Optimal Charging Infrastructure for Electric Vehicles

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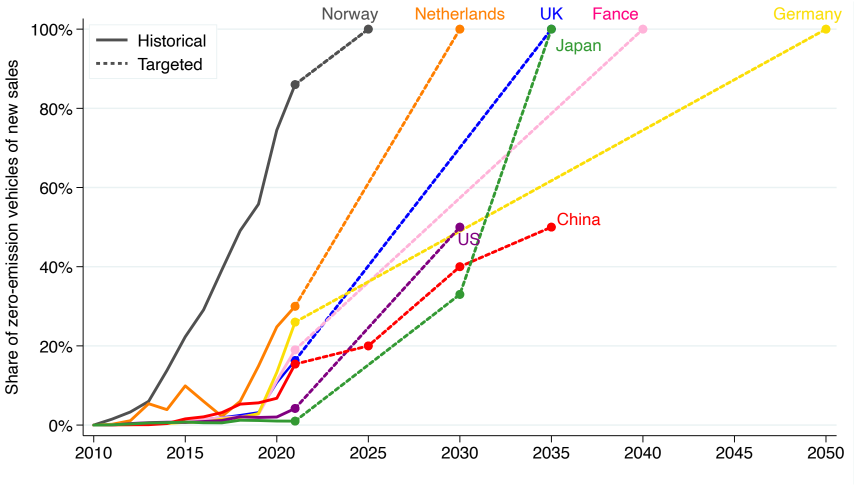
Economics of Transportation in the 21st Century
October 14, 2022
Preliminary

ZEV Targets and EV Shares in 2021



Note: ZEV target and EV market shares for major EV countries. Source: ICCT with authors' updates.

Research Question

- The Bipartisan Infrastructure Law provides $7.5 billion to build a national EV charging network by 2026
- Our research questions:
    1. What would the optimal charging network look like in terms of station density and the spatial pattern?
    2. How can the funding be allocated to effectively promote EVs and to improve social welfare?

Research Framework

1. A model of the two-sided market on EV demand and charging stations
2. Estimation using granular data on EV sales and stations
3. Policy simulations
    - Solve for socially optimal charging network without budget constraint
    - Examine market outcomes under different cost-sharing ratios
    - Find subsidy policies to mimic the social optimal under a budget

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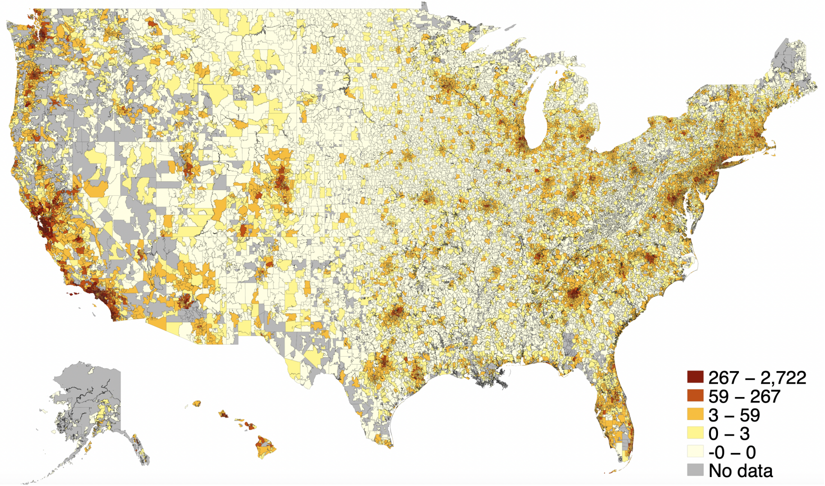
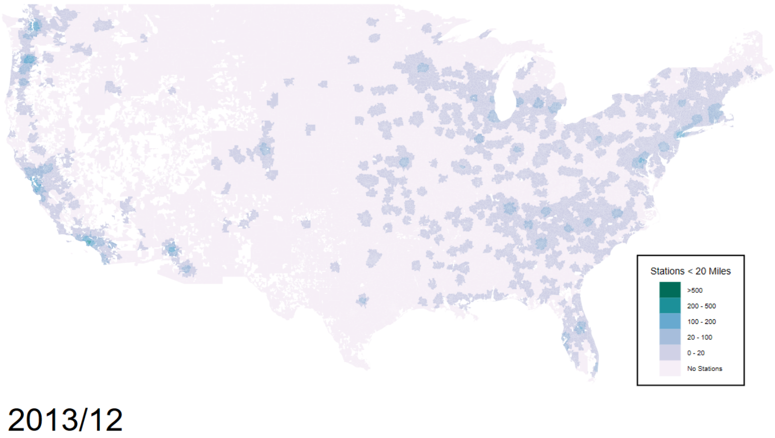
Data Description

