Compatibility and Investment in the U.S. Electric Vehicle Market

Jing Li
MIT Sloan School of Management

Slides to accompany paper draft from January 27th, 2019
Compatibility in product markets

- Product markets vary in compatibility with complementary goods.
Compatibility in product markets

- Product markets vary in compatibility with complementary goods
  - Mobile phones: chargers
Compatibility in product markets

- Product markets vary in compatibility with complementary goods
  - Mobile phones: chargers
  - Checking accounts: ATM networks
Compatibility in product markets

- **Product markets** vary in compatibility with **complementary goods**
  - Mobile phones: chargers
  - Checking accounts: ATM networks
  - Electric vehicles: charging stations
Compatibility in product markets

- **Product markets** vary in compatibility with *complementary goods*
  - Mobile phones: *chargers*
  - Checking accounts: *ATM networks*
  - Electric vehicles: *charging stations*

- Antitrust and policy debates over compatibility
Effect of compatibility theoretically ambiguous

Opposing effects:

1. Increase efficiency: holding investment fixed, consumers are better off
2. Decrease firms’ incentives to invest in complementary goods due to positive spillovers
Electric vehicle market

• Rapidly growing segment of the automobile industry
Electric vehicle market

- Rapidly growing segment of the automobile industry
- Large potential environmental benefits draw billions of dollars in annual subsidies.
Electric vehicle market

- Rapidly growing segment of the automobile industry
- Large potential environmental benefits draw billions of dollars in annual subsidies.
- Charging stations incompatible across car brands
Electric vehicle market

- Rapidly growing segment of the automobile industry
- Large potential environmental benefits draw billions of dollars in annual subsidies.
- Charging stations incompatible across car brands
- E.U. mandate for a particular standard on all stations
- U.S. local electric utilities nationwide considering entry
This paper

What is the impact of compatibility in electric vehicle charging standards?
This paper

What is the impact of compatibility in electric vehicle charging standards?

- Consumer vehicle purchases
This paper

What is the impact of compatibility in electric vehicle charging standards?

- Consumer vehicle purchases
- Car manufacturer investment in charging stations
This paper

What is the impact of compatibility in electric vehicle charging standards?

• Consumer vehicle purchases
• Car manufacturer investment in charging stations
• Social welfare
Empirical Approach

1. Model and estimate electric vehicle demand
2. Model and estimate car manufacturer charging station investment
3. Counterfactual market outcomes and welfare under compatibility
Empirical Approach

1. Model and estimate electric vehicle demand
   • Discrete choice with charging stations as a product characteristic
   • Estimate price and charging station elasticities
   • Identify demand parameters using federal and state subsidy variation
   • Preserve important spatial properties of charging stations

2. Model and estimate car manufacturer charging station investment

3. Counterfactual market outcomes and welfare under compatibility
Empirical Approach

1. Model and estimate electric vehicle demand
   - Discrete choice with charging stations as a product characteristic
   - Estimate price and charging station elasticities
   - Identify demand parameters using federal and state subsidy variation
   - Preserve important spatial properties of charging stations

2. Model and estimate car manufacturer charging station investment
   - Recover costs of building charging stations
   - Make counterfactual computation tractable

3. Counterfactual market outcomes and welfare under compatibility
Main Result

Compatibility in electric vehicle charging standards:

- Decreases number of charging stations built
- Increases number of electric vehicles purchased
Main Result

Compatibility in electric vehicle charging standards:

- Decreases number of charging stations built
- Increases number of electric vehicles purchased
- Increases consumer surplus
- Increases producer surplus in total (not all producers better off)
Contributions to relevant literatures

1. Compatibility and standardization

Empirical: Gross (2016); Lee (2013); Knittel and Stango (2011, 2008); Kuhn and Van Reenen (2009); Ishii (2007); Ho (2006)
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   Wollmann (2018); Crawford et al. (2015); Eizenberg (2014); Nosko (2014); Sweeting (2013); Fan (2013); Draganska et al. (2009)
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3. Electric vehicles
   Environment: Holland et al. (2016); Graff Zivin et al. (2014); Michalek et al. (2011)
   Consumer subsidy design and impact: Clinton and Steinberg (2016); Sheldon et al. (2017); Borenstein and Davis (2015), Holtsmark and Skonhoft (2014)
   Network effects: Li et al. (2017); Springel (2016)
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   Network effects: Li et al. (2017); Springel (2016)

