



The Charging Infrastructure Gap

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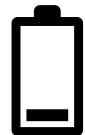
Problem: Insufficient Charging Infrastructure



47k Stations



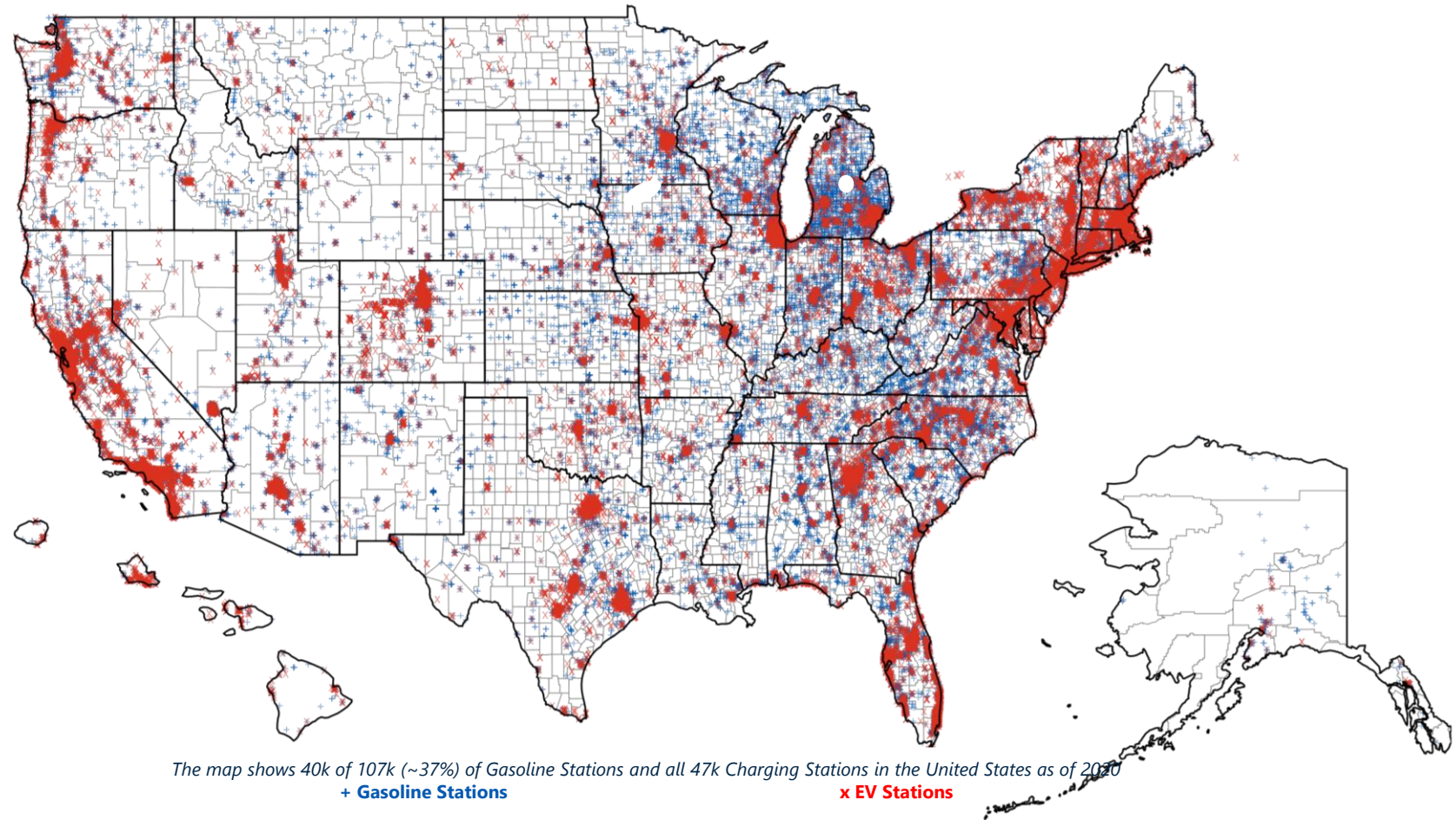
103k Ports



48%
Counties have Zero Stations



23 Million
Have No In-County Station



Prior Works are Computationally Expensive

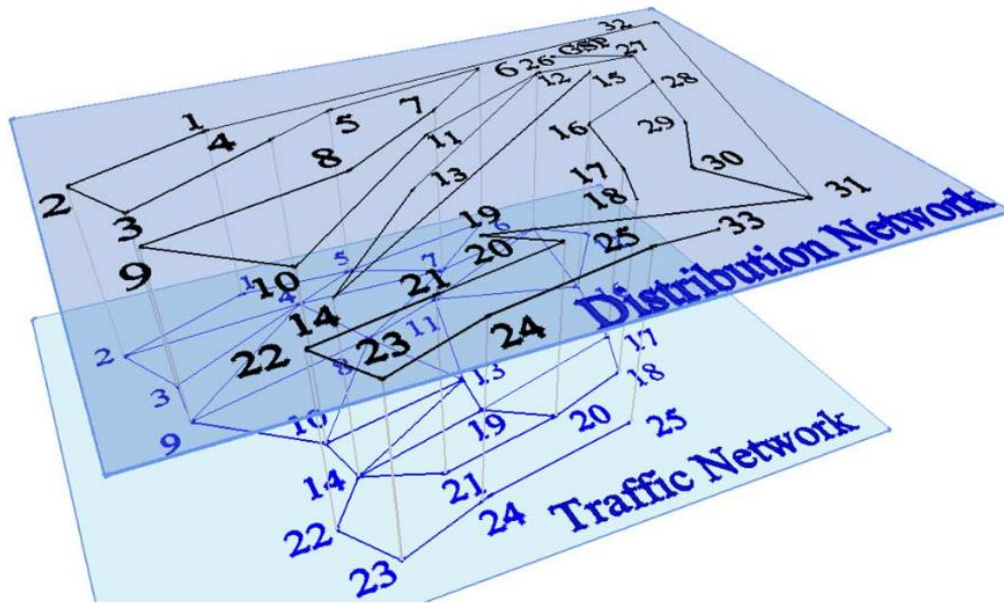
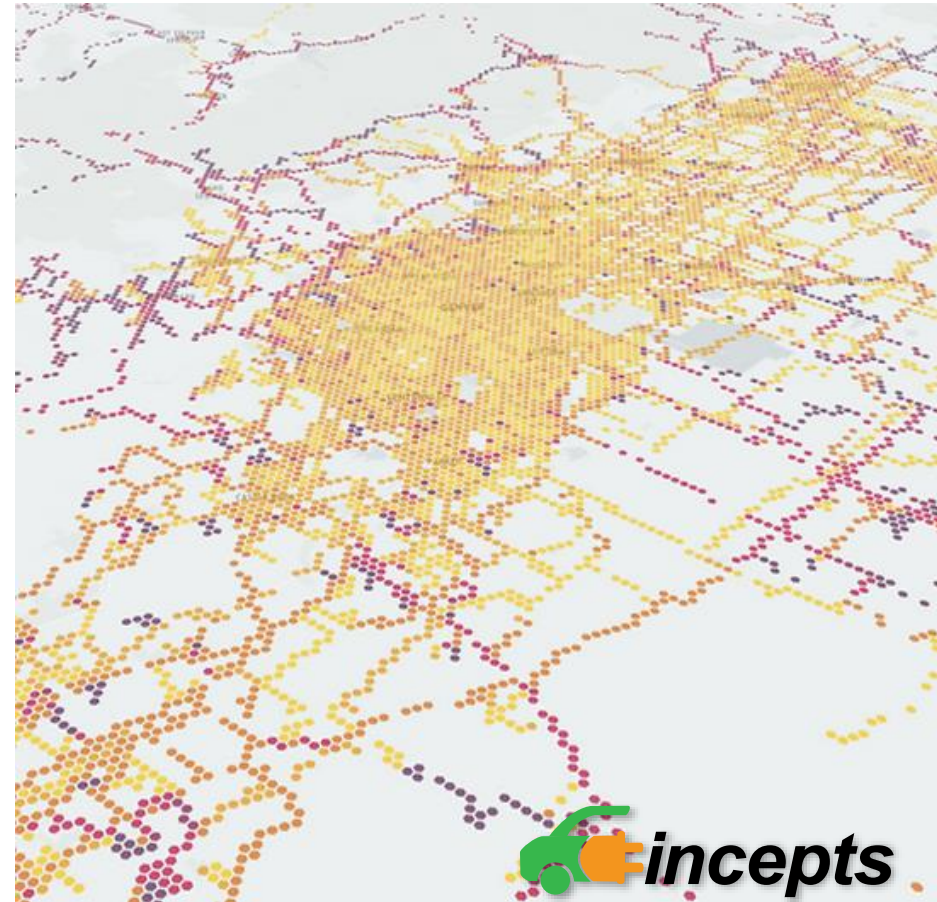
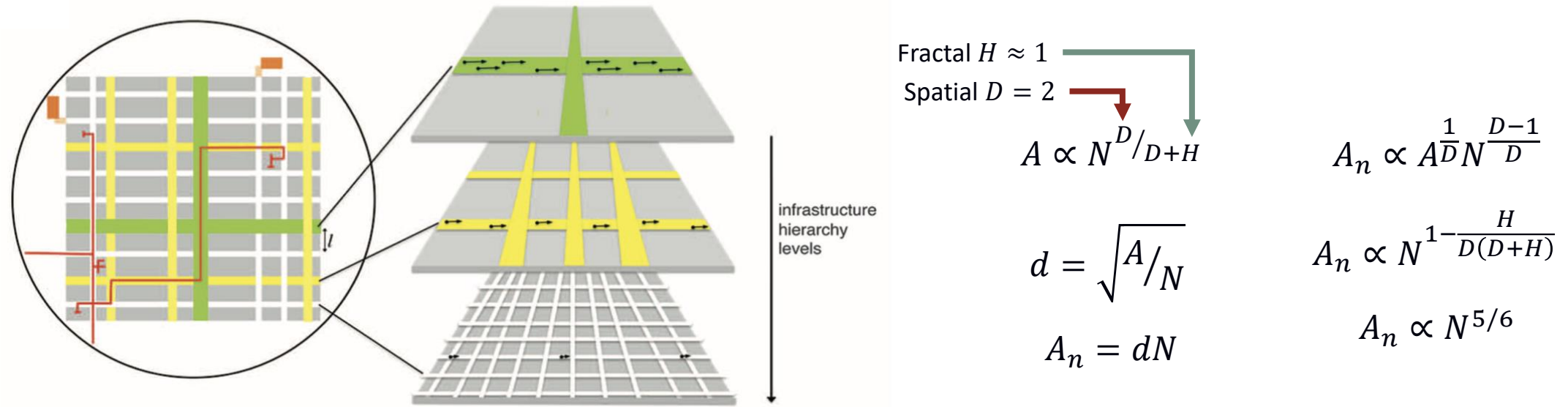


Fig. 4. Test system with 33-node distribution system and a 25-node traffic network. (Gray links: indicate the geographic overlapping of the nodes in the distribution network and nodes in the traffic network).



