The Human Dimensions of Plug-In Hybrid Electric Vehicles in Boulder

Participant Presentation
129 November 2012
Outline of Presentation

**Part One:** Introduction, research design, interest in PHV purchase, feedback, and charging behavior

**Part Two:** Vehicle and smart-plug data

**Part Three:** Ongoing analysis and preliminary conclusions
Community Context
Community Timeline

- **March**: Xcel rate increase announced
- **September**: Xcel declares SGC complete
- **October**: Pricing pilot begins
- **Fall**: Franchise agreement expires
- **December**: SGC declared complete again
- **November**: Boulder votes to explore municipalization
- **October**: IHSD pilot begins
- **November**: 10 cars added to the study
- **October**: Data collection ends, final interview completed
- **May**: Public release of study findings
- **January**: Xcel rate increase
- **October**: Study begins with 18 cars/first household interview completed

**COMMUNITY CONTEXT**

Introduction to the Research

- Toyota sponsored the research at CU
- Xcel Energy was a study partner
- Purposes of the research
- Household selection process
- Charging and gasoline cost estimates provided

Household requirements
- All family members over 21 participated
- Household is an economic unit
- Safe driving records
- Usable garage with outlet
- Wireless internet capability
- Smart meters already installed
## Sampling Matrix and Rate Structure

<table>
<thead>
<tr>
<th></th>
<th>Standard pricing</th>
<th>Time-of-use pricing</th>
<th>Total n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unmanaged charging</td>
<td>31</td>
<td>40</td>
<td>71</td>
</tr>
<tr>
<td>Managed charging</td>
<td>34</td>
<td>37</td>
<td>71</td>
</tr>
<tr>
<td>Total n</td>
<td>65</td>
<td>77</td>
<td>142</td>
</tr>
</tbody>
</table>

**Rate Structure**

<table>
<thead>
<tr>
<th></th>
<th>$/kWh*</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Standard</strong></td>
<td></td>
</tr>
<tr>
<td>Winter (all kWh) and summer (0-500 kWh/month)</td>
<td>0.096</td>
</tr>
<tr>
<td>Summer (500+ kWh/month)</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Time-of-use</strong></td>
<td></td>
</tr>
<tr>
<td>Summer on-peak</td>
<td>0.232</td>
</tr>
<tr>
<td>Winter on-peak</td>
<td>0.11</td>
</tr>
<tr>
<td>Year round off-peak</td>
<td>0.089</td>
</tr>
</tbody>
</table>

*Rates include all “riders” and adjustments by the utility equaling approximately $0.05/kWh

**Peaks and Off-peaks:**
- **Peak:** 2 pm to 8 pm
- **Off-peak:** 8 pm to 2 pm
- **Summer:** June 1 through September 30
- **Winter:** October 1 through May 31
Data Collection and Sample Descriptors

<table>
<thead>
<tr>
<th>Event</th>
<th>Week 1</th>
<th>Weeks 2-3</th>
<th>Week 3</th>
<th>Weeks 4-13</th>
<th>Month 1</th>
<th>Month 2</th>
<th>Month 3</th>
<th>Month 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial contact</td>
<td>Initial</td>
<td>Informed</td>
<td>DMV check</td>
<td>Smart plug</td>
<td>Pre-interview</td>
<td>Weekly online</td>
<td>Post-interview</td>
<td></td>
</tr>
<tr>
<td></td>
<td>contact</td>
<td>consent</td>
<td></td>
<td>installation/</td>
<td>questionnaire</td>
<td>diary entries</td>
<td>interview/</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>meeting</td>
<td></td>
<td>training and</td>
<td></td>
<td></td>
<td>questionnaire</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>vehicle pickup</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

265 drivers in 142 households that own 60 Toyotas and 32 hybrid vehicles

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicles owned</td>
<td>1 – 5</td>
<td>2.25</td>
</tr>
<tr>
<td>Household miles driven/year</td>
<td>1,500 – 50,000 miles</td>
<td>16,628 miles</td>
</tr>
<tr>
<td>Miles/gallon (primary vehicle)</td>
<td>12 – 51</td>
<td>25.5</td>
</tr>
</tbody>
</table>
### Selected Demographics