4. Directed technical change
   Acemoglu et al. (2016); Aghion et al. (2016); Greaker and Midttømme (2016); Jaffe et al. (2005)
Outline of talk

1. Introduction
2. Electric Vehicle Market
3. Model
4. Estimation
5. Mandated Compatibility Counterfactual
6. Conclusion
Outline of talk

1. Introduction
2. Electric Vehicle Market
   - Data
   - Electric vehicle characteristics
   - Charging stations and standards
3. Model
4. Estimation
5. Mandated Compatibility Counterfactual
6. Conclusion
Data

1. Nationwide vehicle sales and characteristics (2011-2015)
2. Charging stations (2010-2015)
Data

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   - Vehicle registration data from IHS Automotive (formerly Polk)
   - Quantities by time (quarter), market (MSA), and model
   - MSRP, fuel efficiency, and other characteristics from EPA, MSN Auto

2. Charging stations (2010-2015)


Introduction Electric Vehicle Market Model Estimation Mandated Compatibility Conclusion Appendix

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   • State congressional records and IRS website
   • State and federal tax incentives for consumer EV purchases
   • State tax incentives for charging station installation

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   • State tax incentives for charging station installation

   • County-level commuting flows from the American Community Survey (2009-2013)
   • Income from the Decennial Census (2010)
Two fuel types of electric vehicles

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>New Models</th>
<th>Modified Existing Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>All-electric</td>
<td>Nissan LEAF</td>
<td>Ford Focus Electric</td>
</tr>
<tr>
<td></td>
<td>BMW i3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Tesla Model S</td>
<td></td>
</tr>
<tr>
<td>Plug-in hybrid</td>
<td>Chevrolet Volt</td>
<td>Toyota Prius Plug-in</td>
</tr>
<tr>
<td>(gasoline backup)</td>
<td></td>
<td>Volkswagen e-Golf</td>
</tr>
</tbody>
</table>
Rapid growth in the electric vehicle market

<table>
<thead>
<tr>
<th></th>
<th>2011</th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of EV models</td>
<td>3</td>
<td>6</td>
<td>15</td>
<td>21</td>
<td>26</td>
</tr>
<tr>
<td>Number of EV brands</td>
<td>3</td>
<td>6</td>
<td>13</td>
<td>15</td>
<td>18</td>
</tr>
<tr>
<td>EV unit sales</td>
<td>13,542</td>
<td>41,643</td>
<td>93,734</td>
<td>140,320</td>
<td>127,699</td>
</tr>
</tbody>
</table>

Table: Electric vehicle sales summary statistics
Entry of all-electric vehicles, 2011-2015

![Graph showing the battery range (miles) vs. base manufacturer suggested retail price ($)](image_url)

- **Nissan Leaf (2011)**
  - Battery Range: [X miles]
  - MSRP: $[Y]

- **Tesla Roadster (2011)**
  - Battery Range: [Z miles]
  - MSRP: $[W]
Entry of all-electric vehicles, 2011-2015
Entry of all-electric vehicles, 2011-2015

<table>
<thead>
<tr>
<th>Battery Range (miles)</th>
<th>Base Manufacturer Suggested Retail Price (MSRP, $)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>100000</td>
</tr>
<tr>
<td>50</td>
<td>90000</td>
</tr>
<tr>
<td>100</td>
<td>80000</td>
</tr>
<tr>
<td>150</td>
<td>70000</td>
</tr>
<tr>
<td>200</td>
<td>60000</td>
</tr>
<tr>
<td>250</td>
<td>50000</td>
</tr>
<tr>
<td>300</td>
<td>40000</td>
</tr>
<tr>
<td>350</td>
<td>30000</td>
</tr>
<tr>
<td>400</td>
<td>20000</td>
</tr>
<tr>
<td>450</td>
<td>10000</td>
</tr>
</tbody>
</table>

- **Nissan Leaf (2011)**
- **Tesla Roadster (2011)**
- **Tesla Model S (2013)**
- **Ford Focus Electric (2012)**
- **Honda Fit EV (2013)**
- **FIAT 500e (2013)**
- **Mitsubishi i-Miev (2012)**
- **smart fortwo electric drive (2013)**
Entry of all-electric vehicles, 2011-2015
Entry of all-electric vehicles, 2011-2015
Entry of all-electric vehicles, 2017-2018
Charging stations sit near parking spaces.