Urban Scaling: A Framework for Modeling Society



$$Y = Y_0 N^\beta$$

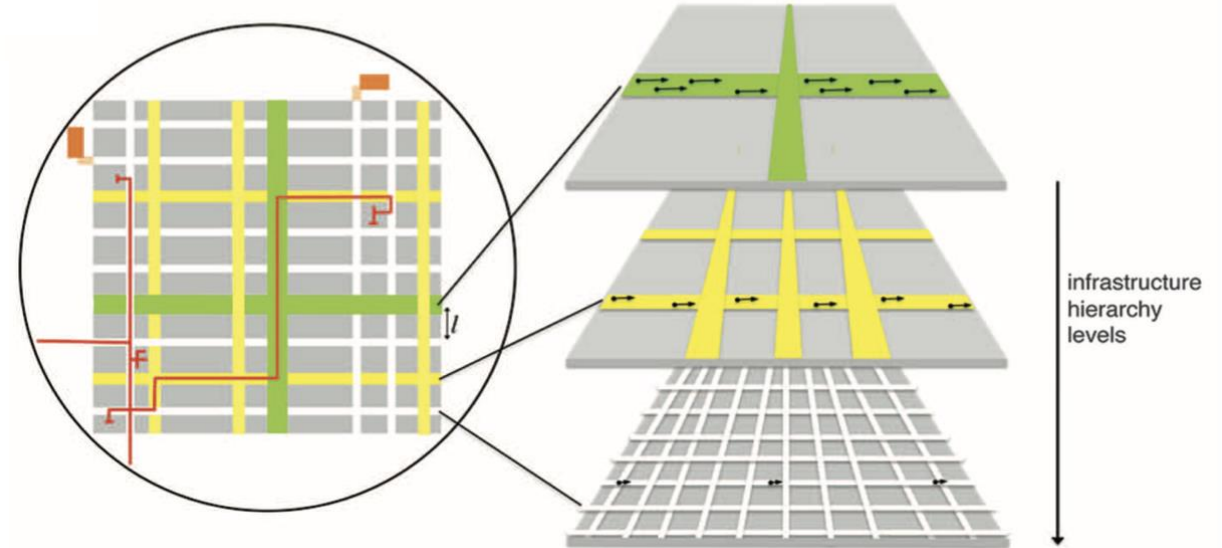
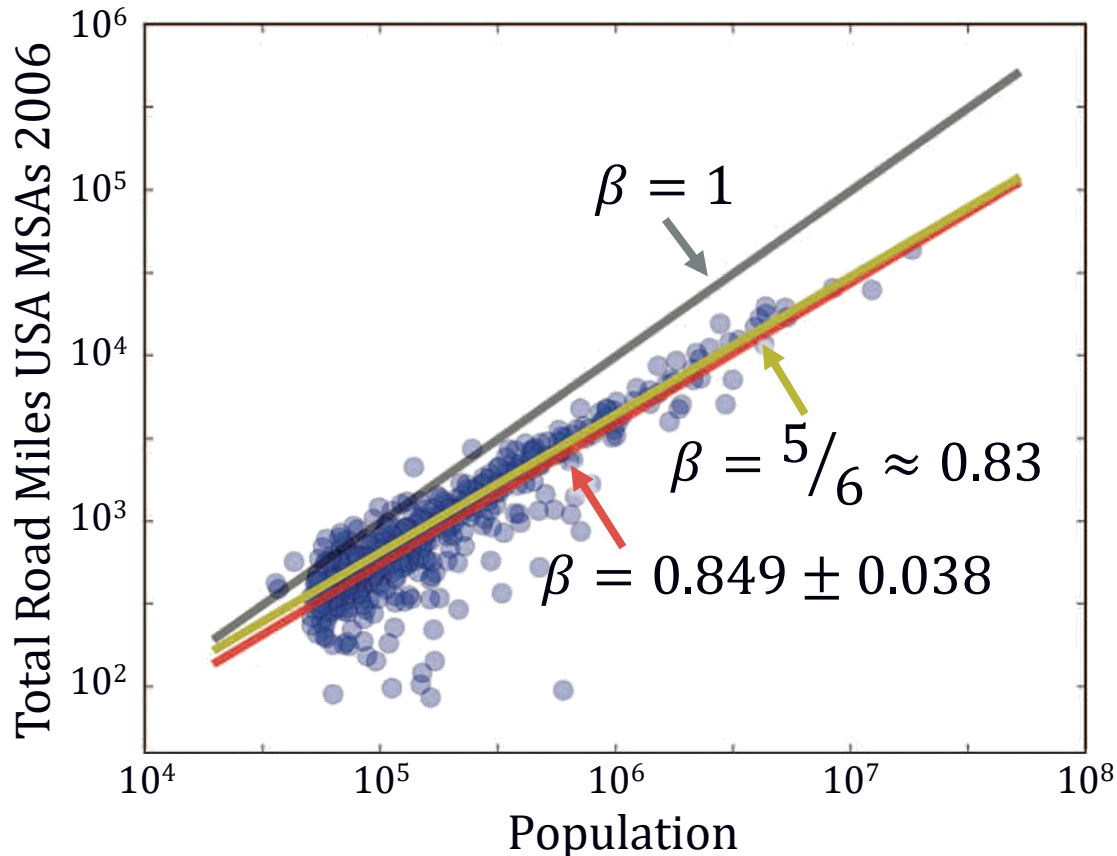
Per Capita

Scaling Exponent

Per Population

Population

Urban Scaling: A Framework for Modeling Society



Fractal $H \approx 1$
Spatial $D = 2$

$$A \propto N^{D/(D+H)}$$

$$A_n \propto A^{\frac{1}{D}} N^{\frac{D-1}{D}}$$

$$d = \sqrt{A/N}$$

$$A_n \propto N^{1 - \frac{H}{D(D+H)}}$$

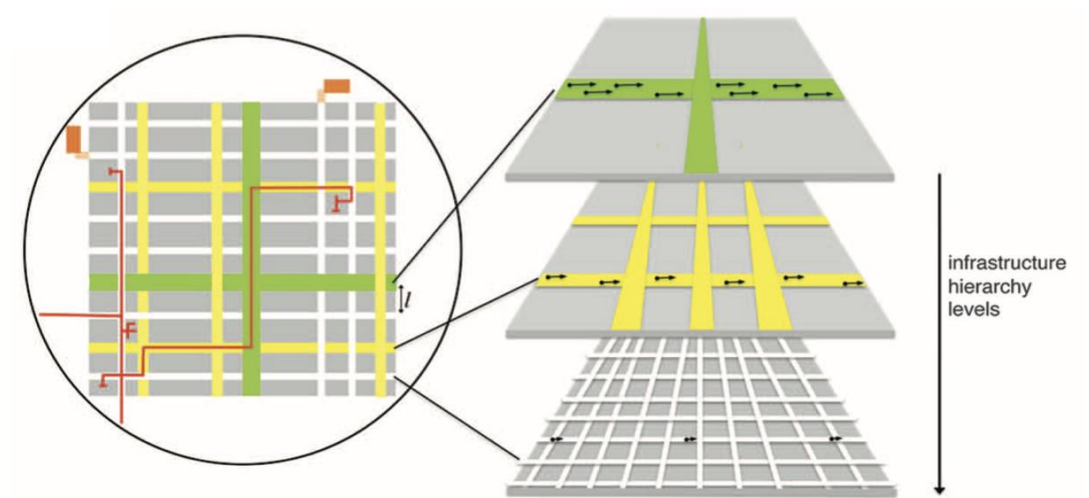
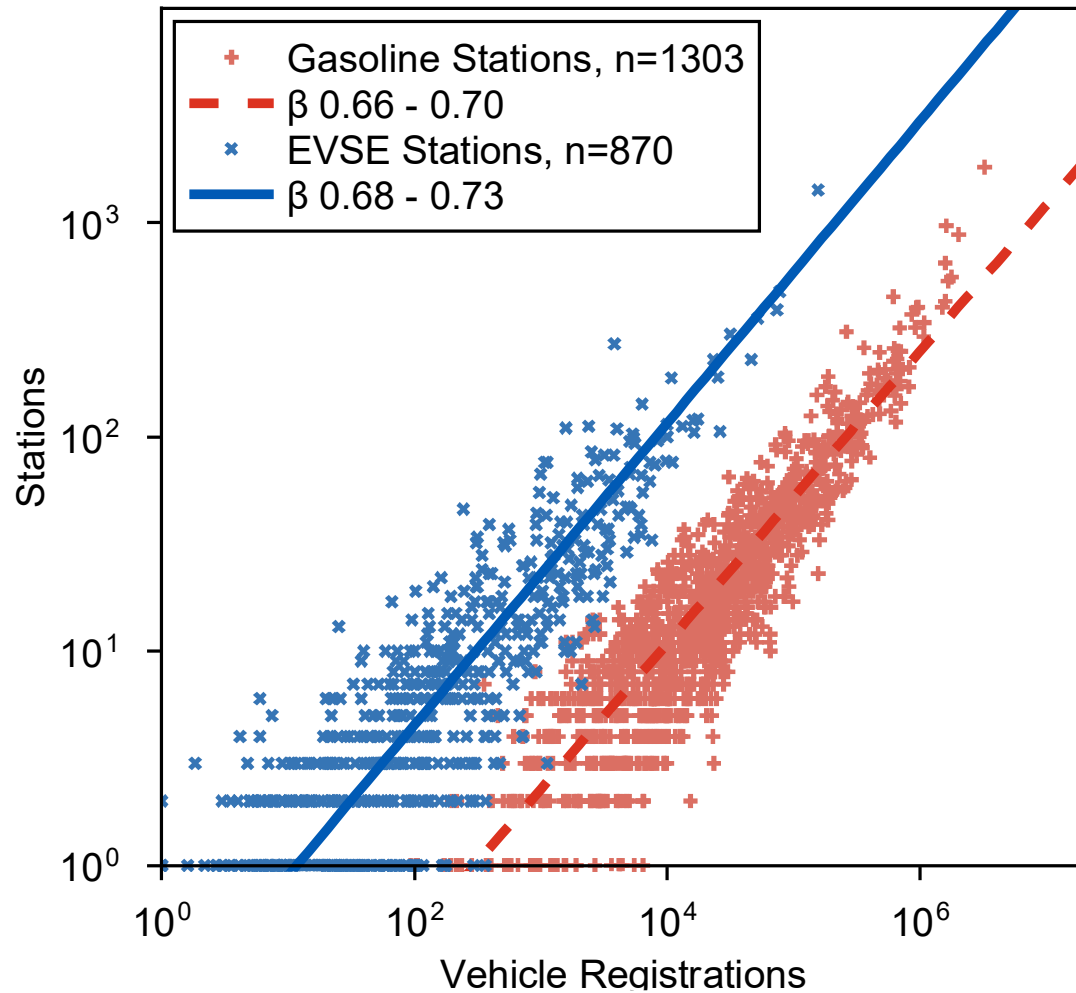
$$A_n = dN$$

