Analysis on the battery size and charging of plug-in hybrid vehicles

Toshiyuki Yamamoto
Nagoya University, Japan
Table of contents

• Background
  – EST: environmentally sustainable transport

• Car market in Japan
  – Fuel efficient cars: hybrid, plug-in hybrid, electric, etc.

• Analyses on battery of plug-in hybrid cars
  – Optimization of battery size
  – Off-peak battery charging
Transport accounts for a significant share of CO$_2$ emissions

World CO2 emissions by sector in 2010

- Residential: 6%
- Other: 10%
- Industry: 20%
- Transport: 22%
- Electricity and heat: 42%


CO2 emissions from transport in 2009 and 2010

- Road: 5.5 Gt CO$_2$
- Other transport: 0.5 Gt CO$_2$

History of transport planning & EST

EST: environmentally sustainable transport

**Structural strategy**
- Demand adjust
  - TDM
- Capacity increase
  - Construction

**Psychological strategy**
- Mobility Management

**Vehicle improvement**
- Low emission
- Alternative fuel
EST scenarios

- EST 1: The high-technology scenario
- EST 2: The capacity constraint scenario
- EST 3: The optimum-combination scenario

<table>
<thead>
<tr>
<th></th>
<th>EST 1</th>
<th>EST 2</th>
<th>EST 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology development</td>
<td>&gt;&gt;BAU</td>
<td>=BAU</td>
<td>&gt;BAU</td>
</tr>
<tr>
<td>Transport activity</td>
<td>=BAU</td>
<td>&lt;&lt;BAU</td>
<td>&gt;BAU</td>
</tr>
</tbody>
</table>

Source: OECD, 1998
Car market in Japan

Passenger car ownership by type in Japan

- Light motor passenger car
- Small passenger car
- Ordinary passenger car

Source: MLIT
## Passenger car sales ranking in Japan in 2012

<table>
<thead>
<tr>
<th>Rank</th>
<th>Model (Automaker)</th>
<th>Sales</th>
<th>Engine type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Prius (Toyota)</td>
<td>317,675</td>
<td>HV</td>
</tr>
<tr>
<td>2</td>
<td>Aqua (Toyota)</td>
<td>266,567</td>
<td>HV</td>
</tr>
<tr>
<td>3</td>
<td>Mira (Daihatsu)</td>
<td>218,295</td>
<td>Light motor</td>
</tr>
<tr>
<td>4</td>
<td>N BOX (Honda)</td>
<td>211,156</td>
<td>Light motor</td>
</tr>
<tr>
<td>5</td>
<td>Fit (Honda)</td>
<td>209,276</td>
<td>Small / HV</td>
</tr>
<tr>
<td>6</td>
<td>Wagon R (Suzuki)</td>
<td>195,701</td>
<td>Light motor</td>
</tr>
<tr>
<td>7</td>
<td>Tanto (Daihatsu)</td>
<td>170,609</td>
<td>Light motor</td>
</tr>
<tr>
<td>8</td>
<td>Move (Daihatsu)</td>
<td>146,016</td>
<td>Light motor</td>
</tr>
<tr>
<td>9</td>
<td>Alto (Suzuki)</td>
<td>112,002</td>
<td>Light motor</td>
</tr>
<tr>
<td>10</td>
<td>Freed (Honda)</td>
<td>106,316</td>
<td>Small / HV</td>
</tr>
</tbody>
</table>

**HV:** hybrid vehicle  

*Source: Nikkei Newspaper*
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
Optimization of battery size

• Analysis on efficiency of plug-in hybrid vehicle using GPS survey data in Toyota City, Japan
Plug-in hybrid vehicle

• EV to HV after running out battery

Charge at home  Run as EV  Run as HV

Daily trip  Longer trip

• Effect of battery size on efficiency

Small battery
• Lighter weight
• Shorter EV range
• Less expensive

Large battery
• Heavier weight
• Longer EV range
• More expensive
Vehicle use survey at Toyota City

- April to Sept. 2011
- 157 vehicles (54 HVs)
- Trajectory by GPS & CAN logger

**CAN**: Control area network
**ODB**: On-board diagnostics

[Images of OBDII adapter and LED indicator]
Observed vehicle usage patterns

Travel distance by day

Vehicle A

Distribution of dist.

Vehicle A

Travel distance by day

Vehicle B

Distribution of dist.

Vehicle B
Assumptions: energy efficiency

- Larger battery causes heavier weight, then lower running efficiency
- +100kg -> EV mode: -0.55 km/kWh
  HV mode: -0.67 km/L

<table>
<thead>
<tr>
<th>Hypothetical Spec.</th>
<th>PHV10</th>
<th>PHV20</th>
<th>PHV30</th>
<th>PHV40</th>
<th>PHV50</th>
</tr>
</thead>
<tbody>
<tr>
<td>EV range (km)</td>
<td>10</td>
<td>20</td>
<td>30</td>
<td>40</td>
<td>50</td>
</tr>
<tr>
<td>Battery size (kWh)</td>
<td>1.60</td>
<td>3.28</td>
<td>5.07</td>
<td>6.98</td>
<td>9.06</td>
</tr>
<tr>
<td>EV mode (km/kWh)</td>
<td>9.02</td>
<td>8.85</td>
<td>8.67</td>
<td>8.48</td>
<td>8.27</td>
</tr>
<tr>
<td>HV mode (km/L)</td>
<td>31.94</td>
<td>31.74</td>
<td>31.52</td>
<td>31.29</td>
<td>31.04</td>
</tr>
</tbody>
</table>
Assumption: Cost and CO2 per km