(a) Level 2; Boston, MA

(b) Level 3 Tesla; Moab, UT
What is a charging standard?

- Two aspects
What is a charging standard?

- Two aspects
  1. A physical connector
What is a charging standard?

- Two aspects
  1. A physical connector
  2. A set of electric signals
What is a charging standard?

- Two aspects
  1. A physical connector
  2. A set of electric signals
- Cars can charge at three speed levels:
What is a charging standard?

- Two aspects
  1. A physical connector
  2. A set of electric signals

- Cars can charge at three speed levels:
  - Levels 1 and 2 (slower speeds)
    - Compatible across all brands and cars
    - Homes, employers, retailers, and government programs
What is a charging standard?

- Two aspects
  1. A physical connector
  2. A set of electric signals

- Cars can charge at three speed levels:
  - Levels 1 and 2 (slower speeds)
    - Compatible across all brands and cars
    - Homes, employers, retailers, and government programs
  - Level 3 (DC, Fast) [MORE DETAIL]
    - Three incompatible standards
    - Built by car manufacturers
Three standards for Level 3

<table>
<thead>
<tr>
<th>Level 3 (DC, Fast) Charging Standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE J1772 Combo</td>
</tr>
<tr>
<td>BMW: i3</td>
</tr>
<tr>
<td>GM: Bolt, Spark EV</td>
</tr>
<tr>
<td>Volkswagen: e-Golf</td>
</tr>
<tr>
<td>Ford</td>
</tr>
<tr>
<td>Chrysler</td>
</tr>
<tr>
<td>Daimler</td>
</tr>
<tr>
<td>Chademo</td>
</tr>
<tr>
<td>Nissan: LEAF</td>
</tr>
<tr>
<td>Mitsubishi: i-MiEV</td>
</tr>
<tr>
<td>Kia: Soul EV</td>
</tr>
<tr>
<td>Toyota</td>
</tr>
<tr>
<td>Peugeot</td>
</tr>
<tr>
<td>Citroën</td>
</tr>
<tr>
<td>Tesla</td>
</tr>
<tr>
<td>Tesla: Model S, X</td>
</tr>
</tbody>
</table>

*Depiction of plug shapes from Alternative Fuel Data Center*
Outline of talk

1. Introduction
2. Electric Vehicle Market
3. **Model**
   - Overview
   - Charging network description and model
   - Consumer utility and firm optimization problem
4. Estimation
5. Mandated Compatibility Counterfactual
6. Conclusion
Overview of each period (quarter)

- **Firms**
  - Compete in static oligopoly, and
  - Maximize electric vehicle profits by choosing quantity and locations of charging stations.

- **Consumers**
  - Consider only present options and characteristics (are myopic), and
  - Maximize utility by choosing among plug-in or non-plug-in (outside option) vehicles.
Each period’s sequence of events

0. Station investments by firms in the previous period arrive.
   Vehicle models from exogenous R&D arrive.
Each period’s sequence of events

0. Station investments by firms in the previous period arrive.
   Vehicle models from exogenous R&D arrive.

1. Firms choose charging station investment.
Each period’s sequence of events

0. Station investments by firms in the previous period arrive.
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1. Firms choose charging station investment.
2. Consumer demand shocks realized.
Each period’s sequence of events

0. Station investments by firms in the previous period arrive.  
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1. Firms choose charging station investment.

2. Consumer demand shocks realized.

3. Firms set prices given demand shocks and product characteristics.
Each period’s sequence of events

0. Station investments by firms in the previous period arrive. Vehicle models from exogenous R&D arrive.
1. Firms choose charging station investment.
2. Consumer demand shocks realized.
3. Firms set prices given demand shocks and product characteristics.
4. Consumers choose which vehicle to purchase given existing charging stations and prices.
Automakers begin building stations after car release.

Data Source: Alternative Fuel Data Center
Automakers begin building stations after car release.
Automakers begin building stations after car release.
Automakers begin building stations after car release.