#### Age (21 to 89)

<table>
<thead>
<tr>
<th>Age</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Under 25</td>
<td>1</td>
</tr>
<tr>
<td>25 to 40</td>
<td>21</td>
</tr>
<tr>
<td>41 to 60</td>
<td>51</td>
</tr>
<tr>
<td>Over 60</td>
<td>27</td>
</tr>
</tbody>
</table>

#### Political views

<table>
<thead>
<tr>
<th>Political views</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very liberal/liberal</td>
<td>72</td>
</tr>
<tr>
<td>Neither</td>
<td>19</td>
</tr>
<tr>
<td>Very conservative/conservative</td>
<td>9</td>
</tr>
</tbody>
</table>

#### Pre-questionnaire (n = 265 drivers)

#### Education

<table>
<thead>
<tr>
<th>Education</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 4 years of college</td>
<td>6</td>
</tr>
<tr>
<td>4-year college degree</td>
<td>37</td>
</tr>
<tr>
<td>Advanced degree</td>
<td>57</td>
</tr>
</tbody>
</table>

#### Household income

<table>
<thead>
<tr>
<th>Household income</th>
<th>Less than $100,000</th>
<th>$100,000 to $150,000</th>
<th>Greater than $150,000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than $100,000</td>
<td>25%</td>
<td>36%</td>
<td>38%</td>
</tr>
</tbody>
</table>

*Does not add to 100 due to rounding*
Household Characteristics

- Couples with children, 43%
- Couples only, 41%
- Single person household, 11%
- Single parent with children, 5%

Pre-interview (n = 116 households)
### Reasons for Participating in the Study

**Why are you interested in being part of the PHV field test?**  
(open-ended question)

<table>
<thead>
<tr>
<th>Response</th>
<th>% of all responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Practical</td>
<td>33</td>
</tr>
<tr>
<td>Altruistic</td>
<td>27</td>
</tr>
<tr>
<td>Technological</td>
<td>22</td>
</tr>
<tr>
<td>Personal enjoyment</td>
<td>14</td>
</tr>
<tr>
<td>Voluntary simplicity/localization</td>
<td>4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Pre-interview (n = 142 households with 328 total volunteered responses)
Views on Global Warming

Which of the following statements comes closest to your belief?

<table>
<thead>
<tr>
<th>Response</th>
<th>Six Americas %</th>
<th>Boulder PHV study %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most scientists think global warming is happening</td>
<td>47</td>
<td>86</td>
</tr>
<tr>
<td>Most scientists think global warming is not happening</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>There is a lot of disagreement among scientists about whether global warming is happening</td>
<td>33</td>
<td>13</td>
</tr>
<tr>
<td>Don’t know enough to say</td>
<td>18</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>101*</td>
<td>100</td>
</tr>
</tbody>
</table>

*Totals may not add to 100 due to rounding

Pre-interview (n = 263 drivers)
### Views on Global Warming

*Assuming global warming is happening, do you think it is:*

<table>
<thead>
<tr>
<th>Response</th>
<th>Six Americas</th>
<th>Boulder PHV Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Caused mostly by human activities</td>
<td>57</td>
<td>66</td>
</tr>
<tr>
<td>Caused mostly by natural changes</td>
<td>33</td>
<td>4</td>
</tr>
<tr>
<td>Caused by human actions and natural changes</td>
<td>5</td>
<td>27</td>
</tr>
<tr>
<td>N/A (there is no global warming)</td>
<td>3</td>
<td>--</td>
</tr>
<tr>
<td>Don’t know/other</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>99</strong>*</td>
<td><strong>99</strong>*</td>
</tr>
</tbody>
</table>

*Pre-interview (n = 257 drivers)*

*Totals may not add to 100 due to rounding*
## Views on Global Warming

How large of an effort should the U.S. make to reduce global warming?

<table>
<thead>
<tr>
<th>Response</th>
<th>Six Americas %</th>
<th>Boulder PHV Study %</th>
</tr>
</thead>
<tbody>
<tr>
<td>No effort</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>A small-scale effort, with small economic costs</td>
<td>17</td>
<td>5</td>
</tr>
<tr>
<td>A medium effort, with medium economic costs</td>
<td>40</td>
<td>31</td>
</tr>
<tr>
<td>A large-scale effort, with large economic costs</td>
<td>34</td>
<td>62</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100</strong></td>
<td><strong>99</strong></td>
</tr>
</tbody>
</table>

*Pre-interview (n = 263 drivers)

*Totals may not add to 100 due to rounding*
PHV Experience

How did you like driving the PHV?