$$A_n \propto N^{5/6}$$

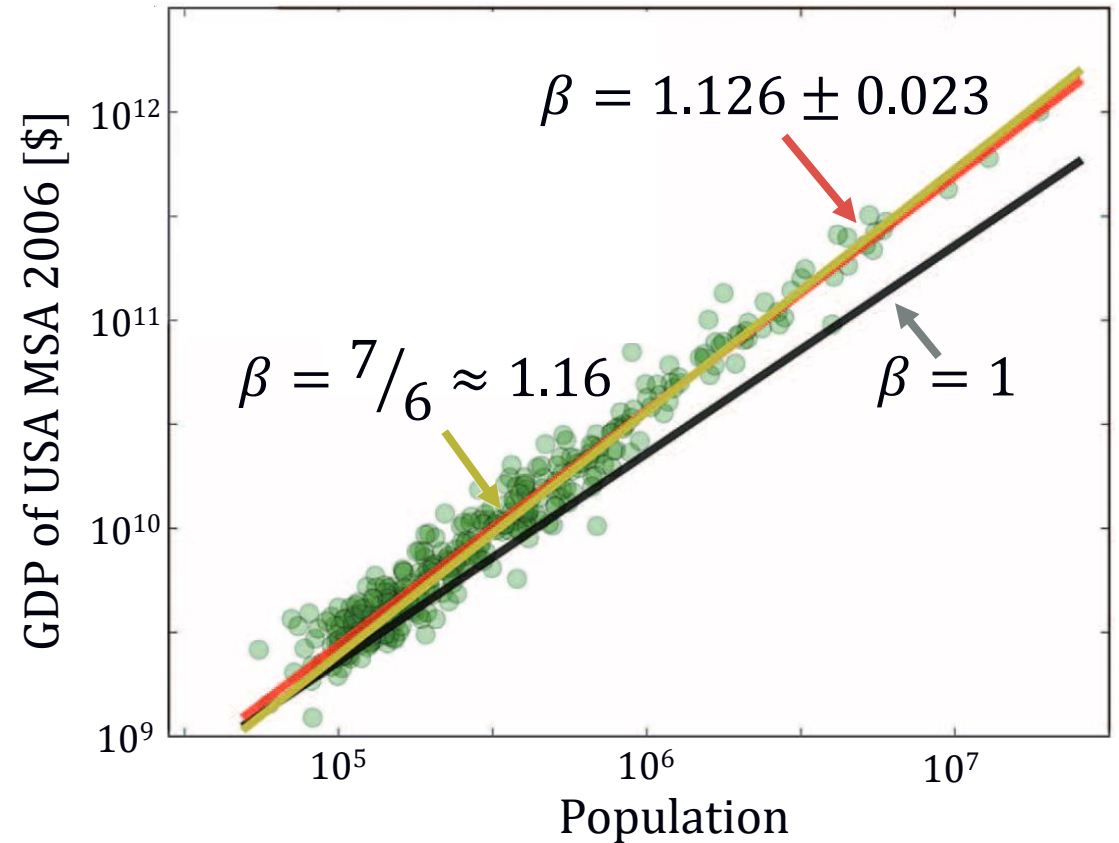
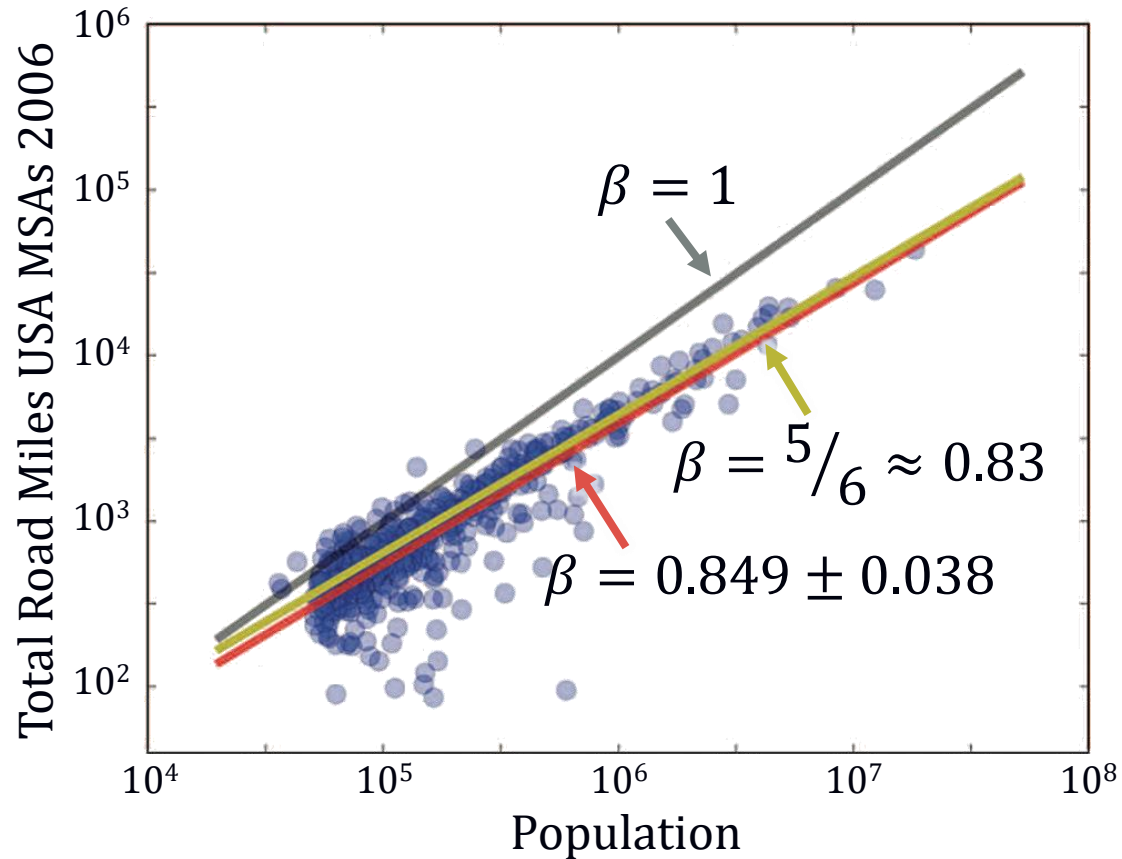
What can we learn from Gasoline Stations?



Stations Scale Sub-linearly with Registrations



Urban Scaling: A Framework for Modeling Society



Scaling Exponents by System

| Y | β | 95% CI | Adj- R^2 | Observations | Country-year |
|----------------------------------|---------|--------------|------------|--------------|----------------|
| New patents | 1.27 | [1.25,1.29] | 0.72 | 331 | U.S. 2001 |
| Inventors | 1.25 | [1.22,1.27] | 0.76 | 331 | U.S. 2001 |
| Private R&D employment | 1.34 | [1.29,1.39] | 0.92 | 266 | U.S. 2002 |
| "Supercreative" employment | 1.15 | [1.11,1.18] | 0.89 | 287 | U.S. 2003 |
| R&D establishments | 1.19 | [1.14,1.22] | 0.77 | 287 | U.S. 1997 |
| R&D employment | 1.26 | [1.18,1.43] | 0.93 | 295 | China 2002 |
| Total wages | 1.12 | [1.09,1.13] | 0.96 | 361 | U.S. 2002 |
| Total bank deposits | 1.08 | [1.03,1.11] | 0.91 | 267 | U.S. 1996 |
| GDP | 1.15 | [1.06,1.23] | 0.96 | 295 | China 2002 |
| GDP | 1.26 | [1.09,1.46] | 0.64 | 196 | EU 1999–2003 |
| GDP | 1.13 | [1.03,1.23] | 0.94 | 37 | Germany 2003 |
| Total electrical consumption | 1.07 | [1.03,1.11] | 0.88 | 392 | Germany 2002 |
| New AIDS cases | 1.23 | [1.18,1.29] | 0.76 | 93 | U.S. 2002–2003 |
| Serious crimes | 1.16 | [1.11, 1.18] | 0.89 | 287 | U.S. 2003 |
| Total housing | 1.00 | [0.99,1.01] | 0.99 | 316 | U.S. 1990 |
| Total employment | 1.01 | [0.99,1.02] | 0.98 | 331 | U.S. 2001 |
| Household electrical consumption | 1.00 | [0.94,1.06] | 0.88 | 377 | Germany 2002 |
| Household electrical consumption | 1.05 | [0.89,1.22] | 0.91 | 295 | China 2002 |
| Household water consumption | 1.01 | [0.89,1.11] | 0.96 | 295 | China 2002 |
| Gasoline stations | 0.77 | [0.74,0.81] | 0.93 | 318 | U.S. 2001 |
| Gasoline sales | 0.79 | [0.73,0.80] | 0.94 | 318 | U.S. 2001 |
| Length of electrical cables | 0.87 | [0.82,0.92] | 0.75 | 380 | Germany 2002 |
| Road surface | 0.83 | [0.74,0.92] | 0.87 | 29 | Germany 2002 |