Data Source: Alternative Fuel Data Center
Automakers begin building stations after car release.
Automakers begin building stations after car release.
Manufacturers pursue different location strategies.
Many possible charging locations in 1-D example

Figure: Need to simplify firms’ action space
Many possible charging locations in 1-D example

Figure: Need to simplify firms’ action space
Many possible charging locations in 1-D example

Figure: Need to simplify firms’ action space
Many possible charging locations in 1-D example

Figure: Need to simplify firms’ action space
Complementarity among stations in 1-D example

- The last station to “connect the dots” increases value of others
Reduce action space and spatial complementarity

Figure: Firms choose whether to build links between cities
Costs of linking cities are linear

![Graph showing a linear relationship between the number of Tesla charging locations outside MSAs and the number of origin-destination pairs. The coefficient is 0.28536971.]
Relevant charging stations for consumers

- Model consumers as taking two types of trips
Relevant charging stations for consumers

- Model consumers as taking two types of trips
  - Local: stations weighted by county-to-county commuting flows
Relevant charging stations for consumers

- Model consumers as taking two types of trips
  - Local: stations weighted by county-to-county commuting flows
  - Inter-city: number of traversable city pairs
Relevant charging stations for consumers

- Model consumers as taking two types of trips
  - Local: stations weighted by county-to-county commuting flows
  - Inter-city: number of traversable city pairs

- Tractable supply side
- Preserves relation of charging locations
  - to consumers’ origins/destinations
  - to other charging locations

- Implicitly assumes uniform value of links
Consumer utility over car purchases

Consumer $i$ maximizes utility by choosing among vehicles $r$ and the outside good 0.

$$U_{irmt} = \delta_{rmt} + \varepsilon_{irmt}$$

$$\delta_{rmt} = \gamma^S f(G_t, \bar{l}) + \gamma^L g(G_t, d_r) - \alpha p_{rmt} + X_{rmt} \beta + \xi_{rmt}$$
Consumer utility over car purchases

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$$\delta_{rmt} = \gamma^S f(G_t, \bar{l}) + \gamma^L g(G_t, d_r) - \alpha p_{rmt} + X_{rmt} \beta + \xi_{rmt}$$

- $p_{rmt}$ is the purchase price
- $G_t$ is the set of existing charging stations
- $f(G_t, \bar{l})$ is the quality of the local charging network
- $g(G_t, d_r)$ is the quality of the national network
- $X_{rmt}$ includes other characteristics, gas and electricity prices, market and time fixed effects
- $\xi_{rmt}$ represents factors such as targeted advertising, demand shocks
- $\varepsilon_{irmt}$ has type I extreme value (logit), represents idiosyncratic preferences
Firm optimization problem

• Each firm $j$ chooses charging station investment $a_{jt}$ to maximize discounted flow of profits.
Firm optimization problem

- Each firm $j$ chooses charging station investment $a_{jt}$ to maximize discounted flow of profits.
- $a_{jt}$ is a vector of length $M + 1$, for $M$ local networks and 1 national long-distance network.
Firm optimization problem

- Each firm $j$ chooses charging station investment $a_{jt}$ to maximize discounted flow of profits.
- $a_{jt}$ is a vector of length $M + 1$, for $M$ local networks and 1 national long-distance network

$$
\pi_{jt}(G_{t-1} + a_t) = \sum_m \sum_{r \in J_{jt}} (p_{rt} - mc_{rt} + ZEV\text{credit}_{rmt}) s_{rmt}(G_{t-1} + a_t, p_t; x_{mt}, \xi_{mt}, \theta) N_{mt}
$$

- Objective:

$$
\max_{a_{jt}} \pi_{jt}(G_{t-1} + a_{-jt} + a_{jt}) - c(a_{jt})
$$

where $c(a_{jt}) = \kappa |a_{jt}| + \omega_{jt}$
Outline of talk

1. Introduction
2. Electric Vehicle Market
3. Model
4. Estimation
   - Identification
   - Zero shares
   - Estimates
5. Mandated Compatibility Counterfactual
Mean utility:

\[ \delta_{rmt} = \gamma^S f(G_t, \bar{I}) + \gamma^L g(G_t, d_r) - \alpha p_{rmt} + X_{rmt} \beta + \xi_{rmt} \]