- **Loved it!** 30%
- **Liked it very much** 38%
- **Liked it pretty much** 22%
- **Liked it a little** 8%
- **Did not like it** 3%

Post-questionnaire (n=262 drivers)

*Totals may not add to 100 due to rounding*
PHV Descriptors

Which of these words best describes the Prius plug-in hybrid electric vehicles? [Please check all that apply]

Post-questionnaire (n=265 drivers)
Symbolic Meaning of the Car

Post-interview (n = 142 households)

Environmentally conscious: 77%

Technologically cutting edge: 23%

Trendsetter, early adopter: 20%

Saving money, efficient: 13%

Proud, smug, status symbol: 12%

Responsible, virtuous, helping society: 11%

Hip, cool, very Boulder: 11%

Affluent, yuppie: 11%

Unmanly: 6%

Nerdy: 5%

Slow driver, old, conservative: 4%

Flashy, pretentious: 4%

Not environmentally conscious: 2%

Percent of all households: 77%
Interest in PHV Purchase and EV Range

Would you consider buying a PHV?

<table>
<thead>
<tr>
<th>Response</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yes</td>
<td>71</td>
</tr>
<tr>
<td>No</td>
<td>29</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

How satisfied are you with the EV range of 14 miles?

<table>
<thead>
<tr>
<th>Response</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very satisfied</td>
<td>8</td>
</tr>
<tr>
<td>Somewhat satisfied</td>
<td>39</td>
</tr>
<tr>
<td>Somewhat dissatisfied</td>
<td>33</td>
</tr>
<tr>
<td>Not at all satisfied</td>
<td>20</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

What would be the ideal EV range (miles) for the PHV?

- 40 miles or less, 60%
- 21-30, 29%
- 31-40, 15%
- 41-50, 18%
- 51-99, 13%
- 100+, 16%
- 14-20, 13%

Post-questionnaire (n = 264 drivers)

Post-interview (n = 142 households)
Dashboard Feedback

How useful were the feedback displays in the car?

- Very useful: 34%
- Quite useful: 31%
- A little useful: 28%
- Not at all useful: 2%
- DK/didn’t use them: 5%

Did you sometimes drive in a way to optimize fuel economy?

<table>
<thead>
<tr>
<th>Response</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Almost always</td>
<td>28</td>
</tr>
<tr>
<td>Most of the time</td>
<td>31</td>
</tr>
<tr>
<td>Some of the time</td>
<td>23</td>
</tr>
<tr>
<td>Hardly ever</td>
<td>8</td>
</tr>
<tr>
<td>Never</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

Post-questionnaire (n=261 drivers)
Smart-Meter and Smart-Plug Feedback

How often did you look at the smart-meter and smart-plug websites? (Post)

<table>
<thead>
<tr>
<th>Website</th>
<th>Never, once or twice</th>
<th>A few times</th>
<th>Often</th>
<th>Totals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smart meter</td>
<td>68</td>
<td>21</td>
<td>12</td>
<td>100</td>
</tr>
<tr>
<td>Smart plug</td>
<td>70</td>
<td>22</td>
<td>9</td>
<td>101*</td>
</tr>
</tbody>
</table>

*Does not add to 100 due to rounding

Post-interview (n = 141 households)
Charging Scenarios

Beginning
- Standard: 25%
- Time-of-use: 29%
- Unmanaged: 22%
- Managed: 25%

Pricing
- Standard: 38%
- Time-of-use: 24%

Ending
- Standard: 35%
- Time-of-use: 18%
- Unmanaged: 29%
- Managed: 35%

Chi square = 20.326, p ≤ .000
(n = 92 households, modified sample)
Anomalous Cases

9%

Standard/Managed → stayed Managed (7 cases)
Forgot how, thought they were TOU, for the study, wanted to charge during the day

Standard/Unmanaged → changed to Managed (1 case)
1 changed so their car wasn’t charging when their Christmas lights were on

