Analysis on Battery Charging Behavior of Electric Vehicles

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Outline

- Introduction
- Battery charging behavior
  - Within trip
  - At home
- Conclusions
Battery electric vehicles and Plug-in hybrid vehicle in Japan

i-MiEV 2009

Leaf 2010

Prius plug-in hybrid 2012

More energy efficient, but more electricity dependent
## Charging types

<table>
<thead>
<tr>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>120V (SAE J1772)</td>
<td>240V (SAE J1772)</td>
<td>&gt;=480V (CHAdeMO technology)</td>
</tr>
<tr>
<td>100V (Japan)</td>
<td>200V (Japan)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Normal charging (aka slow charging)</th>
<th>Fast charging (aka quick or rapid charging)</th>
</tr>
</thead>
<tbody>
<tr>
<td>requires several hours to completely charge a fully depleted battery and can be performed at home</td>
<td>provides an 80% charge in 30 minutes</td>
</tr>
</tbody>
</table>
Fast charger deployment in Japan

Source: CHAdeMO Association
Fast charger density

Charging stations are located:
- Workplaces & leisure places (47.3%)
- Car sales shops (40.4%)
- Parking lots (4.8%)
- Motorways (2.8%)
- Convenience stores (2.5%)
- Gas stations (2.2%)
Battery charging within trip

Trade-off between battery size and fast charger density

How to optimize battery size & fast charger deployment?

• Drivers charge battery before empty
• Charging behavior should be understood
Focus of this study: Mid-trip fast charging

Christensen et al. (2010): fast-charging infrastructure is the most important need if EVs are to come into widespread use.

Mid-trip fast-charging is more representative of the intended demand for fast charging than beginning-of-trip and end-of-trip fast-charging.
Data

• Investigator: Japan Automobile Research Institute
• Sample: 252 company cars & 247 private cars
• Survey period: 2 years (2011.2-2013.1)
• Survey area: 42 out of 47 prefectures in Japan

• **Built-in data logger with GPS & communication unit:** clock time, location, vehicle state (driving, normal charging, fast charging), odometer reading, use of air-conditioner & heater, state of charge
Field trial and data profiles

Number of Sampled EVs

- **commercial vehicles**: vehicles owned by fleets, include business vehicles and government vehicles
- **private vehicles**: vehicles owned by households

<table>
<thead>
<tr>
<th>Battery Capacity</th>
<th>10.5&amp;16 kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Driving Mileage</td>
<td>120&amp;180 km</td>
</tr>
</tbody>
</table>
Field trial and data profiles

Trip frequency per day

Average trip frequency per day:
Commercial vehicles: 8.7
Private vehicles: 5.0

* Trip: travel distance between engine starting and engine stopping
Field trial and data profiles

Trip distance

Average trip distance:
Commercial vehicles: 4.5km
Private vehicles: 5.9km

* Trip: travel distance between engine starting and engine stopping
Field trial and data profiles

Frequency of normal charging per month

- Commercial vehicles: 16.2
- Private vehicles: 13.1

Average frequency of normal charging per month:
Field trial and data profiles

Average frequency of fast charging per month:
Commercial vehicles: 0.8
Private vehicles: 2.3
Company cars are charged at the end of the working hours regardless of SOC.
Distribution of SOC at fast charge

**SOC: state of charge**

- **Company cars**
- **Private cars**

Battery capacity is not fully utilized
Stochastic frontier model of SOC at fast charging within trip

• Driver avoids running out of power

\[
\text{Actual remaining electricity to start charging} \geq \text{Subjective minimum electricity}
\]

• Inefficiency is added to minimum electricity

\[
\text{Actual remaining electricity} = \text{Subjective minimum electricity} + \text{Inefficiency}
\]

• Stochastic cost frontier model is applied
Charging behavior of battery usage

➤ Methodology

✓ Motivating phenomenon: An EV will be stranded without charge if there are no charging stations within the range provided by the remaining charge

$RE_0 \leq RE_1$

The minimum required electricity to prevent being stranded

The actual remaining electricity when a fast-charging begins

✓ Data characteristics: Unbalanced panel data
  • 140 vehicles, 2011.2-2013.1

✓ User characteristics: heterogeneity
  • Personality: risk-adverse, adventurer
  • Perception: station availability, electricity consumption

Random parameters stochastic frontier model
Charging behavior of battery usage

Random parameters stochastic frontier model

\[ y_{it} = \alpha + w_i + \beta' x_{it} + v_{it} + u_{it} \]

remaining electricity when a fast-charging begins

\[ w_i \sim N[0, \sigma_w^2] \]

random vehicle specific effect

\[ v_{it} \sim N[0, \sigma_v^2] \]