- Concern: prices and charging stations are correlated with \( \xi_{rmt} \)
- Use plausibly exogenous variation from government subsidies and assumptions on action timing
Identification: Prices

Mean utility:

\[ \delta_{rmt} = \gamma^S f(G_t, \bar{I}) + \gamma^L g(G_t, d_r) - \alpha p_{rmt} + X_{rmt} \beta + \xi_{rmt} \]

- Instrument 1: state tax credits that vary across car, state, and time
- Instrument 2: federal tax credits that vary across car
- Identification assumption: policy variation exogenous conditional on market and time fixed effects
  - Idiosyncratic months when subsidies begin and end
  - Range of reasons given by lawmakers
- Adding BLP instruments does not change the price parameter estimate.
Identification: Stations

Mean utility:

$$\delta_{rmt} = \gamma^S f(G_t, \bar{l}) + \gamma^L g(G_t, d_r) - \alpha p_{rmt} + X_{rmt} \beta + \xi_{rmt}$$

- Instrument 1: state subsidies that vary across state and time
- Instrument 2: lagged levels of charging stations
- Identifying assumption:
  - Stations take at least one period to arrive after firms choose investment
  - Arrival of stations in period $t$ uncorrelated with

$$\nu_{rm,t} = \xi_{rm,t} - \rho \xi_{rm,t-1}$$
Some products have zero market shares.

- Zero market shares a common problem in empirical demand analysis
- Practical challenge: cannot invert predicted share function because $\log(0)$ is undefined.
- Theoretical challenge: the model predicts strictly positive shares.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>10%</th>
<th>Median</th>
<th>90%</th>
<th># Obs.</th>
<th>% Zeros</th>
</tr>
</thead>
<tbody>
<tr>
<td>All vehicle sales</td>
<td>13,798.7</td>
<td>28,488.5</td>
<td>1,140</td>
<td>3,973.5</td>
<td>37,471</td>
<td>40,200</td>
<td>0</td>
</tr>
<tr>
<td>Plug-in sales</td>
<td>20.4</td>
<td>50.2</td>
<td>0</td>
<td>1</td>
<td>16</td>
<td>40,200</td>
<td>35.7</td>
</tr>
<tr>
<td>- 2011 plug-in sales</td>
<td>9.5</td>
<td>35.0</td>
<td>0</td>
<td>2</td>
<td>18</td>
<td>1,424</td>
<td>15.5</td>
</tr>
<tr>
<td>- 2012 plug-in sales</td>
<td>10.7</td>
<td>49.1</td>
<td>0</td>
<td>2</td>
<td>17</td>
<td>3,910</td>
<td>23.0</td>
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<tr>
<td>- 2013 plug-in sales</td>
<td>11.8</td>
<td>47.8</td>
<td>0</td>
<td>1</td>
<td>20</td>
<td>7,966</td>
<td>30.8</td>
</tr>
<tr>
<td>- 2014 plug-in sales</td>
<td>12.0</td>
<td>61.1</td>
<td>0</td>
<td>1</td>
<td>20</td>
<td>11,694</td>
<td>33.2</td>
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<tr>
<td>- 2015 plug-in sales</td>
<td>8.4</td>
<td>42.8</td>
<td>0</td>
<td>1</td>
<td>13</td>
<td>15,206</td>
<td>45.5</td>
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<tr>
<td>Observed market share</td>
<td>.00085</td>
<td>.0019</td>
<td>0</td>
<td>.00024</td>
<td>.0023</td>
<td>40,200</td>
<td>35.7</td>
</tr>
</tbody>
</table>
Empirical Bayes estimator of market shares

- Demand estimation uses true market share $s^0$.
- Observe $K_{rm}$ purchases of product $r$ out of $N_m$ total purchases
- Observed market share:
  $$\hat{s}_{rm}^{MLE} = \frac{K_{rm}}{N_m}$$
- Replace with empirical Bayes estimator for market share:
  $$K_{rm} \sim \text{Binomial}(N_m, s_{rm}^0)$$
  $$s_{rm}^0 \sim \text{Beta}(\lambda_{1rm}, \lambda_{2rm})$$
  $$\hat{s}_{rm} = \frac{\lambda_{1rm} + K_{rm}}{N_m + \lambda_{1rm} + \lambda_{2rm}}$$
- Consistent with logit demand model theory (McFadden (1974))
Empirical Bayes posteriors