18%

Time-of-Use/Unmanaged → stayed Unmanaged (11 cases)
Forgot how, self-managed, experimented, realized it was cheaper to drive on electricity even with TOU rates

Time-of-Use/Managed → changed to Unmanaged (5 cases)
Didn’t like set charging schedule too inconvenient, didn’t want to buy gas, confused about TOU dates

Post-interview (n = 92 households)
Patterns of Change

**Changed or experimented**

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>M</td>
<td>40</td>
<td>40</td>
</tr>
</tbody>
</table>

**Stayed the same**

<table>
<thead>
<tr>
<th></th>
<th>S</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>M</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>
Charging Management Behaviors

Number of households
Post-interview (n = 86 households)
## Electricity vs. Gasoline

### Costs per Charge

**Standard vehicle:** 30 mpg; fuel cost - $3.75/gal.

**PHV:**
- Battery size (kWh): 5.2
- Range (miles): 13
- Gals. equivalent: 0.43

<table>
<thead>
<tr>
<th>Electricity Cost $/kWh</th>
<th>Standard Tier 1</th>
<th>Standard Tier 2</th>
<th>TOU Summer On-peak</th>
<th>TOU Winter On-peak</th>
<th>TOU Off-peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost per charge</td>
<td>$0.46</td>
<td>$0.73</td>
<td>$1.22</td>
<td>$0.55</td>
<td>$0.42</td>
</tr>
<tr>
<td>Electric equivalent $/gal. of gas</td>
<td>$1.07</td>
<td>$1.68</td>
<td>$2.82</td>
<td>$1.26</td>
<td>$0.98</td>
</tr>
<tr>
<td>Savings per gallon</td>
<td>$2.68</td>
<td>$2.07</td>
<td>$0.93</td>
<td>$2.49</td>
<td>$2.77</td>
</tr>
</tbody>
</table>

*Source: Xcel Energy, Inc.*
Part Two

• Summary of vehicle and smart-plug data analysis
• Driving patterns
• Charging patterns
• Comparisons between ending charging scenarios: managed and unmanaged households

Slides for Part Two were prepared by Dragan Maksimovic, Ph.D., Co-PI
Analysis Overview

• Data from 27 vehicles in 138 Boulder households (data logger data)
• Smart plug data on vehicle electricity use
• Around 12,000 vehicle trips, total of 91,000 miles
• Total of around 27 MWh of electricity used for charging
An Example of Data Logged

Vehicle speed [km/h]

Charging power [kW]

Battery EV state of charge (SOC) [%]

Combined vehicle and smart-plug data

From vehicle data logger

From smart-plug data logger

An Example of Data Logged

Vehicle speed [km/h]

0 50 100
14 15 16 17 18 19 20

Charging power [kW]

0 2
14 15 16 17 18 19 20

Battery EV state of charge (SOC) [%]

0 50 100
14 15 16 17 18 19 20

5.2 miles trip

1.8 miles trip

0.2 miles trip

1.9 miles trip

2.7 kWh charging event

2.1 kWh charging event

hour (time of day)

From vehicle data logger

From smart-plug data logger

Combined vehicle and smart-plug data

5.2 miles trip

1.8 miles trip

0.2 miles trip

1.9 miles trip

2.7 kWh charging event

2.1 kWh charging event

hour (time of day)
Average for Boulder households: 68 mpg
Driving Patterns

Average trip distance: 7.6 miles (12.2 km)
Average number of trips per day: 3.2
• 88% of trips are shorter than 13.2 miles (vehicle EV range)
• On average fuel economy peaks at over 90 mpg for 2- to 5-mile trips
• On longer trips, fuel economy converges to an average of 54.4 mpg
Boulder Households: Charging Patterns

Average number of charging events per day: 0.8
Average charging electricity consumed per day: 2.3 kWh
Boulder Households: Charging Patterns

About 60% of trips ending at home followed by charging

About 3% of trips ending away from home followed by charging

Overall, 27% of trips followed by charging
When does charging occur?