<table>
<thead>
<tr>
<th>Mode</th>
<th>Gasoline (JPY/L)</th>
<th>Electric (JPY/kWh)</th>
<th>CO2 emission (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline</td>
<td>138</td>
<td></td>
<td>2.3</td>
</tr>
<tr>
<td>Electric</td>
<td></td>
<td></td>
<td>0.39</td>
</tr>
<tr>
<td>Daytime</td>
<td>17.05</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nighttime</td>
<td>9.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CV (15km/L)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV (30km/L)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHV10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHV20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHV30</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHV40</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PHV50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EV</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Nighttime charge: Daytime charge: HV mode or CV
Assumption: charging timing

Charge once in a day at the beginning of the day

Case 1: One day travel distance < EV range

Run as EV

Cost = electricity price (JPY/km) × distance

Case 2: One day travel distance > EV range

Run as EV Run as HV

Cost = electricity price (JPY/km) × EV range
   + gasoline price (JPY/km) × (distance – EV range)
Results: All vehicles changes to one type of vehicle

Reduced running cost per year

- PHV is more cost effective than HV
- Larger battery is better for running cost, but the difference is small
Results: All vehicles changes to one type of vehicle

Reduced CO2 per year

• PHV is more energy efficient than HV
• Larger battery is better for CO2 reduction, but the difference is small
Results: if car price is considered?

<table>
<thead>
<tr>
<th>Vehicle price</th>
<th>Prius (grade S)</th>
<th>2,320,000 JPY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prius PHV</td>
<td>3,200,000 JPY</td>
<td></td>
</tr>
</tbody>
</table>

Difference = $3,200,000 - 2,320,000 - 450,000 (subsidy by Government)

= **430,000 JPY**

Average reduced running cost by replacing Prius to Prius PHV is **18,500 JPY**

More than 20 years ownership is needed to cover initial cost!

Average difference in running cost per year between HV (30km/L) and PHV

<table>
<thead>
<tr>
<th></th>
<th>PHV10</th>
<th>PHV20</th>
<th>PHV30</th>
<th>PHV40</th>
<th>PHV50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Running cost (JPY / year)</td>
<td>-10386</td>
<td>-15878</td>
<td>-19504</td>
<td>-22081</td>
<td>-23650</td>
</tr>
<tr>
<td>CO₂ emission (kg/year)</td>
<td>-110.7</td>
<td>-155.1</td>
<td>-181.9</td>
<td>-197.8</td>
<td>-204.1</td>
</tr>
</tbody>
</table>
Assumption: hypothetical subsidy

Government subsidy

+200,000, +250,000, +300,000 JPY
(Tokyo & Aichi pref. exempt car tax for 5 years, which means about 200,000 JPY)

Car price

30,000 JPY / kWh for battery cost is assumed, and car price is adjusted according to battery size

Most cost efficient vehicle is chosen for each driver considering 10 years of ownership
Results: most cost efficient car

- Without additional subsidy, PHV is not chosen
- More subsidy replaces HV by PHV
Results: CO2 reduction

- If gasoline car is prohibited, more reduction is gained
- More subsidy contributes few more reduction
Off-peak battery charging

• Analysis on charge timing choice behavior of plug-in hybrid vehicles in Toyota City, Japan
Smart Melit (Smart Mobility & Energy Life in Toyota City) project

- 67 new houses
- 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 charging

PHV charging
DRP (demand response point)

- Peak pricing by point system
- Low at daytime (solar energy) & high at evening (more activity at home)
Example of electricity demand pattern

Scheduled to fill-up at 4:00
Charge timing choice behavior

- Multinomial logit model

- 12 Prius plug-in hybrid vehicles
- 2011/10/1 to 2012/10/31
- 4615 cases
Descriptive analysis

Distribution of returning home timing

Time of day

Charge timing choice by returning home timing

Without DRP

With DRP
Charge timing choice by returning home timing

**Without DRP**
- Other
- Just after came home

**With DRP**
- Other
- Cheapest timing
- Just after came home

**Resulting charge timing distribution**

**Without DRP**

**With DRP**
## 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><strong>DRP price for high ecological minded person</strong></td>
<td>-0.044**</td>
</tr>
<tr>
<td></td>
<td><strong>DRP price for low ecological minded person</strong></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><strong>DRP price for high ecological minded person</strong></td>
<td>-0.016**</td>
</tr>
<tr>
<td></td>
<td><strong>DRP price for low ecological minded person</strong></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>
<tr>
<td>Log-likelihood (0)</td>
<td></td>
<td>-5774</td>
</tr>
<tr>
<td>Log-likelihood at convergence</td>
<td></td>
<td>-4415</td>
</tr>
<tr>
<td>Adjusted rho-square</td>
<td></td>
<td>0.233</td>
</tr>
</tbody>
</table>

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

Base case:
Higher ecological minded male driver returned home in evening after 5 km drive

<table>
<thead>
<tr>
<th></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>67%</td>
<td>12%</td>
<td></td>
<td>21%</td>
</tr>
<tr>
<td>Evening price 20.9 -&gt; 28 JPY</td>
<td>48%</td>
<td>6%</td>
<td>31%</td>
<td>15%</td>
</tr>
<tr>
<td>Midnight price 20.9 -&gt; 10 JPY</td>
<td>46%</td>
<td>6%</td>
<td>34%</td>
<td>14%</td>
</tr>
<tr>
<td>Distance 5km -&gt; 20km</td>
<td>16%</td>
<td>9%</td>
<td>53%</td>
<td>22%</td>
</tr>
</tbody>
</table>
Conclusions

• More energy efficient vehicles, but more electricity dependent

• Larger battery does not necessarily means more energy efficient

• Peak spreading for battery charge can be brought by pricing