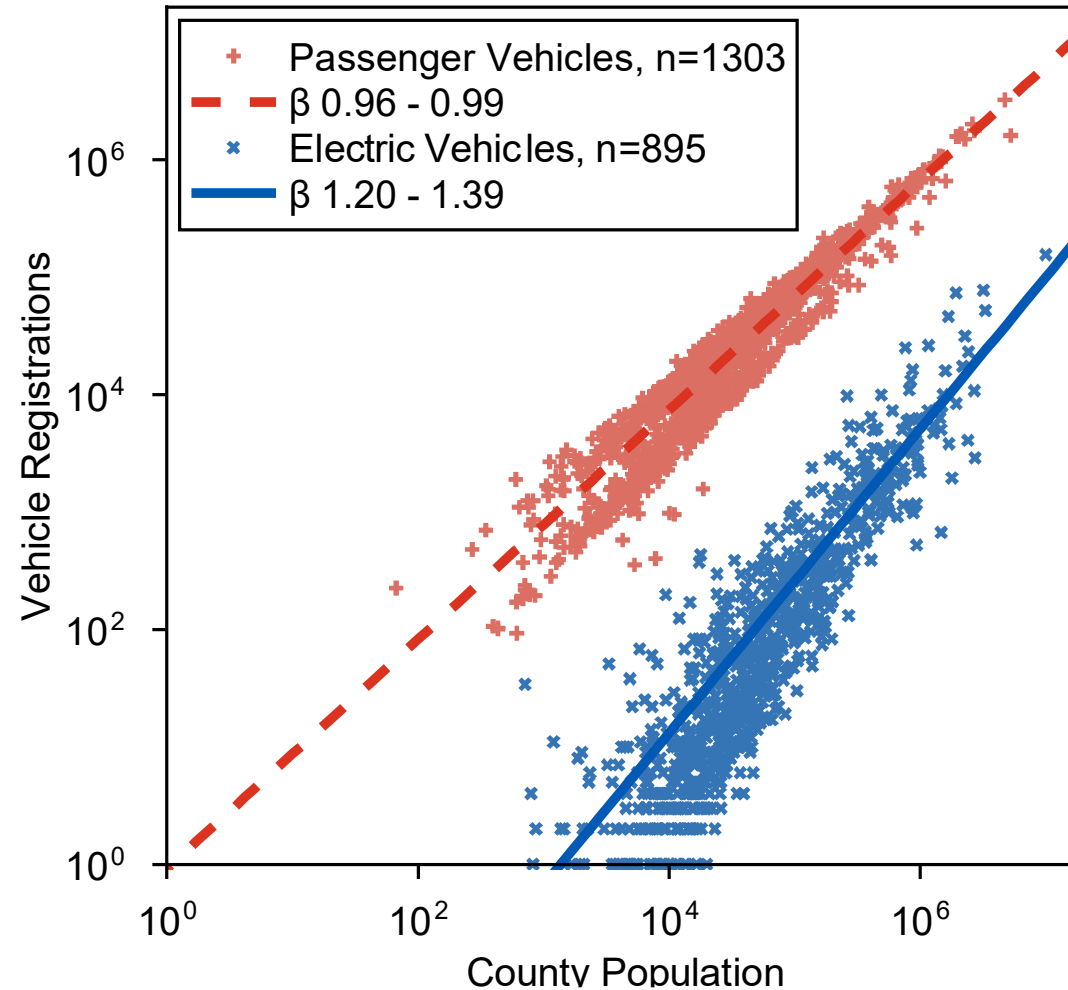
| System | β |
|-------------------------|---------|
| Interactions per Capita | 1/6 |
| Socioeconomic Rates | 7/6 |
| Individual Needs | 1 |
| Network Volume | 5/6 |

Socioeconomic Rates

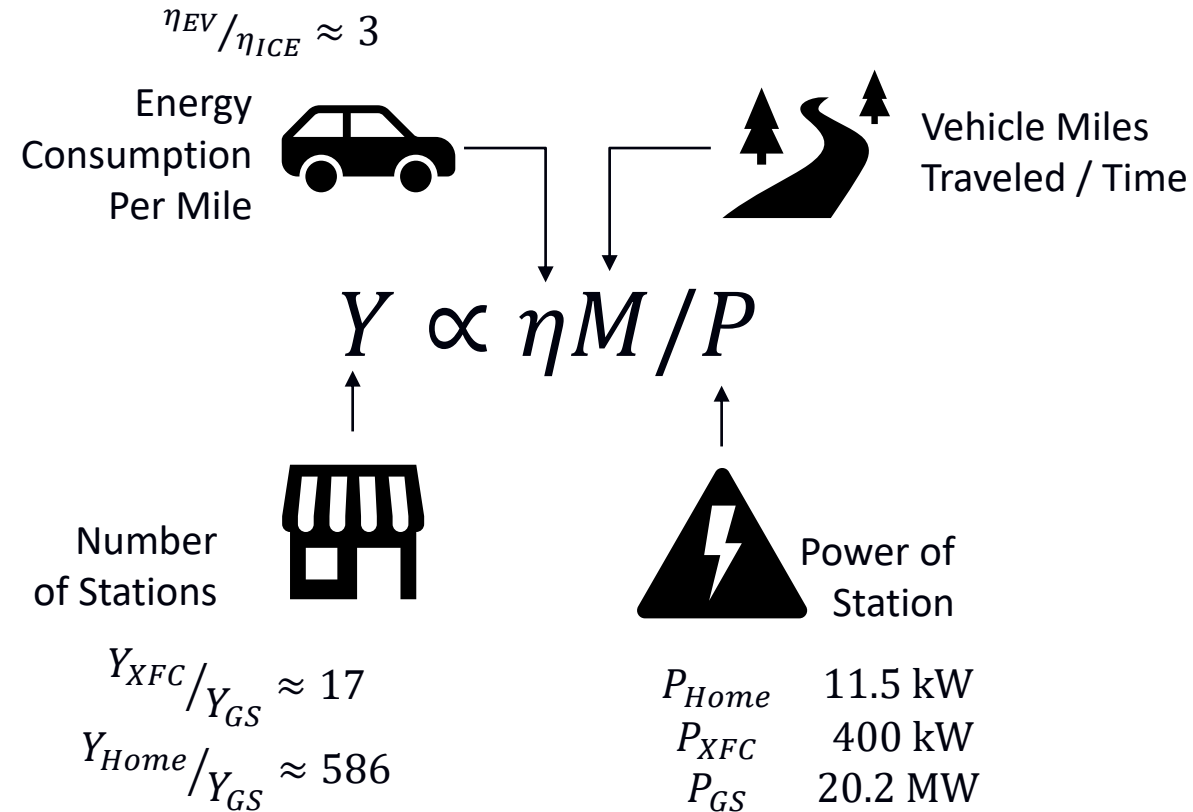
Individual Needs

Network Volume

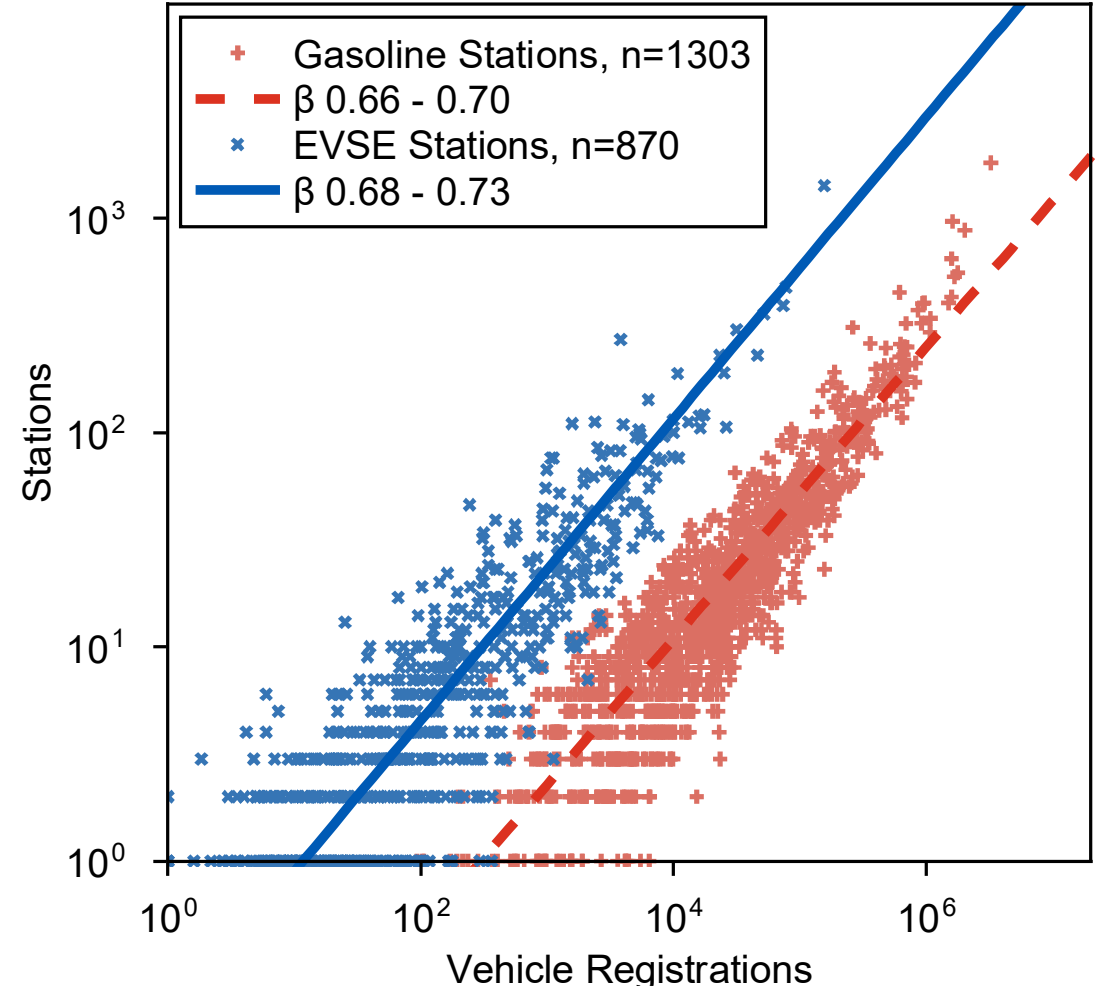
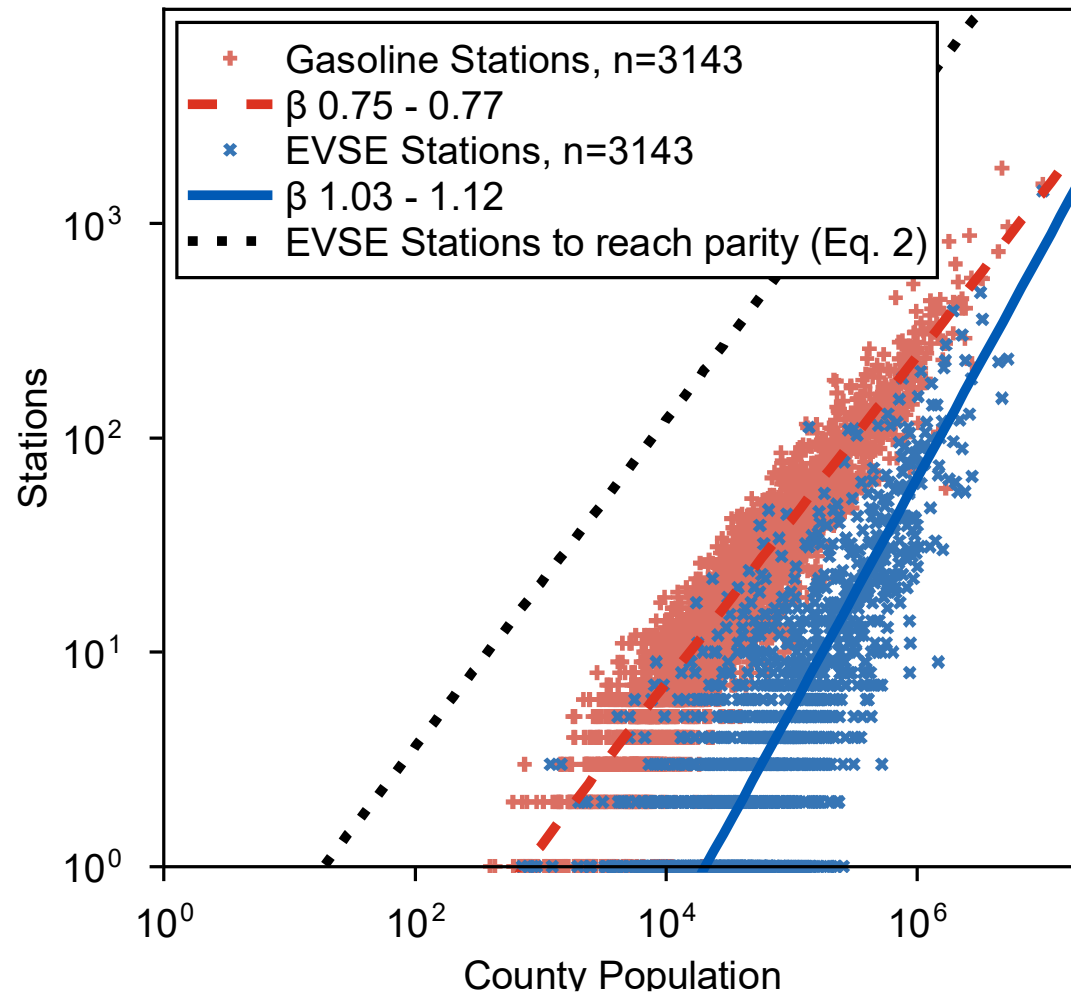
Adoption skews towards Population Centers