Symmetric random random error

One-sided random error

\[ u_{it} = |U_{it}|, U_{it} \sim N[0, \sigma_u^2] \]

Inefficiency in fast charging

i : EV

\( t \) : trial period
# Charging behavior of battery usage

## Model specification

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Remaining electricity</th>
<th>———</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Independent variables</strong></td>
<td>Number of Charging stations</td>
<td>TEPCO’s experience (2009)</td>
</tr>
<tr>
<td></td>
<td>Familiarity with whole charging station network</td>
<td>Dingemans &amp; Sperling &amp; Kitamura (1986)</td>
</tr>
<tr>
<td></td>
<td>Usage of Air-conditioning or heater</td>
<td>109Wh/km (both off), 186Wh/km (both on)</td>
</tr>
<tr>
<td></td>
<td>Battery capacity</td>
<td>———</td>
</tr>
<tr>
<td></td>
<td>Travel patterns</td>
<td>Kitamura &amp; Sperling (1987)</td>
</tr>
<tr>
<td></td>
<td>Price for fast-charging</td>
<td>Plummer &amp; Haining &amp; Sheppard (1998)</td>
</tr>
<tr>
<td></td>
<td>Latter half of trial</td>
<td>Dingemans &amp; Sperling &amp; Kitamura (1986)</td>
</tr>
<tr>
<td></td>
<td>Electricity company</td>
<td>Stations exclusively for members</td>
</tr>
</tbody>
</table>
## Charging behavior of battery usage

<table>
<thead>
<tr>
<th>Variable</th>
<th>Working days</th>
<th>Non-working days</th>
<th>Working days</th>
<th>Non-working days</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>coefficient</td>
<td>t-stat</td>
<td>coefficient</td>
<td>t-stat</td>
</tr>
<tr>
<td>Constant (E[α])</td>
<td>3.687**</td>
<td>6.96</td>
<td>33.815</td>
<td>1.01</td>
</tr>
<tr>
<td>Number of charging stations 1</td>
<td>—</td>
<td>—</td>
<td>-3.954</td>
<td>-0.88</td>
</tr>
<tr>
<td>Number of charging stations 2</td>
<td>-0.051</td>
<td>-0.71</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Number of charging stations 3</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Tokyo &amp; Kanagawa</td>
<td>-0.151</td>
<td>-0.31</td>
<td>-30.761</td>
<td>-0.92</td>
</tr>
<tr>
<td>Osaka &amp; Saitama</td>
<td>1.397**</td>
<td>3.01</td>
<td>-32.762</td>
<td>-0.97</td>
</tr>
<tr>
<td>Familiarity</td>
<td>-0.066</td>
<td>-0.31</td>
<td>-0.098</td>
<td>-0.09</td>
</tr>
<tr>
<td>Air-conditioning or heater</td>
<td>-0.037</td>
<td>-0.31</td>
<td>0.143</td>
<td>0.35</td>
</tr>
<tr>
<td>High-capacity battery</td>
<td>2.153**</td>
<td>9.97</td>
<td>0.623</td>
<td>1.59</td>
</tr>
<tr>
<td>Number of trips</td>
<td>0.048*</td>
<td>2.54</td>
<td>0.028</td>
<td>0.41</td>
</tr>
<tr>
<td>VMT</td>
<td>-0.004*</td>
<td>-2.25</td>
<td>0.001</td>
<td>0.15</td>
</tr>
<tr>
<td>Speed (0,20]</td>
<td>-0.107</td>
<td>-0.39</td>
<td>0.435</td>
<td>0.27</td>
</tr>
<tr>
<td>Speed (40~)</td>
<td>-0.107</td>
<td>-0.46</td>
<td>0.434</td>
<td>0.36</td>
</tr>
<tr>
<td>Free</td>
<td>0.152</td>
<td>0.78</td>
<td>0.172</td>
<td>0.31</td>
</tr>
<tr>
<td>Paid</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Latter half</td>
<td>0.375*</td>
<td>2.33</td>
<td>0.421</td>
<td>0.55</td>
</tr>
<tr>
<td>Electricity</td>
<td>1.202**</td>
<td>4.06</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Log likelihood function</td>
<td>-2357.871</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Std(u), Std(v), Std(w)</td>
<td>2.083,1.191,1.209</td>
<td>1.975,1.121,2.787</td>
<td>1.633,1.093,1.282</td>
<td>1.971,0.955,1.257</td>
</tr>
<tr>
<td>Observations</td>
<td>1187</td>
<td>317</td>
<td>2575</td>
<td>1325</td>
</tr>
<tr>
<td>Unbalanced panels</td>
<td>33</td>
<td>10</td>
<td>89</td>
<td>85</td>
</tr>
</tbody>
</table>