- Annual EV sales by model by zip, and vehicle attributes 2013-19
- Charging stations with location, entry time, and characteristics
- 2017 National Household Travel Survey
- Demographics, foot traffic at POIs, road network and vehicle traffic

EV Sales by Zip Code in 2019

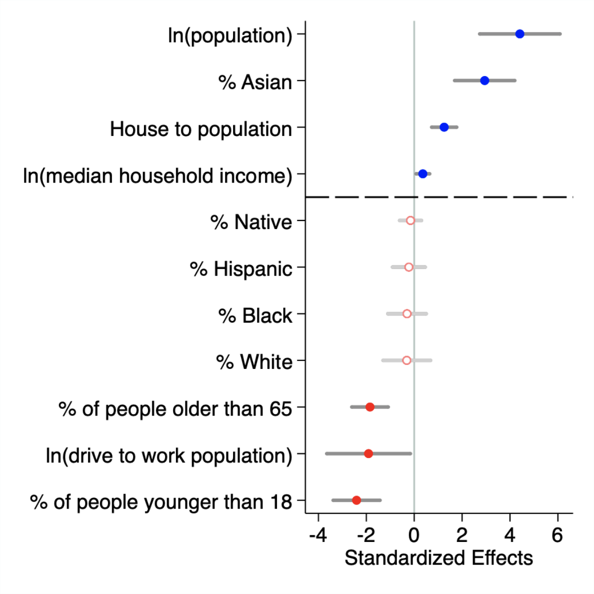


Charging Station Density



- No. of stations within 20 miles by zipcode.

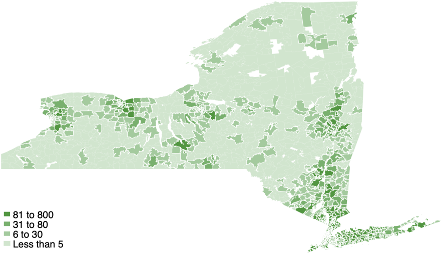
Charging Stations and Demographics



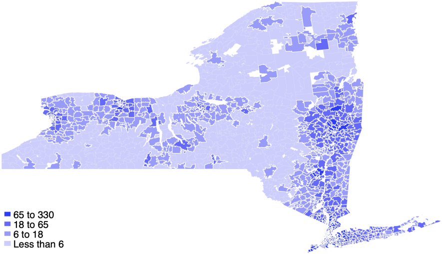
EV Stock and Charging in New York in 2021

Top 10 states

(a) EV Stock



(b) Chargers



Empirical Model Overview

EV demand Station entry

EV demand

$$\max_{j \in \{\mathcal{J}_{ev}, 0\}} u_{mij}(\mathbf{x}_j, \mathbf{z}_{mi}, \mathbf{k}_m)$$

$\mathbf{x}$: product attributes

$\mathbf{z}$: demographics

$\mathbf{k}$: charging access

Station entry

$$\pi_{mt}(\mathbf{w}_{mt}) \gtreqless C_t - \delta C_{t+1}$$

π: current-period profit

$\mathbf{w}$: EV stock, VMT, traffic, competition

Empirical Model Overview

Better charging access
promotes EV adoption

EV demand

$$\max_{j \in \{\mathcal{J}_{ev}, 0\}} u_{mij}(\mathbf{x}_j, \mathbf{z}_{mi}, \mathbf{k}_m)$$

$\mathbf{x}$: product attributes
$\mathbf{z}$: demographics
$\mathbf{k}$: charging access