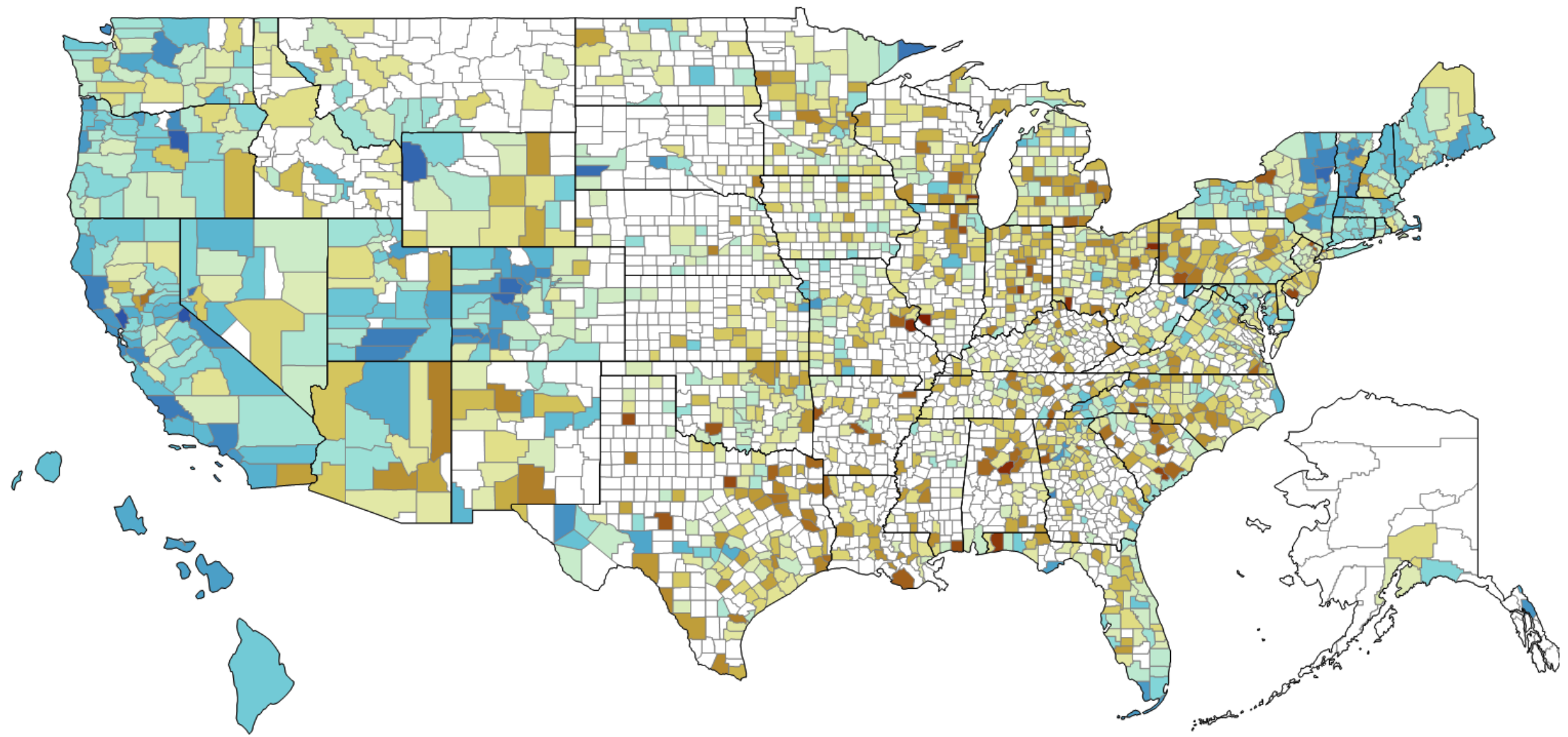


Assume a “Power Equivalent” Charging Station

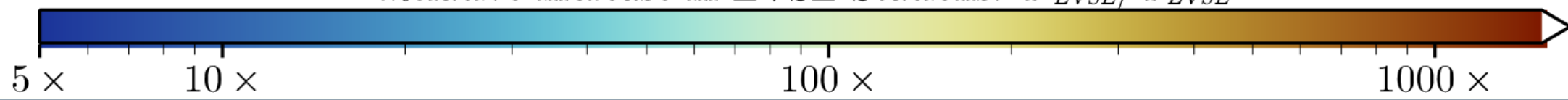


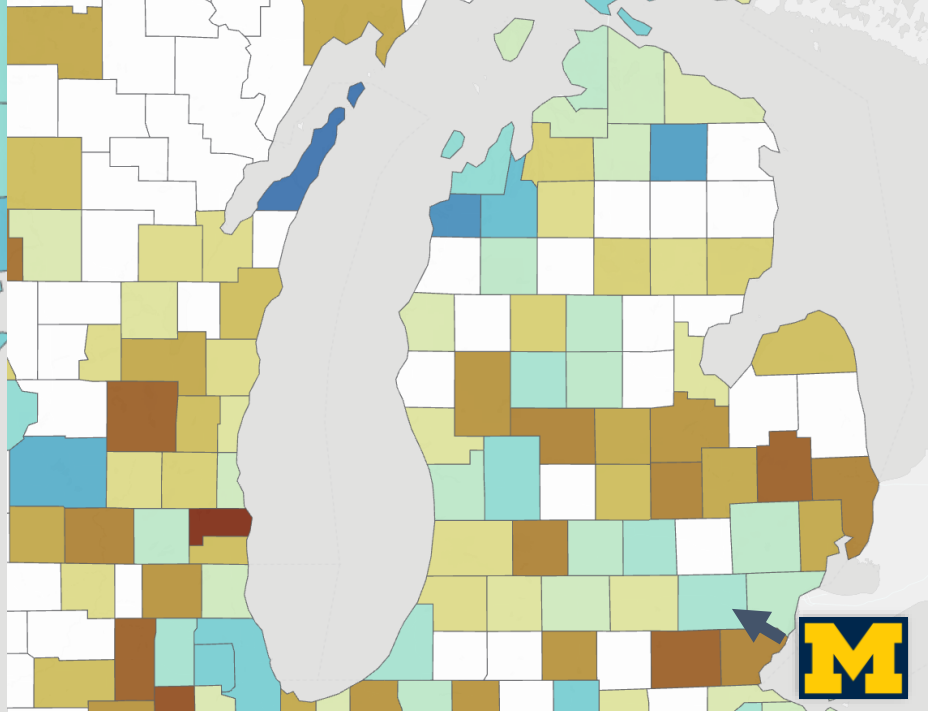
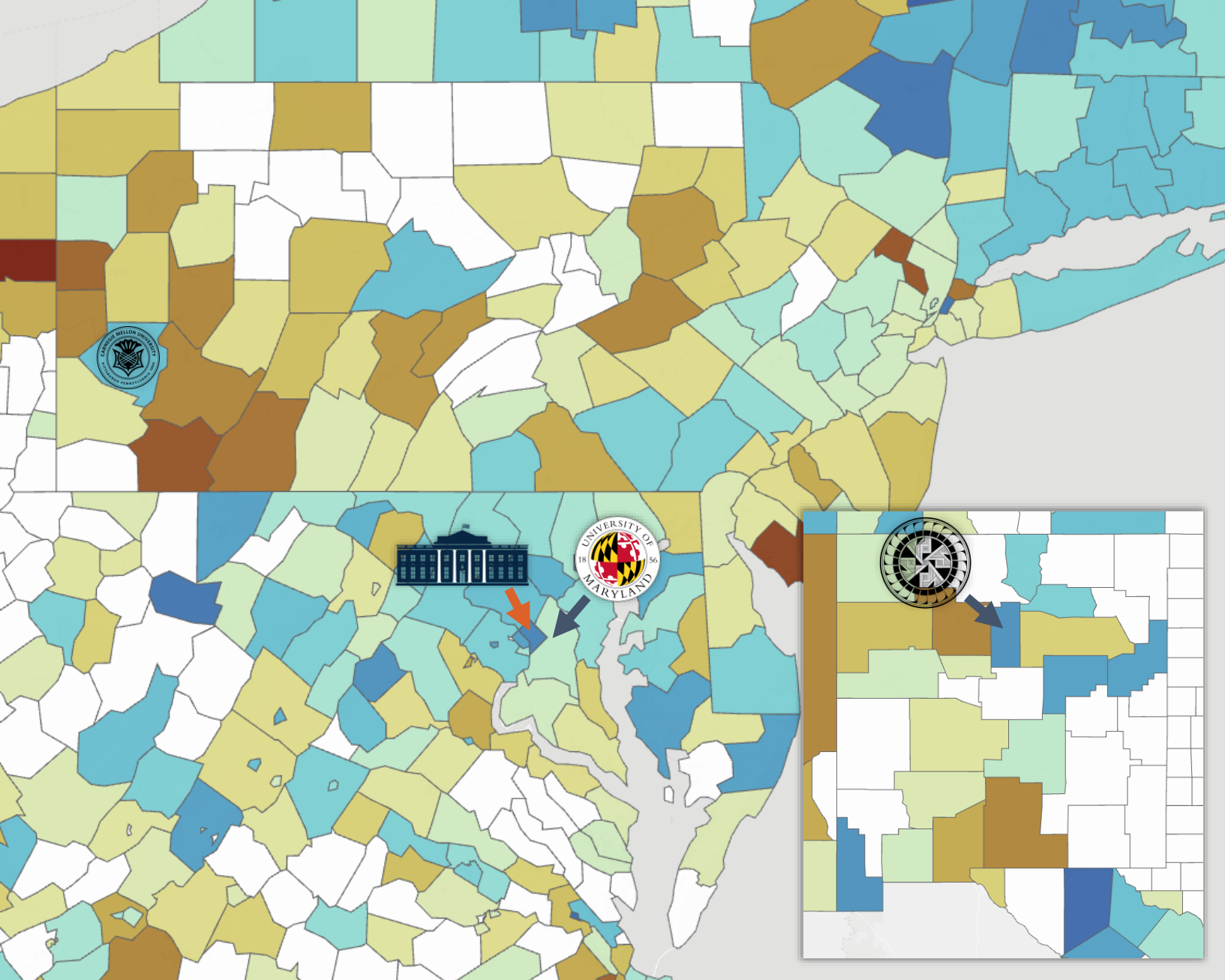
Stations for “Power” Parity with Gasoline





