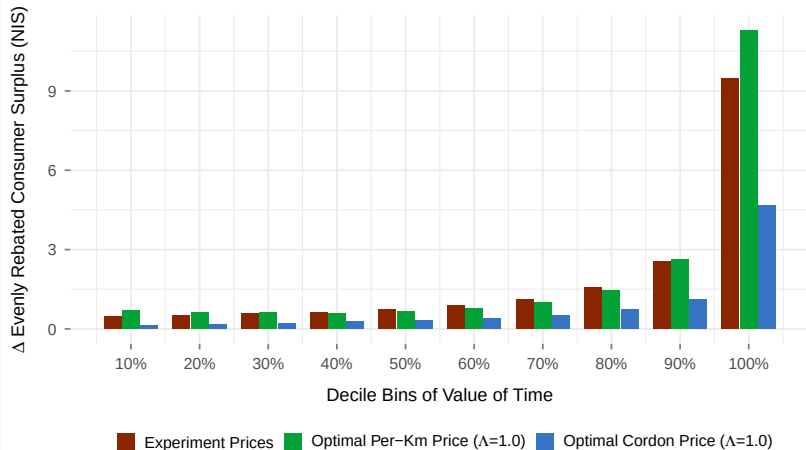
Uniformly Rebated ΔCS by SES Bin



► Pareto rebate

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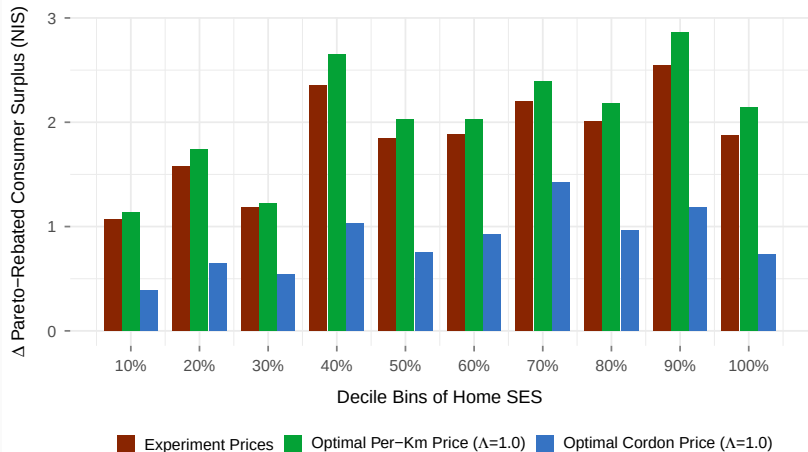
Uniformly Rebated ΔCS by Value of Time Bin



► By SES bin

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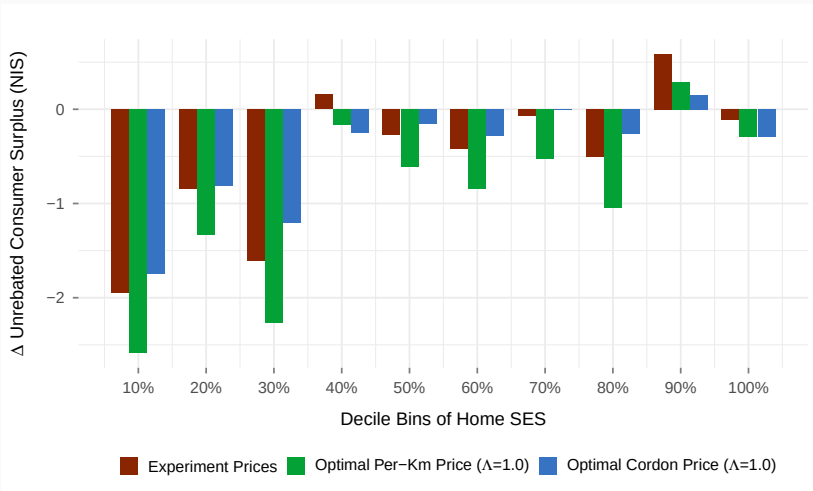
Pareto-Rebated ΔCS by SES Bin