**,  * significance at 1%, 5% level
Distribution of subjective minimum and actual remaining charge

personal-use vehicles on working day

- Subjective minimum remaining charge has peak at 3.6kWh
- 1.5kWh of average inefficiency is estimated
Distribution of subjective minimum and actual remaining charge

commercial-use vehicles on working day

- Same peak of minimum remaining charge
- Larger (1.8kWh) average inefficiency is estimated
Battery charging at home

• Analysis on charge timing choice behavior of plug-in hybrid vehicles in Toyota City, Japan
  – This is a part of the results obtained by joint research with Toyota Motor Corporation
Smart Melit (Smart Mobility & Energy Life in Toyota City) project

- Toyota City, Japan
- 67 new houses, some with plug-in hybrid Prius
- HEMS (Home Energy Management System)
- DRP (demand response point) system
Smart house

Visualization by HEMS (home energy management system)

DRP (demand response point) portal

PHV charger

PHV

PHV charging monitor
Example of electricity demand curve

Scheduled to fill-up at 4:00
DRP (demand response point)

- Peak pricing by point system
- Low at daytime (solar energy) & high at evening (more activity at home)
Many cars return home at 18 to 20 o’clock, which potentially cause peak demand
Charging time is shifted by demand response point system

With demand response point

W/O demand response point
Charge timing choice model

- Multinomial logit model

- No charge
- Just after came home
- Cheapest timing
- Other

- 12 Prius plug-in hybrid vehicles
- 2011/10/1 to 2012/10/31
- 4615 cases
## Charge timing choice model

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Variable</th>
<th>Coef.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No charge</strong></td>
<td>Constant</td>
<td>1.34**</td>
</tr>
<tr>
<td></td>
<td>Drive distance (&lt;24 km)</td>
<td>-0.10**</td>
</tr>
<tr>
<td></td>
<td>Long distance dummy (&gt;24 km)</td>
<td>-0.38**</td>
</tr>
<tr>
<td><strong>Just after came home</strong></td>
<td>Price for energy conscious person</td>
<td>-0.044**</td>
</tr>
<tr>
<td></td>
<td>Price for energy unconscious person</td>
<td>-0.065**</td>
</tr>
<tr>
<td></td>
<td>Return home at daytime (9-16)</td>
<td>0.70**</td>
</tr>
<tr>
<td><strong>Cheapest time</strong></td>
<td>Constant</td>
<td>-0.69**</td>
</tr>
<tr>
<td></td>
<td>Price for energy conscious person</td>
<td>-0.016**</td>
</tr>
<tr>
<td></td>
<td>Price for energy unconscious person</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Housewife dummy</td>
<td>0.66**</td>
</tr>
<tr>
<td></td>
<td>Return home at evening (17-23)</td>
<td>1.41**</td>
</tr>
<tr>
<td><strong>Other</strong></td>
<td>Constant</td>
<td>-0.96**</td>
</tr>
<tr>
<td></td>
<td>Return home at evening (17-23)</td>
<td>0.65**</td>
</tr>
<tr>
<td></td>
<td>Same as the last charge dummy</td>
<td>2.21**</td>
</tr>
</tbody>
</table>

Log-likelihood (0)          -5774  
Log-likelihood at convergence -4415  
Adjusted rho-square        0.233  

** 1%, * 5%
## Sensitivity of the estimated model

**Base case:** High energy conscious male driver returned home in evening after 10 km drive

<table>
<thead>
<tr>
<th>Electricity price</th>
<th>No charge</th>
<th>Just after came home</th>
<th>Cheapest timing</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>No DRP (20.9 JPY)</td>
<td>35%</td>
<td>47%</td>
<td></td>
<td>18%</td>
</tr>
<tr>
<td>Evening price</td>
<td>36%</td>
<td>8%</td>
<td>38%</td>
<td>19%</td>
</tr>
<tr>
<td>20.9 -&gt; 28 JPY</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ Midnight price</td>
<td>34%</td>
<td>7%</td>
<td>42%</td>
<td>18%</td>
</tr>
<tr>
<td>20.9 -&gt; 10 JPY</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Charge timing is easier to change than the timing of air conditioner usage, etc.
Conclusions

• Battery capacity is not fully utilized, and measures to improve efficiency are needed
• Battery charging at home causes significant electricity demand, but the timing can be controlled by peak pricing