Relative increase in EVSE Stations: \hat{Y}_{EVSE}/Y_{EVSE}





| | Scale Adjusted EVSE Gap |
|----------------------------|-------------------------|
| District of Columbia | 26 |
| Santa Fe Institute | 30 |
| Carnegie Mellon University | 54 |
| University of Michigan | 83 |
| University of Maryland | 94 |

Scaling behavior for electric vehicle chargers and road map to addressing the infrastructure gap

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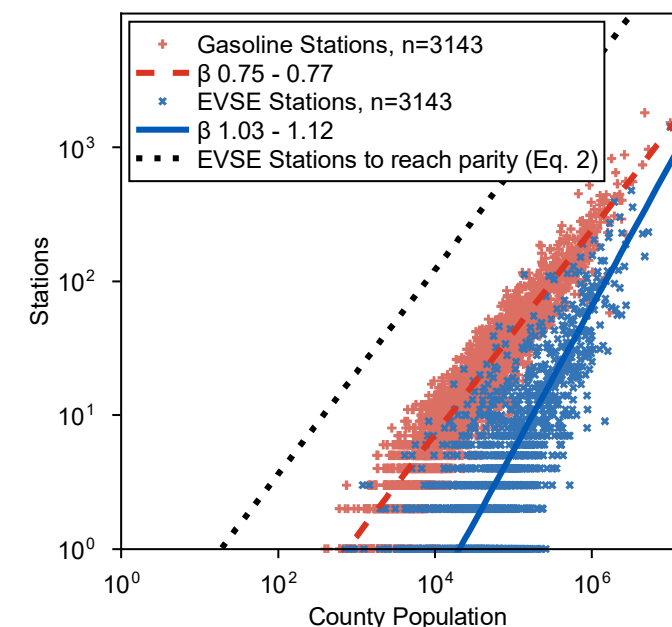
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 [10.1093/pnasnexus/pgad341](https://doi.org/10.1093/pnasnexus/pgad341)

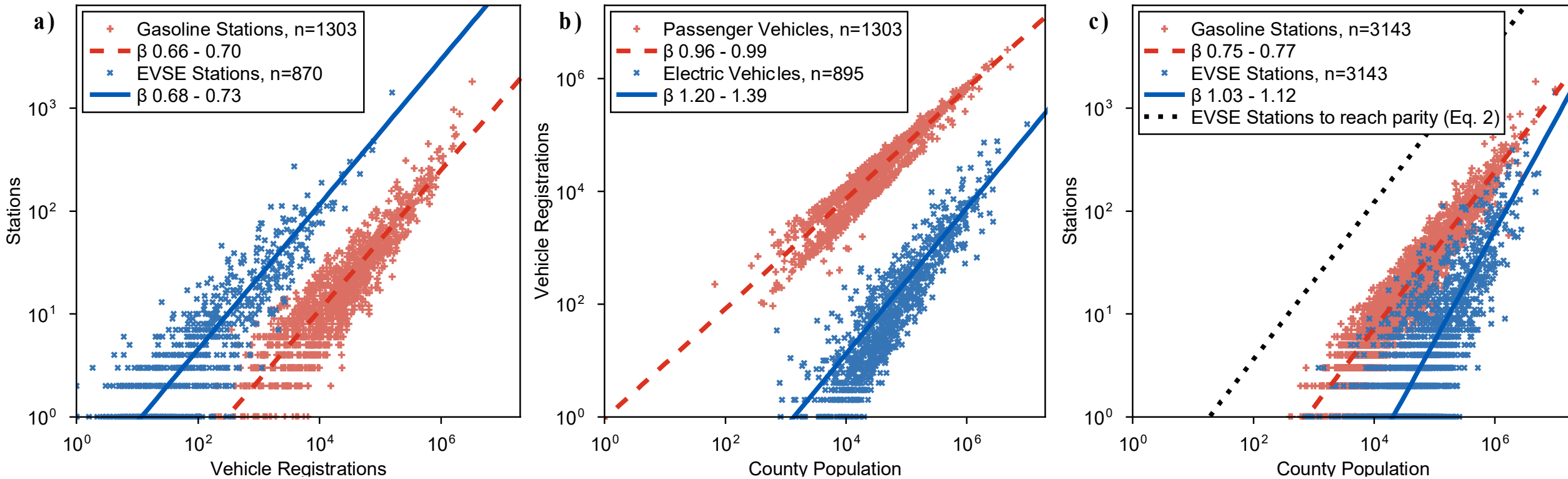
[Interactive Map](#)



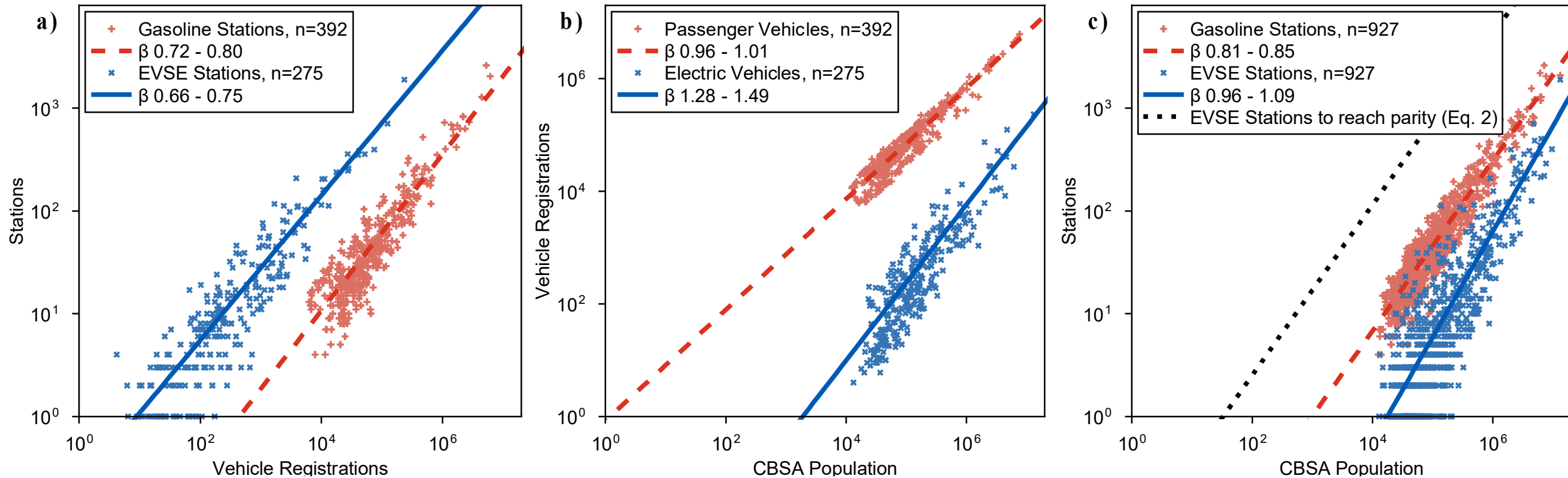


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Scaling Behavior of Gasoline & EVSE Stations