- Estimate hyperparameters of the Beta-Binomial distribution.
- Priors from 50 markets closest in income per capita

<table>
<thead>
<tr>
<th>Market Share</th>
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<th>Std. Dev.</th>
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<td>.0019</td>
<td>0</td>
<td>.00024</td>
<td>.0023</td>
<td>40,200</td>
<td>35.7</td>
</tr>
<tr>
<td>Posterior</td>
<td>.00082</td>
<td>.0015</td>
<td>.00027</td>
<td>.00035</td>
<td>.0020</td>
<td>40,200</td>
<td>0</td>
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# Demand estimation results

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>Logit</th>
<th>Logit with Random Coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OLS (1)</td>
<td>IV (2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>RC IV (3)</td>
</tr>
<tr>
<td>log(Price)</td>
<td>-2.316***</td>
<td>-2.732***</td>
</tr>
<tr>
<td></td>
<td>(0.0787)</td>
<td>(0.625)</td>
</tr>
<tr>
<td>log(Local Level 2) × PHEV</td>
<td>0.0931***</td>
<td>0.129***</td>
</tr>
<tr>
<td></td>
<td>(0.0177)</td>
<td>(0.0295)</td>
</tr>
<tr>
<td>log(Local Level 2) × BEV</td>
<td>0.0614**</td>
<td>0.0912***</td>
</tr>
<tr>
<td></td>
<td>(0.0245)</td>
<td>(0.0339)</td>
</tr>
<tr>
<td>log(Local Level 3) × PHEV</td>
<td>-0.00300</td>
<td>0.0236**</td>
</tr>
<tr>
<td></td>
<td>(0.00904)</td>
<td>(0.0114)</td>
</tr>
<tr>
<td>log(Local Level 3) × BEV</td>
<td>0.0580***</td>
<td>0.0671***</td>
</tr>
<tr>
<td></td>
<td>(0.00776)</td>
<td>(0.00867)</td>
</tr>
<tr>
<td># City pairs × PHEV</td>
<td>-0.234</td>
<td>-0.902*</td>
</tr>
<tr>
<td></td>
<td>(0.300)</td>
<td>(0.509)</td>
</tr>
<tr>
<td># City pairs × BEV</td>
<td>0.00552***</td>
<td>0.00524**</td>
</tr>
<tr>
<td></td>
<td>(0.00155)</td>
<td>(0.00267)</td>
</tr>
</tbody>
</table>
Model estimates are close to industry estimates.

- **Demand parameters**
  - Tesla adapter retail price: $450
  - Predicted consumer surplus change: $426 average ($932 for Tesla purchasers)

- **Charging station costs**
  - Engineering estimates of Level 3 charging station costs: $150,000
  - Costs from firm profit first-order condition: $96,540 (Chademo) and $132,960 (Combo)
Outline of talk

1. Introduction
2. Electric Vehicle Market
3. Model
4. Estimation
5. Mandated Compatibility Counterfactual
6. Conclusion
Overview

• Held fixed:
  • car prices
  • other vehicle characteristics, such as driving range.
  • arrival of car models

• Three steps
  1. Demand response to unified standard, holding stations fixed in quantity and location
  2. Firms re-optimize station locations, holding quantity fixed
  3. Firms re-optimize both locations and quantities of stations
Traversability of national network under unified standard

**Figure:** Traversability is defined as the number of city pairs that can be reached using charging stations between them, normalized by the total number of city pairs.
# Step 1: Charging station investment fixed