Station entry

$$\pi_{mt}(\mathbf{w}_{mt}) \gtrless C_t - \delta C_{t+1}$$

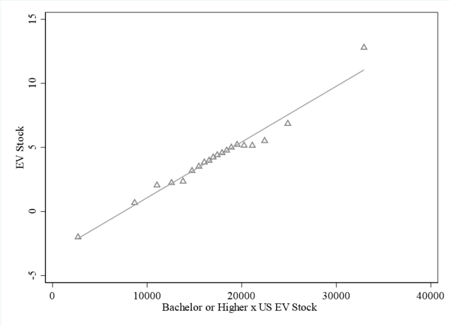
π: current-period profit
$\mathbf{w}$: EV stock, VMT, traffic, competition

Higher EV adoption
incentivizes station entry

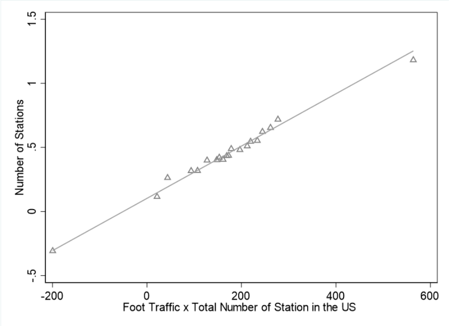
Estimation Strategy

- GMM for EV demand and station entry ▸ exclusion restrictions
  - Pop. share with college education in m × national stock at t
  - Foot traffic in m × national stations at t
  - Micro-moments: shares by income group among EV buyers, ...

(a) 1st-stage: residualized EV Stock$_{mt}$



(b) 1st-stage: residualized station$_{mt}$



Estimation Results

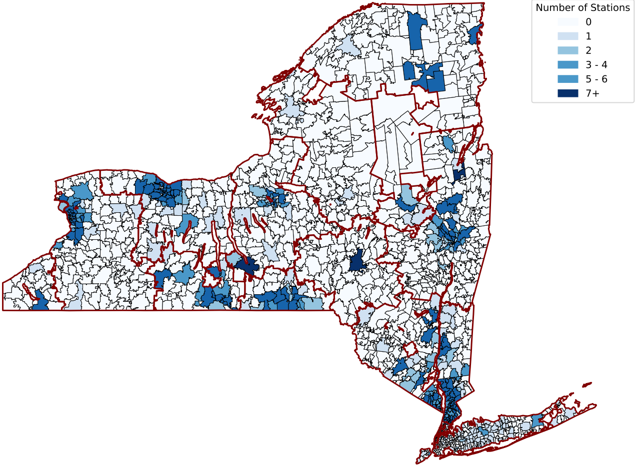
- EV demand: ▸ parameter estimates
  - EV demand increases with charging station density
  - Average station elasticity: 0.88
  - Consumer preference heterogeneity based on observed (income, VMT) and unobserved demographics
  - Average price elasticity: -2.52
- Station entry: ▸ parameter estimates
  - Charging demand increases with foot traffic and decreases with distance
  - Demand for charging at level-3 stations is stronger than level-2
  - Average markup per kWh: 20 cents. Decreases with competition

Simulation Setup

- Focus on level-3 stations and hold level-2 stations fixed
- Initialize the starting point at 2021 and simulate forward to 2026
- Assume certain cost-sharing ratio for the fixed cost
- Solve for investment decisions and EV sales for each commuting zone