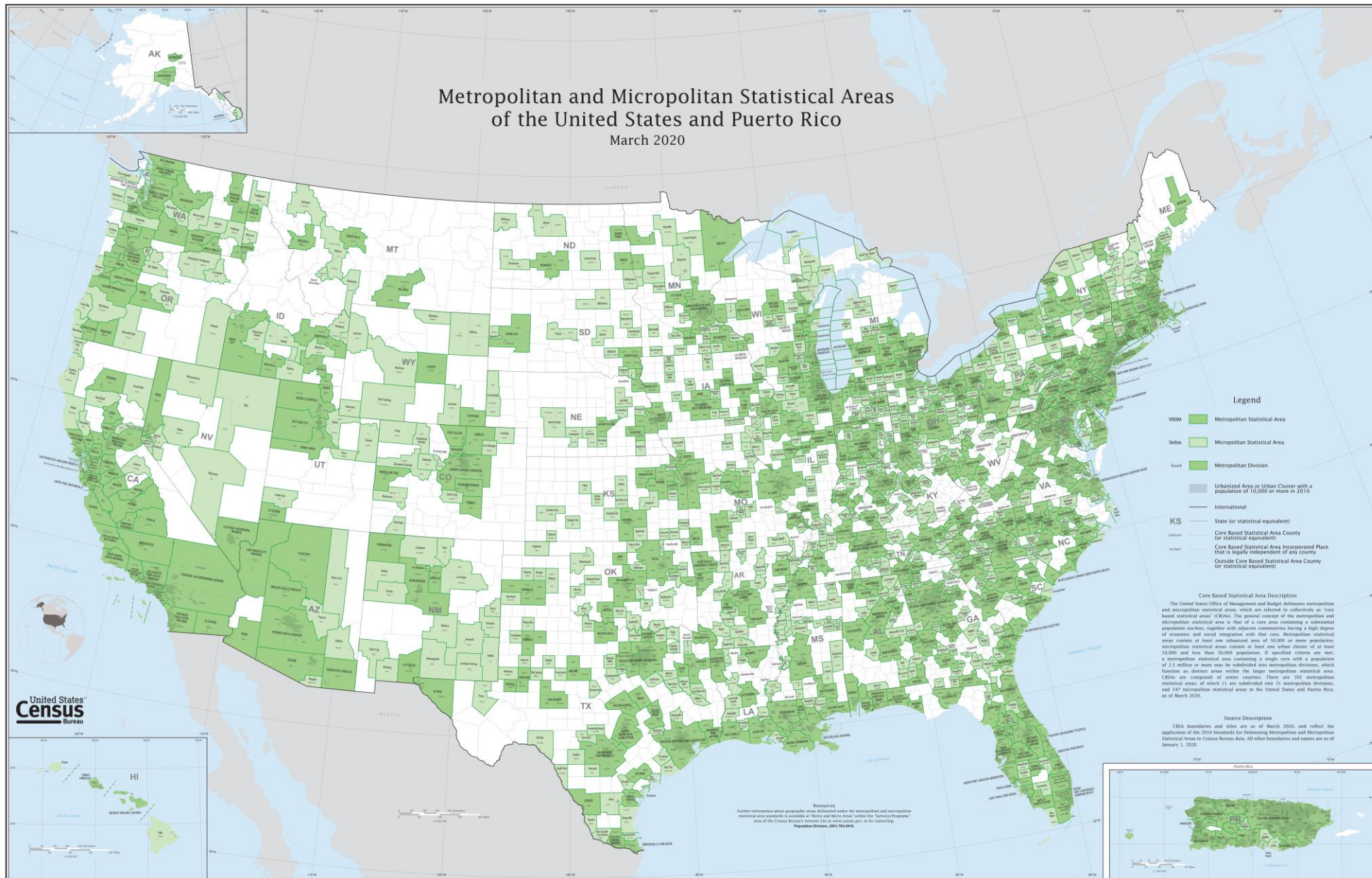


Scaling with Core-Base Statistical Areas



Metropolitan and Micropolitan Statistical Areas of the United States and Puerto Rico

March 2020



Scaling Abroad

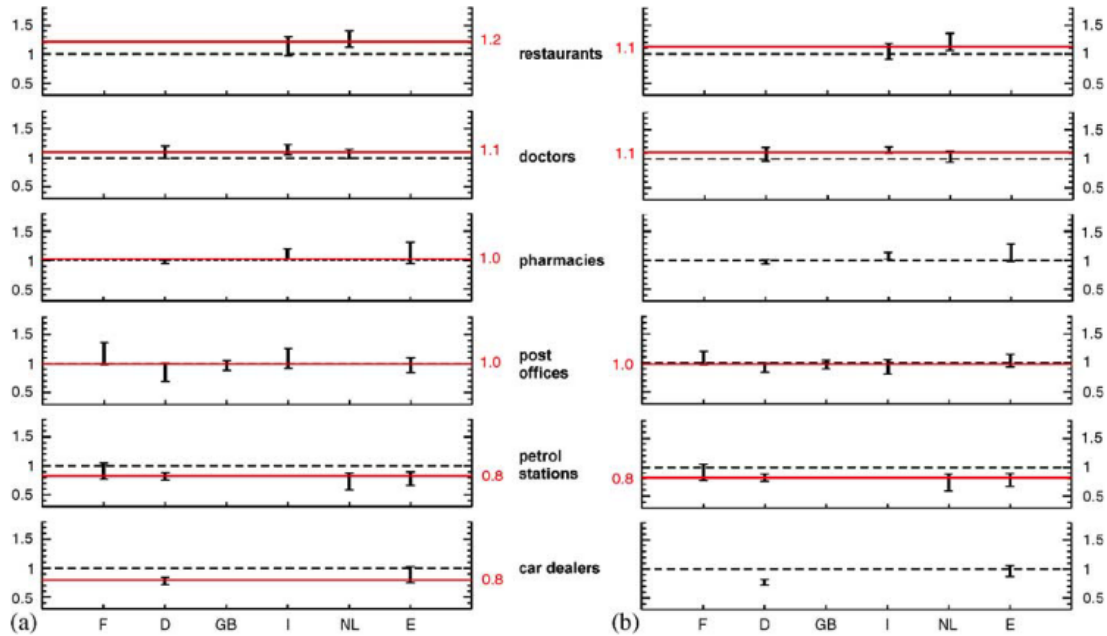
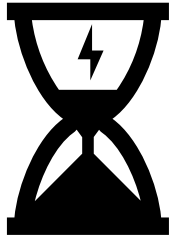


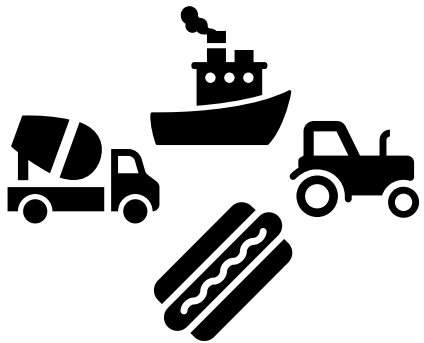
Fig. 2. Scaling exponents and confidence intervals for different supply systems and countries (a) when double-logarithmically scaled original data are used, (b) when the data are logarithmically binned before the regression is made. The countries are: France (F), Germany (D), Great Britain (GB), Italy (I), The Netherlands (NL), and Spain (E).

| | | City model | | | | Person model |
|--------|--------------|------------------------------------|----------------------------------|--------------------------|---------------------------------|-----------------------|
| | | Log-normal | | Gaussian | | |
| | | $\delta = 2$ (min. sq. fit) | $\delta \in [1, 3]$ | $\delta = 1$ | $\delta \in [1, 2]$ | |
| UK | database | | | | | |
| | Income | 0.97 (0.04) \rightarrow^* | 0.97(0.04) \rightarrow^* | 1.07(0.15) \nearrow | 0.97(0.05) \rightarrow | 1.06(0.15) \nearrow |
| | Railroads | 1.04 (0.13) \rightarrow^* | 1.03(0.10) \rightarrow^* | 1.21(0.10) \nearrow | 1.05(0.12) \rightarrow | 1.19(0.16) \nearrow |
| | Patents | 0.99 (0.12) \rightarrow | 0.97(0.13) \rightarrow | 1.07(0.26) \rightarrow | 0.96(0.27) \rightarrow | 1.04(0.25) \nearrow |
| USA | GDP | 1.11 (0.03) \nearrow | 1.11(0.02) \nearrow | 1.14(0.03) \nearrow | 1.12(0.02) \nearrow | 1.12(0.02) \nearrow |
| | Roads | 0.85(0.03) \searrow | 0.82 (0.03) \searrow | 0.82(0.04) \searrow | 0.81(0.04) \searrow | 0.81(0.04) \searrow |
| EU | Cinema Cap. | 1.00(0.09) \rightarrow | 0.90 (0.06) \circ | 0.95(0.07) \rightarrow | 0.92(0.06) \circ | 0.93(0.08) \searrow |
| | Cinema Usa. | 1.46(0.19) \nearrow | 1.00(0.30) \rightarrow | 1.13(0.13) \nearrow | 1.13 (0.11) \circ | 1.06(0.09) \nearrow |
| | Museums Usa. | 1.42 (0.12) \nearrow | 1.35(0.15) \nearrow | 1.80(0.34) \nearrow | 1.39(0.22) \nearrow | 1.46(0.21) \nearrow |
| | Theaters | 0.91(0.09) \rightarrow | 0.92 (0.11) \rightarrow | 1.47(0.30) \nearrow | 1.14(0.19) \nearrow | 1.09(0.16) \nearrow |
| | Libraries | 0.80(0.10) \searrow | 0.81(0.09) \searrow | 0.87(0.14) \searrow | 0.78 (0.08) \searrow | 0.76(0.12) \searrow |
| OECD | GDP | 1.12(0.06) \nearrow | 1.11(0.05) \nearrow | 1.09(0.08) \nearrow | 1.13 (0.05) \nearrow^* | 1.05(0.07) \nearrow |
| | Patents | 1.29 (0.27) \rightarrow | 1.12(0.21) \rightarrow | 1.28(0.33) \nearrow | 1.13(0.21) \rightarrow | 1.08(0.17) \nearrow |
| Brazil | GDP | 1.04(0.02) \nearrow | 1.04 (0.02) \nearrow | 2.00(0.44) \nearrow | 1.09(0.05) \nearrow | 1.17(0.04) \nearrow |
| | Aids | 0.74(0.03) \searrow | 0.61 (0.05) \searrow | 1.13(0.11) \nearrow | 0.81(0.04) \searrow | 1.04(0.05) \nearrow |
| | External | 1.03(0.01) \nearrow | 1.02 (0.01) \circ | 1.04(0.04) \nearrow | 1.02(0.01) \nearrow | 1.01(0.03) \nearrow |

Modeling Assumptions: Power Equivalency

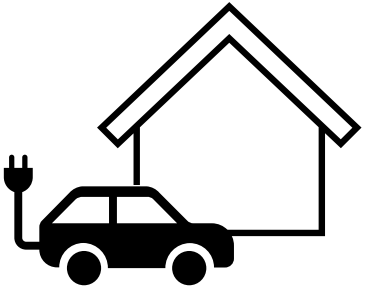


Neglects the impact of Charging Time on Consumer Behavior



Neglects alternative uses of Gasoline Stations

- Off-highway consumption of Gasoline (Marine, Landscaping, etc.)
- Attached Convenience Store / Food Mart



Neglects Heterogenous Charging Stations

- Treats Home Chargers as a “Gas Station” in your home
- Ignores variation in Charger Power

Assume the existence of a "Power Equivalent" EV Station

$$\frac{Y_{EVSE}}{Y_{GS}} \propto \frac{\eta_{EV} P_{GS}}{\eta_{ICE} P_{EVSE}}$$

$$P_{GS} = \text{Gasoline Flow Rate} \times \frac{\text{Energy}}{\text{Gallon}}$$

$$P_{GS} = 10 \frac{\text{gallons}}{\text{minute}} \times 33.7 \frac{\text{kWh}}{\text{gallon}} \rightarrow 20.2\text{MW}$$