<table>
<thead>
<tr>
<th>Standard</th>
<th>Status Quo</th>
<th>Counterfactual</th>
<th>Δ Quantity</th>
<th>% Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chademo</td>
<td>80,673</td>
<td>80,271</td>
<td>-402</td>
<td>-.5</td>
</tr>
<tr>
<td>Combo</td>
<td>27,289</td>
<td>31,650</td>
<td>4,361</td>
<td>16.0</td>
</tr>
<tr>
<td>Tesla</td>
<td>46,009</td>
<td>68,383</td>
<td>22,374</td>
<td>48.6</td>
</tr>
<tr>
<td>Other Plug-Ins</td>
<td>262,956</td>
<td>259,164</td>
<td>-3,792</td>
<td>-1.44</td>
</tr>
<tr>
<td><strong>Total Change (Level 3)</strong></td>
<td></td>
<td></td>
<td>26,333</td>
<td>17.1</td>
</tr>
<tr>
<td><strong>Total Change (All Plug-Ins)</strong></td>
<td></td>
<td></td>
<td>22,541</td>
<td>5.5</td>
</tr>
</tbody>
</table>
Step 2: Firms choose new locations

- Two challenges resolved by demand specification:
  - Reduce action space
  - Vehicle sales due to each action spatially independent
Step 2: Firms choose new locations

- Two challenges resolved by demand specification:
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  - Vehicle sales due to each action spatially independent
- Location problem is equivalent to computational problem called *fractional knapsack*
Step 2: Firms choose new locations

- Two challenges resolved by demand specification:
  - Reduce action space
  - Vehicle sales due to each action spatially independent
- Location problem is equivalent to computational problem called *fractional knapsack*
- Greedy algorithm gives optimal placement.
- Find equilibrium in each period by simulating firms playing iterated best-response
Step 2: Firms disperse stations more under compatibility

- Incompatibility: 165 markets (out of 344) with 0 charging stations
- Compatibility: 82 markets with 0 charging stations

Figure: Number of markets with charging station presence from each coalition
## Step 3: Firms and consumers re-optimize - Welfare

<table>
<thead>
<tr>
<th>Simulated Counterfactual Outcomes</th>
<th>Difference Across Regimes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incompatible (I) (1)</td>
<td>Compatible (C) (2)</td>
</tr>
<tr>
<td>Social Planner (SP) (3)</td>
<td>(C-I) (4)</td>
</tr>
<tr>
<td></td>
<td>(SP-I) (5)</td>
</tr>
<tr>
<td></td>
<td>(SP-C) (6)</td>
</tr>
<tr>
<td>A. SOCIAL WELFARE ($millions)</td>
<td></td>
</tr>
<tr>
<td>∆Social Welfare</td>
<td>2289.998 (1141.106)</td>
</tr>
<tr>
<td></td>
<td>4220.684 (638.902)</td>
</tr>
<tr>
<td></td>
<td>1930.686 (1361.262)</td>
</tr>
<tr>
<td>∆Consumer Surplus</td>
<td>490.017 (1146.154)</td>
</tr>
<tr>
<td></td>
<td>3104.464 (555.232)</td>
</tr>
<tr>
<td></td>
<td>2614.446 (1416.486)</td>
</tr>
<tr>
<td>Producer Vehicle Profits</td>
<td>1852.124 (287.890)</td>
</tr>
<tr>
<td></td>
<td>1447.159 (417.790)</td>
</tr>
<tr>
<td></td>
<td>-404.965 (512.623)</td>
</tr>
<tr>
<td>Nissan</td>
<td>-195.539 (56.665)</td>
</tr>
<tr>
<td></td>
<td>-278.675 (127.097)</td>
</tr>
<tr>
<td></td>
<td>-83.136 (98.641)</td>
</tr>
<tr>
<td>BMW</td>
<td>668.706 (81.246)</td>
</tr>
<tr>
<td></td>
<td>760.580 (127.553)</td>
</tr>
<tr>
<td></td>
<td>91.874 (143.222)</td>
</tr>
<tr>
<td>Tesla</td>
<td>1255.872 (227.337)</td>
</tr>
<tr>
<td></td>
<td>821.064 (229.020)</td>
</tr>
<tr>
<td></td>
<td>-434.808 (281.513)</td>
</tr>
</tbody>
</table>

- $W(Social\ Planner) > W^F(Compatible) > W^F(Incompatible)$
## Step 3: Firms and consumers re-optimize - Stations