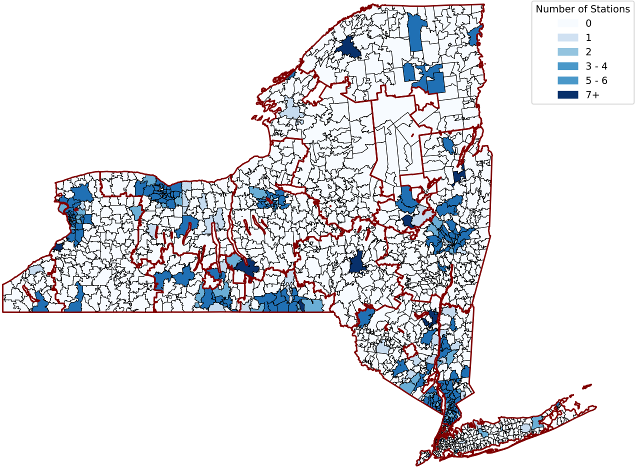
Key assumptions

No. of Level-3 Stations by 2026 at Baseline



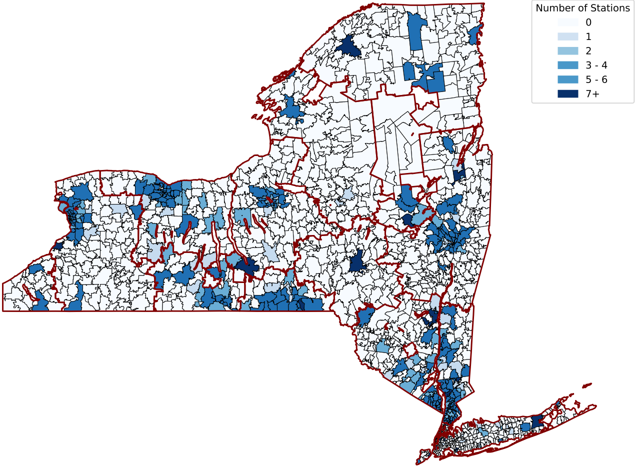
- No subsidies for station entry. 1351 stations

No. of Level-3 Stations by 2026 with 30% Cost-sharing



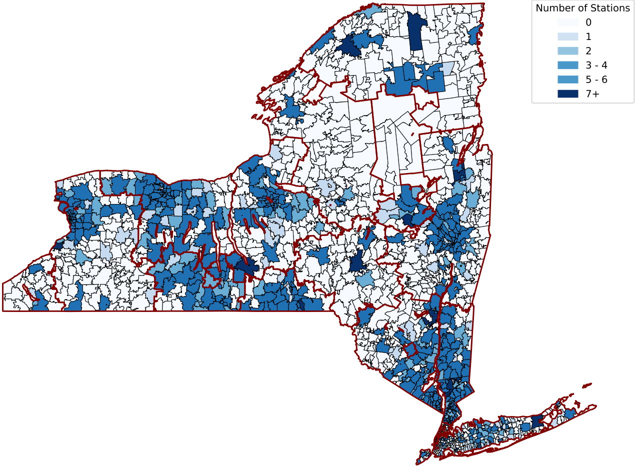
- Total subsidies (2012-2026): $77 million. 1682 stations.

No. of Level-3 Stations by 2026 with 50% Cost-sharing



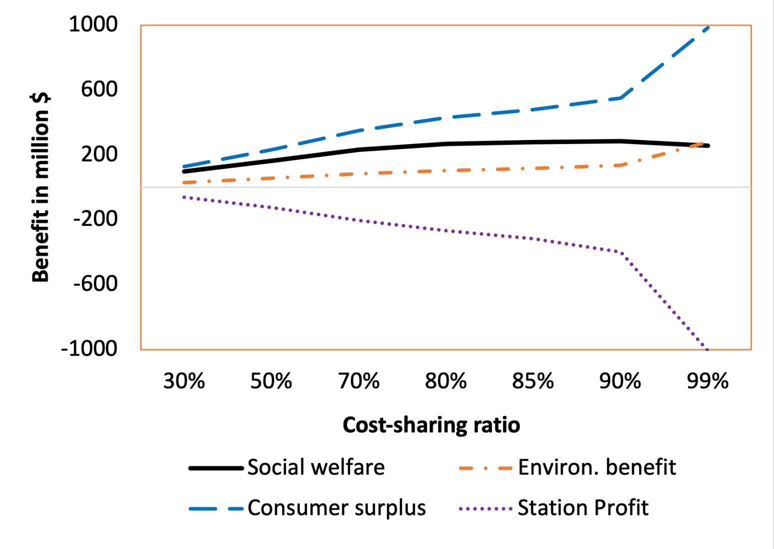
- Total subsidies (2012-2026): \$159 million. 2012 stations