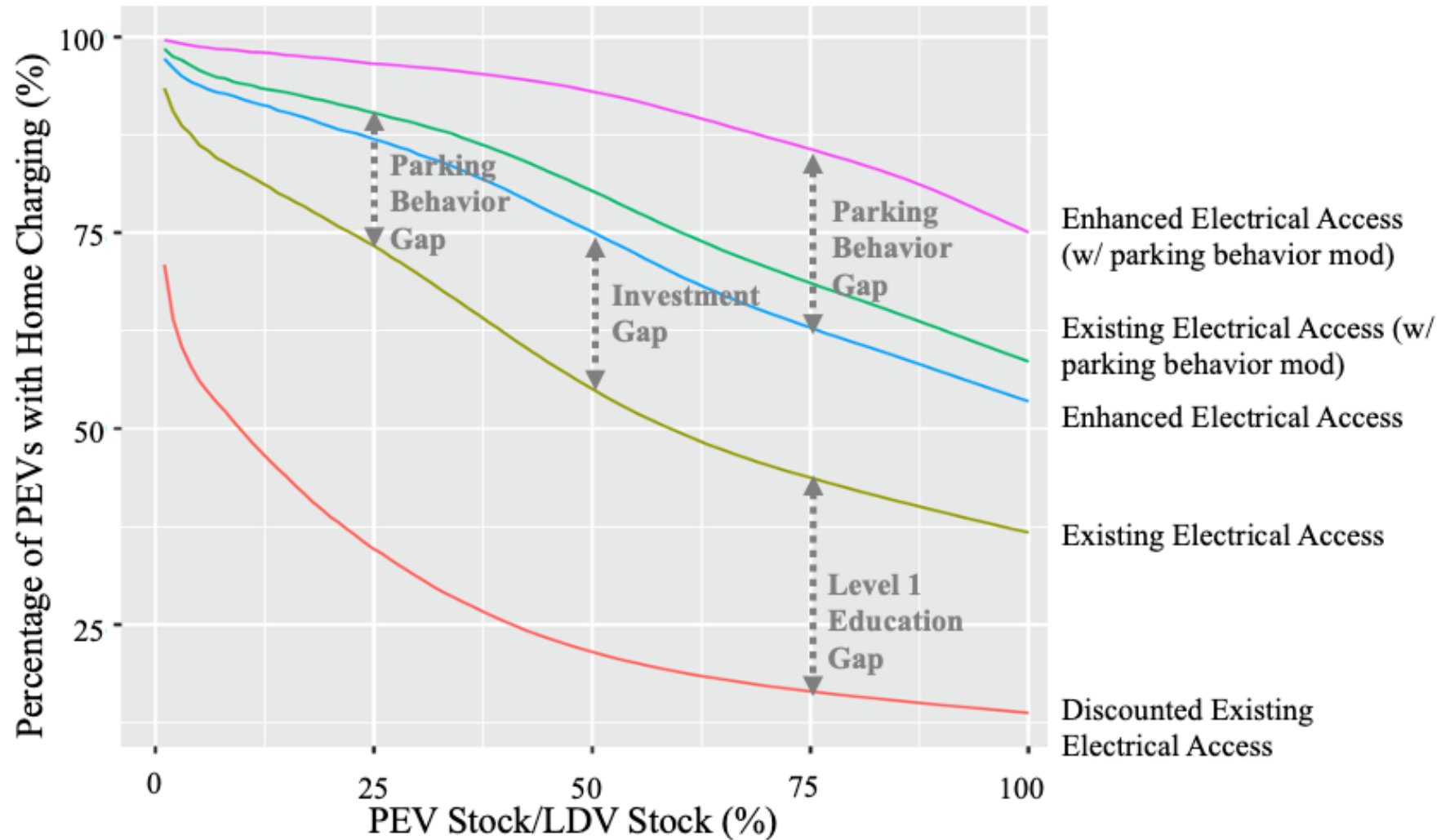
$$P_{EVSE} = 400\text{kW}$$

$$\eta_{EV} / \eta_{ICE} \approx 3$$

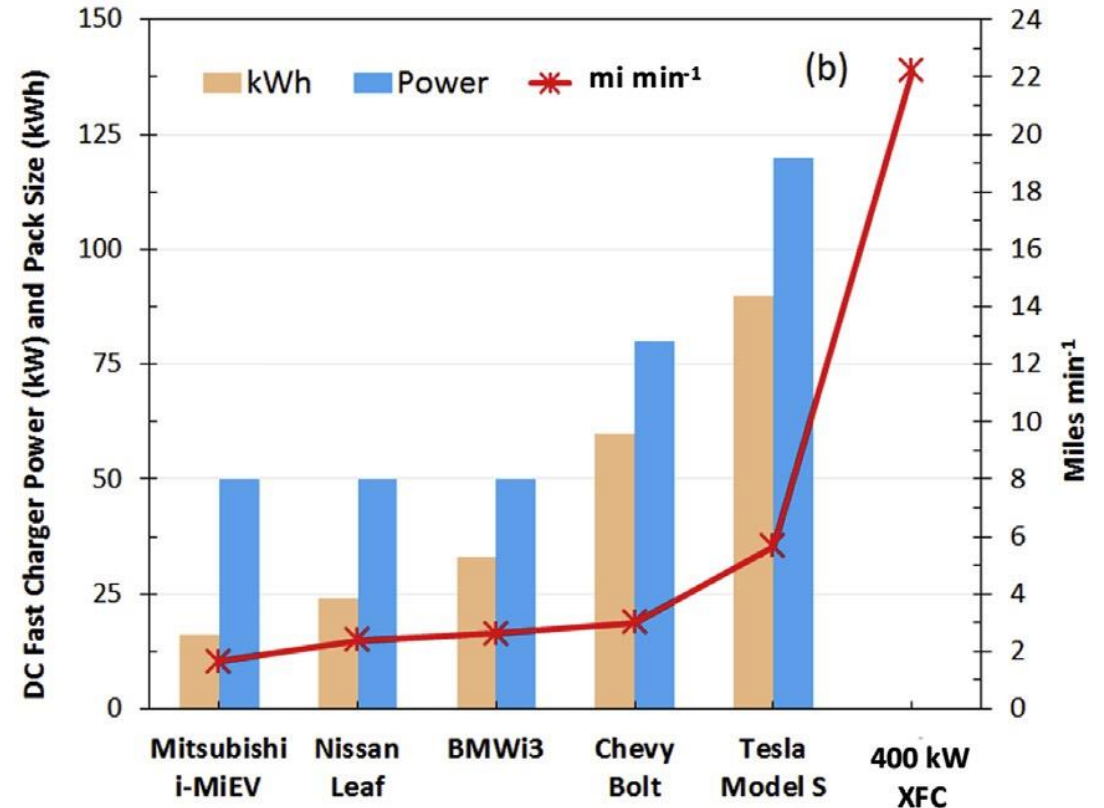
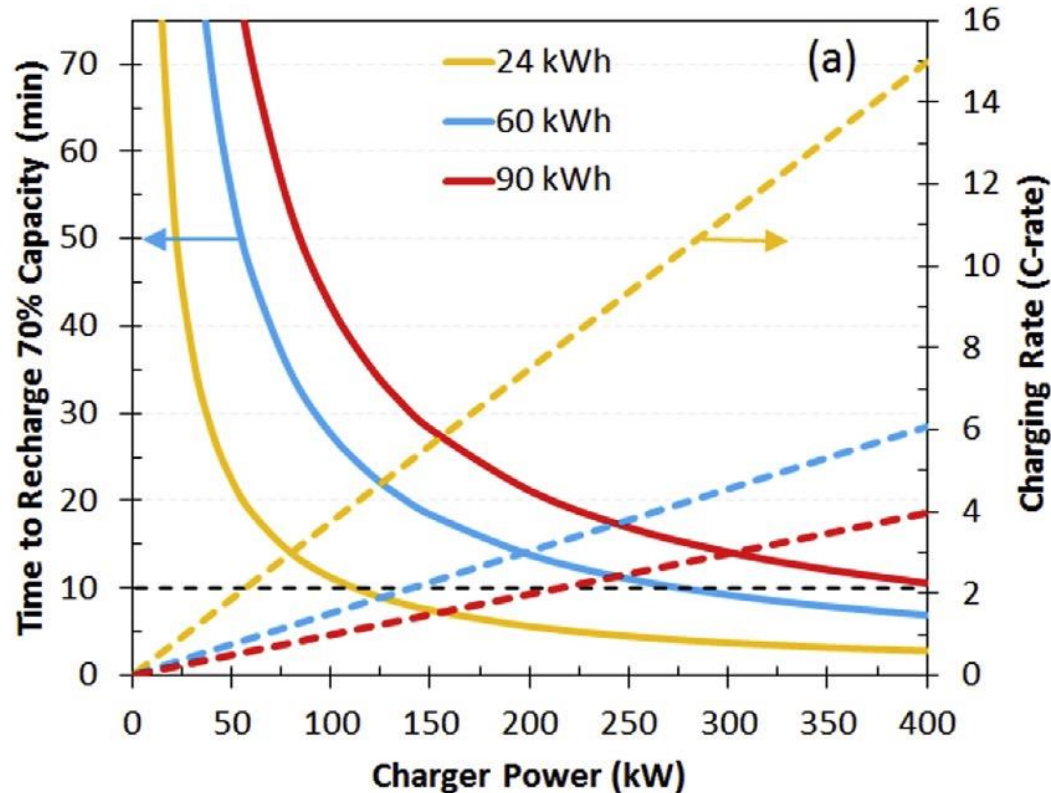
$$Y_{EVSE} / Y_{GS} \approx 17$$



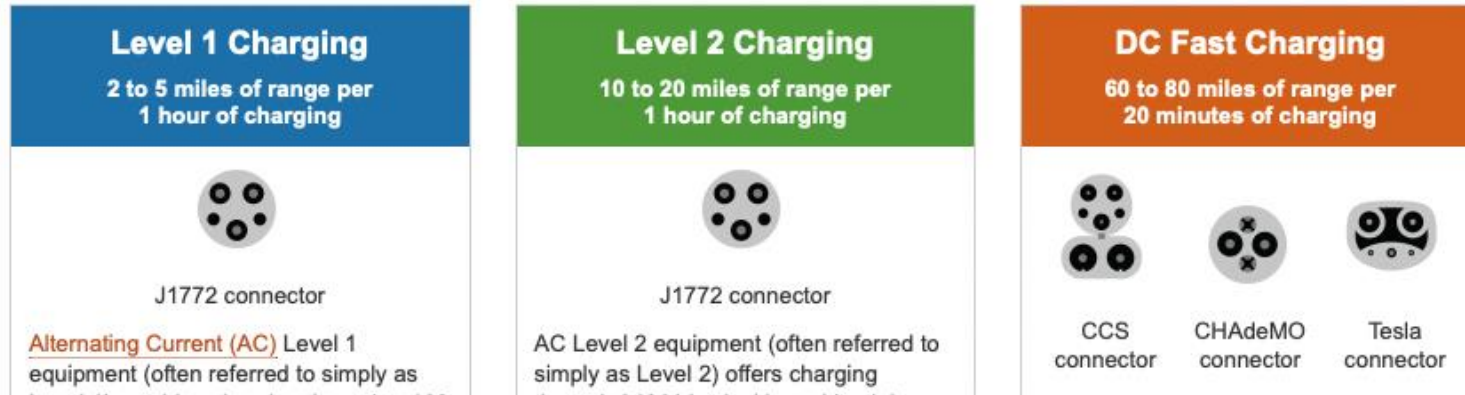
Access to Home Charging is Uncertain



Comparisons to Existing Technology



Charging Station Terminology



1 Station Location