<table>
<thead>
<tr>
<th>Simulated Counterfactual Outcomes</th>
<th>Difference Across Regimes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incompatible (I) (1)</td>
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</tr>
<tr>
<td>Social Planner (SP) (3)</td>
<td>(C-I) (4)</td>
</tr>
<tr>
<td></td>
<td>(SP-I) (5)</td>
</tr>
<tr>
<td></td>
<td>(SP-C) (6)</td>
</tr>
<tr>
<td><strong>B. NUMBER OF CHARGING LOCATIONS</strong></td>
<td></td>
</tr>
<tr>
<td>Total No. Locations</td>
<td></td>
</tr>
<tr>
<td>1868.510 (150.628)</td>
<td>1816.367 (192.070)</td>
</tr>
<tr>
<td>built by Nissan</td>
<td></td>
</tr>
<tr>
<td>1237.510 (150.628)</td>
<td>1185.367 (192.070)</td>
</tr>
<tr>
<td>built by BMW</td>
<td></td>
</tr>
<tr>
<td>380.000 (0.000)</td>
<td>380.000 (0.000)</td>
</tr>
<tr>
<td>built by Tesla</td>
<td></td>
</tr>
<tr>
<td>251.000 (0.000)</td>
<td>251.000 (0.000)</td>
</tr>
</tbody>
</table>
**Step 3: Firms and consumers re-optimize - EV sales**

<table>
<thead>
<tr>
<th>Simulated Counterfactual Outcomes</th>
<th>Difference Across Regimes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incompatible (I)</td>
<td>Compatible (C)</td>
</tr>
<tr>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>C. EV UNITS SOLD (thousands)</td>
<td></td>
</tr>
<tr>
<td>Total EV Units</td>
<td>488.173</td>
</tr>
<tr>
<td></td>
<td>(67.840)</td>
</tr>
<tr>
<td>Chademo</td>
<td>127.564</td>
</tr>
<tr>
<td></td>
<td>(66.454)</td>
</tr>
<tr>
<td>SAE Combo</td>
<td>15.670</td>
</tr>
<tr>
<td>Tesla</td>
<td>83.953</td>
</tr>
<tr>
<td>Other Plug-In</td>
<td>260.986</td>
</tr>
<tr>
<td></td>
<td>(3.502)</td>
</tr>
</tbody>
</table>
Conclusion

- Mandating compatibility in charging standards improves social welfare.
- Electric vehicle charging compatibility will become more important as US government and local utilities consider building charging stations.
Electric vehicle charging adapter

- Adapter must overcome two challenges
  1. Physical connection
  2. Electric communication signals

- Currently only a single adapter exists
  - Tesla-to-Chademo one-way adapter released in 2015
  - 2-3 years of engineering effort
  - Other directions incompatible
Tesla-to-Chademo adapter
State tax credits as price variation

Figure: Data source: National Conference of State Legislatures and state legislative records. State tax credits available in September 2015, $1,500 to $7,500 per car.
Federal tax credits as price variation
## Demand estimation results

<table>
<thead>
<tr>
<th>VARIABLES</th>
<th>(1) OLS</th>
<th>(2) IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>log(Price)</td>
<td>-2.316***</td>
<td>-2.732***</td>
</tr>
<tr>
<td></td>
<td>(0.0787)</td>
<td>(0.625)</td>
</tr>
<tr>
<td>log(Local Level 2) × PHEV</td>
<td>0.0931***</td>
<td>0.129***</td>
</tr>
<tr>
<td></td>
<td>(0.0177)</td>
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<td>0.00552***</td>
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<tr>
<td></td>
<td>(0.00155)</td>
<td>(0.00267)</td>
</tr>
<tr>
<td>BEV dummy</td>
<td>-1.889***</td>
<td>-2.276***</td>
</tr>
<tr>
<td></td>
<td>(0.133)</td>
<td>(0.217)</td>
</tr>
<tr>
<td>Battery range</td>
<td>0.00760***</td>
<td>0.00915***</td>
</tr>
<tr>
<td></td>
<td>(0.00104)</td>
<td>(0.00174)</td>
</tr>
<tr>
<td>Observations</td>
<td>40,200</td>
<td>35,418</td>
</tr>
<tr>
<td>R-squared</td>
<td>0.376</td>
<td>0.388</td>
</tr>
<tr>
<td>Minimum Eigvalue Stat (IV F-stat)</td>
<td>59.42</td>
<td></td>
</tr>
</tbody>
</table>

Standard errors clustered by model-market; market and MSA FE included.