No. of Level-3 Stations by 2026 with 90% Cost-sharing

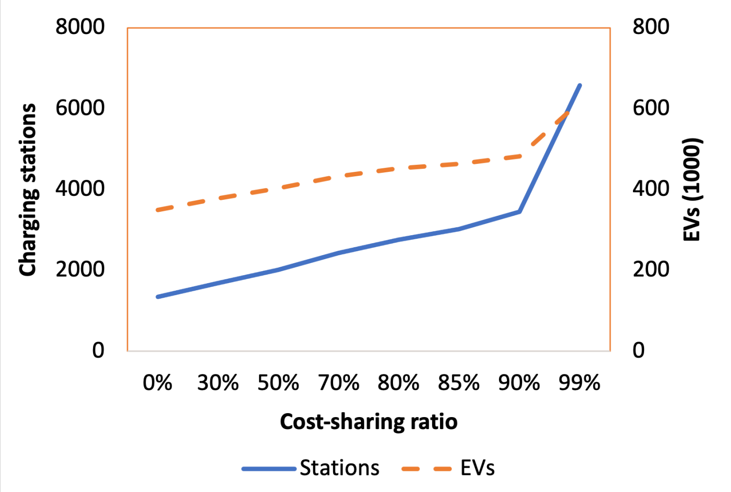


- Total subsidies (2012-2026): $530 million. 3455 stations

Welfare under Cost-sharing (relative to baseline)



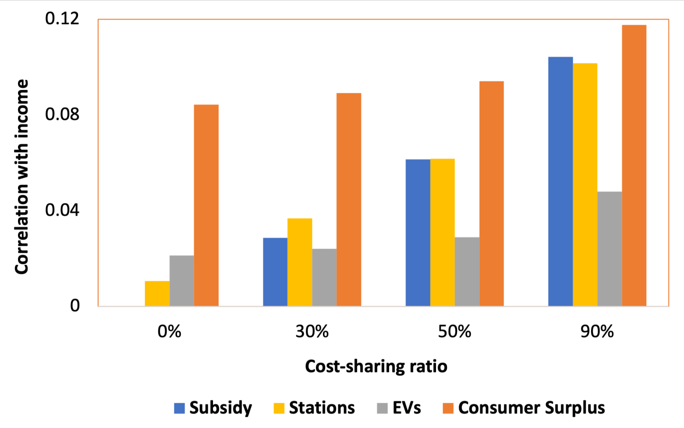
EV Adoption and Charging Stations



Impact Heterogeneity w.r.t. Income

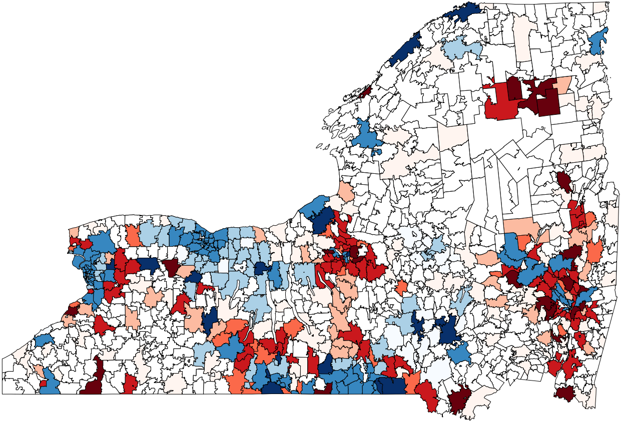
▸ Population size

- Correlation between zip-level income with outcomes



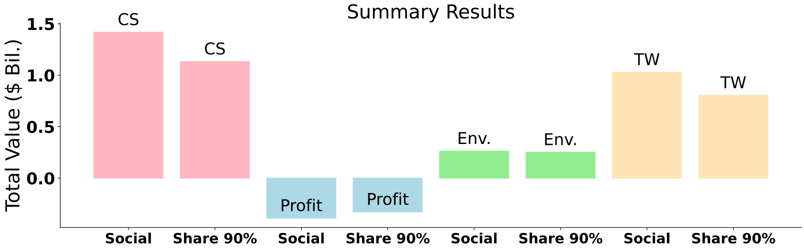
Socially optimal vs. 90% cost-sharing

- No. of stations under socially optimal relative to 90% cost-sharing
- Warm color: under-subsidized areas; cool color: over-subsidized



Socially optimal vs. 90% cost-sharing

- Better targeting leads to more stations, and higher consumer surplus
- Socially optimal network leads to a 30% increase in welfare