For managed households, probability of charging events peaks from 8 pm to 10 pm.
Charging Electricity Consumption

charging power demand per household per day (kW)

ending as unmanaged
ending as managed

time of day (hour)
Ideal Electricity Demand Potentials
for Hypothetical Public Charging Stations in Boulder

Ideal potential electricity demand computed based on the time per day a vehicle spends parked on average in the area shown:

A North Broadway shopping center
B 28th & Diagonal
C Multiple parking lots around 29th St. Mall
D Multiple downtown parking lots
• Overall fuel economy depends primarily on
  o Trip length
  o Frequency of charging
• In Boulder, majority (around 88%) of trips are within the vehicle EV range
• Electricity displaces up to about 30% of total of energy consumed per mile
• In Boulder, about 27% of trips are followed by a charging event
  o Many different real-life reasons
  o Lack of charging infrastructure
Part Three

- Ongoing analysis
- Conclusions
Use of Charging Stations

Alfalfa’s Market
Use of Charging Stations

North Boulder Rec Center

South Boulder Rec Center
Use of Charging Stations

Wolf Law Building
Satisfaction with the PHV
(Interview and Data Logger Data)

- Is higher when the starting and ending SOC is higher
- Is higher when the cars used more electricity each day
- Is higher when the distance between charges is shorter

<table>
<thead>
<tr>
<th>How did you like driving the PHV?</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loved it</td>
<td>57</td>
</tr>
<tr>
<td>Liked it</td>
<td>37</td>
</tr>
<tr>
<td>Did not like it</td>
<td>6</td>
</tr>
<tr>
<td>Total n</td>
<td>142</td>
</tr>
</tbody>
</table>

Correlations significant at $p \leq 0.01$
Satisfaction with EV Range
(Interview and Data Logger Data)

- Is higher at lower household average speeds
- Is higher when average household trips are shorter
- Is higher when more driving is in EV mode
- Is lower as kWh/km goes up

<table>
<thead>
<tr>
<th>Satisfaction with EV Range</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>No</td>
<td>76</td>
</tr>
<tr>
<td>Yes</td>
<td>24</td>
</tr>
<tr>
<td>Total n</td>
<td>135</td>
</tr>
</tbody>
</table>

Correlations significant at $p \leq 0.01$
Correlation of Average Monthly Electricity Costs, 4 Months after the Field Test and the Same 4 Months One Year Before

Ongoing Analysis
Off-site Charging

TOU’s used significantly more kWh’s overall . . .

At home

At home, TOU and standard households used essentially the same number of kWh’s.

“Trips”

TOU households drove more miles and took more “trips,” but durations of trips and distances travelled were essentially the same.

Away from home

Away from home, TOU households used significantly more kWh’s and charged longer.
It wasn’t always smooth sailing
Accidents

It wasn’t always smooth sailing
Accidents

It wasn’t always smooth sailing
Conclusions

- By and large, households actively managed their charging
- We discovered seven discrete categories* of charging-management behavior
- Most households did not use online feedback to manage their vehicle charging

*Set smart-plug programming for unmanaged, set around TOU hours, set for overnight, left programming as it was, forgot about it, self-managed, stayed managed
More Conclusions

- Households tended to find managed charging inconvenient
- To use managed charging, TOU households prefer a simple “set-it-and-forget-it” approach with easy override
- Electricity pricing drove charging-management behavior
- Time-cost/convenience were also important
Thank you! Any questions?

Barbara C. Farhar, Ph.D.
Principal Investigator
303-492-5452
barbara.farhar@colorado.edu
Participant Quotes

• “[…] The other day, a police officer pulled up next to the car and asked how I liked it. Of course, I almost had a heart attack because I thought ‘Did I not turn on my signal; what did I do that was wrong?’”

• “For the first time we thought we could function with a small car. We’d never considered that before.”

• “Uh, oh. My wife wondered out loud if we needed to buy a plug-in Prius. I think she’s beginning to like it.”
Participant Quotes

• “I’ve been testing the acceleration a bit in EV mode, because the torque of the electric engine seems to make the PHV perform very well. It’s like driving a souped-up sports car rather than a high-mileage vehicle.”

• “I have never driven a hybrid before this Prius and I have been impressed by how much the car graphic display has caused me to drive more efficiently. Regardless of what car I drive in the future, my understanding of energy (fuel) use related to acceleration has improved dramatically and changed my driving habits.”