► Uniform rebate

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(Raw) ΔCS by SES Bin w/o Toll Revenue



Adding One Lane to Every Highway Welfare Comparison

Equilibrium (drivers re-optimize trip & departure choices)

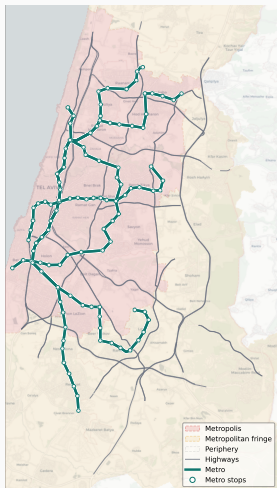
	Mean	SD	Q25	Median	Q75
Trip Probability (pp)	4.13	5.76	0.08	1.62	6.03
Distance / Day (km)	0.88	2.32	0.01	0.15	0.81
Price / Trip (NIS)	0.00	0.00	0.00	0.00	0.00
Duration / Trip (mins)	-2.51	3.26	-3.77	-1.22	-0.05
Speed / Trip (km/h)	4.20	4.57	0.28	2.91	6.78
Raw Consumer Surplus (NIS/day)	1.75	5.08	0.01	0.30	1.51
Rebated Consumer Surplus (NIS/day)	1.75	5.08	0.01	0.30	1.51

Fixed departure choices (baseline choice shares held fixed)

	Mean	SD	Q25	Median	Q75
Trip Probability (pp)	0.00	0.00	0.00	0.00	0.00
Distance / Day (km)	0.00	0.00	0.00	0.00	0.00
Price / Trip (NIS)	0.00	0.00	0.00	0.00	0.00
Duration / Trip (mins)	-6.65	9.31	-10.21	-2.42	-0.12
Speed / Trip (km/h)	13.55	13.91	0.66	9.41	23.60
Raw Consumer Surplus (NIS/day)	3.12	8.85	0.03	0.49	2.76
Rebated Consumer Surplus (NIS/day)	3.12	8.85	0.03	0.49	2.76

Benchmark: What If We Built Transit Instead?

► Baseline Metrics



Planned Tel Aviv metro set to open in **2037**

- ~> Faster transit for **about 10%** of trips
 - 2.7%** *direct* (subway + walk)
 - 7.1%** *combo* (subway + bus/rail)
- ~> Among those: transit time ↓ **~5 min**
- ~> Drive/transit time ratio ↑ **12%–20%**

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Benchmark: What If We Built Transit Instead?

	Direct metro	Combo metro	Not improved
Share of trips (%)	2.7	7.1	90.3
Transit mins saved	5.56	4.67	0.00
Δ Eqm. trip probability (pp)	-1.03	-0.29	0.01
Δ Eqm. CS (NIS / trip-day)	0.41	-0.02	0.01

- Speed gains are small in every group: 0.01–0.07 km/h on avg
- Welfare gains concentrated among drivers w/ direct metro access

Transit Quality: Driving vs. Transit Duration Ratio

Best modes (median start time)	N	Share	P10	Median	P90	Mean
Walk Only	7,883	11.4%	0.29	0.61	1.52	0.85
1 bus	35,297	51.2%	0.40	0.73	1.43	0.87
2 bus	17,590	25.5%	0.38	0.66	1.13	0.73
3 bus	5,945	8.6%	0.38	0.64	1.03	0.68
4+ bus	1,484	2.2%	0.40	0.61	0.93	0.65
Has rail	737	1.1%	0.37	0.63	0.98	0.67
Other	28	0.0%	0.48	0.71	1.31	0.84

Ratio of imputed driving duration to best transit duration, by best-modes bucket (median start time; one row per habitual trip).

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