Preliminary Findings

- \$175 million federal funding to NY during 2022-2026 can support about 50% cost-sharing. Increasing stations by 49% and EVs by 15%
- A higher cost-sharing appears justifiable. The cost-sharing ratio of 90%, or \$530 million during 2022-2026 for NY leads to the highest welfare
- Uniform subsidies benefit high-income areas more. More so for a higher cost-sharing
- Place-based vs. uniform cost-sharing. Lower subsidies for locations with stronger private incentives. Gains from targeted subsidies about 30%

Next Steps

- Allow long-distance trips
- Add road network and vehicle traffic in the analysis
- Distinguish facility types
- Expand the analysis to the whole U.S.
- Additional suggestions?

THANKS FOR THE SUPPORT!

Charging Stations in 2022

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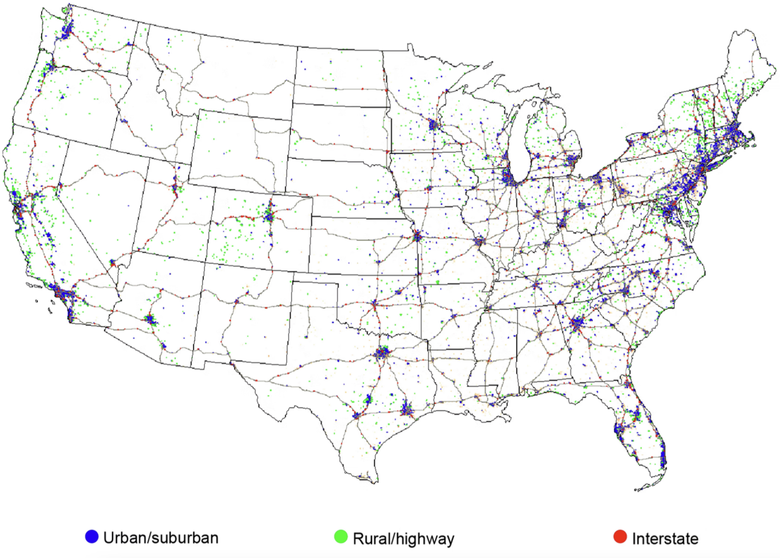

Source: IEA Global EV Outlook 2022

Charging Facility Type in 2021

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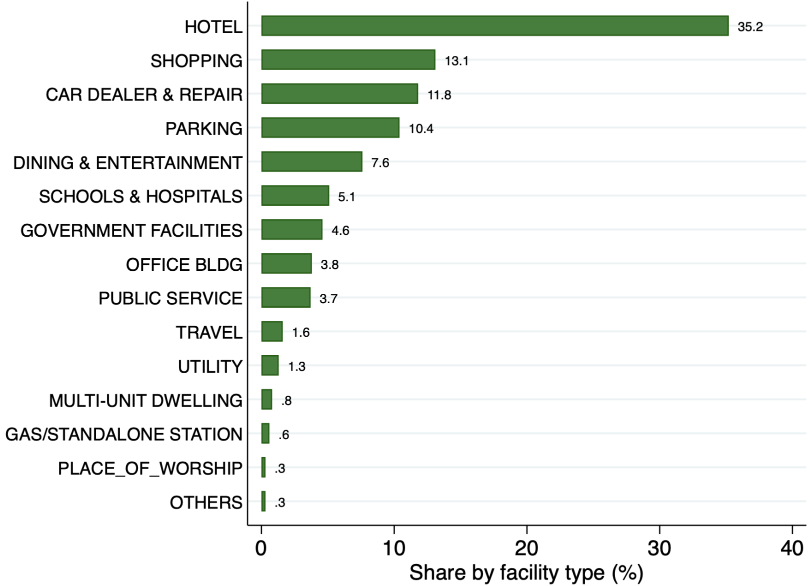

Charging Network over Time

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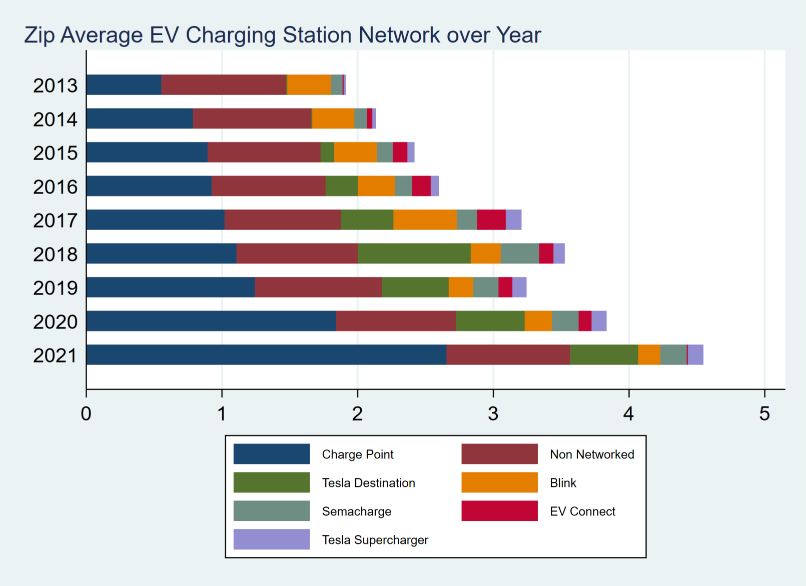

Charging Stations by State in 2021

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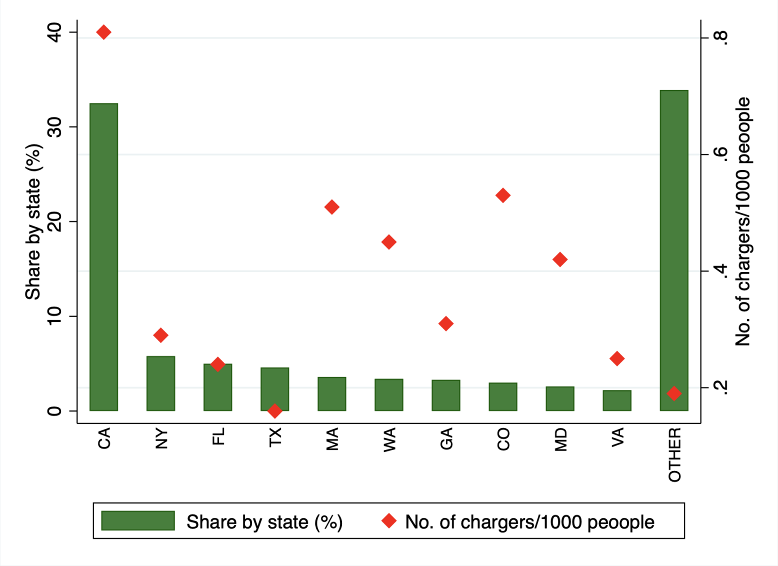

Empirical Model: EV Demand

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- Consumers choose among a set of EV models and an outside good (e.g., a gasoline model) based on preferences and available choices
- Utility of consumer i from choice j in location m

$$u_{ijm} = \alpha_i(p_j - s_{ij}) + x_j\beta_i + \gamma_i \sum_{l=1}^{n} \omega(z_l, d_{lm})k_l + \varepsilon_{ijm},$$

- α_i, β_i and γ_i: heterogeneous consumer preference, f(income, VMT)

$$\alpha_i = -e^{\bar{\alpha} + y_i \alpha_y^P + \nu_i^P \sigma^P}$$

$$\theta_i = \bar{\theta} + y_i \theta_y + vmt_i \theta_{vmt} + \nu_i^\theta \sigma^\theta, \forall \theta \in \{\beta, \gamma\}$$

- $\sum_{l=1}^{n} \omega(z_l, d_{lm})k_l$ characterizes station density in a location. d_{lm}: distance; k_l: station count

Empirical Model: Charging Investment

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- Free-entry condition: indifferent between entering at t and $t+1$ for type τ

$$\pi_m^\tau \gtreqless C_t^\tau - \delta C_{t+1}^\tau$$

- Period-profit function from providing charging and/or being an ancillary service:

$$\pi_m^\tau = q_m^\tau r_m^\tau + \varepsilon_{r_m}$$

  - q_m^τ: total charging at a type-τ station in m
  - r_m^τ markup per kWh: $\frac{\lambda_1}{1+\lambda_2 \bar{k}_m}, \bar{k}_m = \sum_{j=1}^n \frac{k_j}{d_{jm}+1}$

Empirical Model: Charging Investment

- $q_m^\tau = \sum_{l=1}^n Q_l S_{lm}^\tau$: charging at m come from many locations
  - Q_l is total charging from EVs in l
  - S_{lm}^τ is the share allocated to charging type τ at m

$$Q_l = \frac{vmt_l \times EVstock_l}{fuelefficiency_l}$$

$$S_{lm}^\tau = \underbrace{\frac{exp\left[\psi^1 \times foot_l + \psi^2 \times d_{lm} + \psi^3 \log(\sum_{s\in T_m} exp(\varphi_0^s + \varphi_1^s k_m^s))\right]}{\sum_{j=1}^n exp\left[\psi^1 \times foot_j + \psi^2 \times d_{lj} + \psi^3 \log(\sum_{s\in T_j} exp(\varphi_0^s + \varphi_1^s k_j^s))\right]}}_{\text{Prob. of charging at } m}$$

$$\times \underbrace{\frac{exp(\varphi_0^\tau + \varphi_1^\tau k_m^\tau)}{\sum_{s\in T_m} exp(\varphi_0^s + \varphi_1^s k_m^s)}}_{\text{Prob. of charging at type } \tau} \times \underbrace{\frac{1}{k_m^\tau}}_{\text{Prob. of charging at a given station}} .$$

Estimation Strategy: GMM

- Moment conditions for EV demand:
  - BLP IVs: of EV models, battery capacity, driving range, vehicle size
  - Micro-moments: shares by income group among EV buyers; shares of EV buyers by income group among new vehicle buyers; shares by VMT group among EV buyers
- Moment conditions for station entry:
  - Interaction of national EV stock with: (1) share of college degree or higher by zip, (2) foot traffic by zip, (3) foot traffic within 20 miles, (4) annual VMT per driver by zip
  - Interactions of foot traffic by zip with: (1) national stations, and (3) national L3 stations

First stage

Estimation Results: EV Demand

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	Para.	S.E.
Linear para.		
Range	0.173	(0.042)
HP/Weight	-0.001	(0.010)
Vehicle Size	0.436	(0.136)
Non-linear para.		
Price ($\bar{\alpha}$)	5.252	(0.028)
Price*Income (α_y^P)	-1.564	(0.004)
Station density	17.463	(0.128)
Station density*VMT	-0.127	(0.002)
Random Coefs. (σ)		
Price (σ^P)	3.330	(0.019)
Constant	9.338	(0.112)

$$\alpha_i = -e^{\bar{\alpha} + y_i \alpha_y^P + v_i^P \sigma^P}$$

Notes: unit of observation for the GMM objective function is model by commuting zone by year. Zone-year FEs, fuel type (BEV/PHEV) FEs, and Firm FEs included.

Estimation Results: Charging Investment

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	Para.	S.E.
Markup (in $\$/\mathbf{kWh}$)		
Constant (λ_1)	0.320	(0.012)
Competition effect (λ_2)	0.046	(0.003)
Charging Location Choice		
Foot traffic (ψ^1)	0.805	(0.030)
Distance (ψ^2)	-1.430	(0.081)
Expected Utility of Charging (ψ^3)	1.594	(0.055)
Charging Type Choice		
L3 Stations FE (φ_0)	1.065	(0.038)
Number of Stations (φ_1)	0.071	(0.004)

Notes: unit of observation is zip by year. Zip FEs included.

Simulation Assumptions

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Parameters	Value	Notes
Fixed costs		
Level 2	\$20,000 (4 ports)	4% decline/yr
Level 3	\$200,000 (4 ports)	4% decline/yr
Charging at home vs. outside		
Charging at home	80%	
Environmental benefit		
Carbon and local pollutants	\$700-1974	

Note: the environmental benefit is the lifetime benefit of an average EV relative to a gasoline vehicle in NY. The lower bound is from "Benefit-Cost Analysis of Electric Vehicle Deployment in New York State," NYSERDA (2019). The upper bound is based on author's calculation. Results in the slides are based on the lower bound.

Impact Heterogeneity w.r.t. Population Size

Income

- Correlation between zip-level population size with outcomes