A Corridor-Centric Approach to Planning Electric Vehicle Charging Infrastructure

In Honor of Professor David Boyce – his 50th NARSC Conference

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Outline

• Introduction
• Preliminaries
• Design model and solutions
• Special cases
• Case study
Introduction

• Why alternative fuel vehicles?
  – Energy security: transportation heavily depends on imported oil.
  – Environmental concerns: transportation emits roughly a quarter of the world’s GHG, and a major contributor to most air pollutants. *Ohnishi, 2008*
Introduction

• Why electric vehicles?
  – EV are energy efficient: with a well-to-wheel efficiency around 1.15 km/mJ, Evs are almost as twice as efficient as Toyota Prius (Romm, 2006).
  – Electric cars have zero emission at the point of operation (Samaras & Meisterling, 2008)
  – EV could reduce GHG emissions, subject to the source of electricity.
Introduction

• EV is gaining market share in the US and around the world
  – Plug-in EV sales are expected to account for 0.3 percent of all cars sales by 2015 *(Newman, 2010)*
  – President Obama promised “one million electric vehicles on the road by 2015” *(Energy Speech Fact Sheet)*
  – $2.4 billion in the US federal grants to further development of EVs *(Canis, 2011)*
Barriers to the adoption of EVs

• EV batteries are still expensive and limited by range, owing to the lack of technology breakthrough
• The underdeveloped supporting infrastructure, particularly the lack of fast refueling facilities, makes current EVs unsuitable for medium and long distance travel.

Rapid adoption of EVs can benefit from:

– Better access to charging facilities, and/or

Cheaper batteries with greater capacity
Literature

• Locating charging facilities near the urban activity centers of EV owners so as to maximize the overall accessibility.
  – Set covering or P-median facility location models (Daskin 1995, Dashora et al., 2010; Frade et al., 2011; Chen et al., 2013; Sweda and Klabjan, 2011)

• Locating charging facilities to intercept flows between origin-destination pairs.
  – Minimize cost while enforcing a recharging logic to ensure all flows are served. (Wang & Lin, 2009; Mak et al., 2013)

• Hybrid models that consider both point and O-D demands (Wang & Wang, 2010; Hodgson & Rosing, 1992)
Research questions

• If the society can freely decide the capacities of charging facilities and batteries, how that decision can be made in an optimal way?
• Which factors should have important influences on the decision?
• What policies may be implemented to facilitate the optimal allocation of resources for expanding these capacities?
Research approach

• A simple optimization model
  – To minimize the total cost of providing charging facilities and manufacturing batteries, while ensuring all EV users can complete their trips with a desired level of service.

• Focus on trips along corridors long enough to trigger range anxiety
  – These medium-range-low-frequency trips traditionally served by passenger cars are likely one of the main reasons why single-car families have to say no to the current generation of EVs.
Basics about charging stations

• Three types of charging facilities available for EVs in the US (Morrow et al., 2008).
  • Level 1: standard 120 VAC, up to 1.44 kW charging power
  • Level 2: 240 VAC, up to 10 kW.
  • Level 3: 480 VAC, up to 60 kW – 150 kW.

• EVs may be charged at home, in public areas and at some work places (Pound, 2012).

• The US now has between 6000 - 7000 charging stations: the majority (more than 5000) are privately owned.

• Nearly 80% of all existing charging stations are level 2. (US Department of Energy)
Basics about batteries

• Many types of batteries are currently available in the market, with different energy capacities and prices.
• An important performance measure: distance that an EV runs on each unit of battery energy consumed ($\beta = 2.5$).
• Charging time depends on the type of the battery but mostly on the power of the charging facilities and battery’s charging efficiency ($\alpha$): $t_r = \alpha \frac{E}{P}$ ($\alpha=1.3$)
Model setting

• Consider long corridor with a maximum length of $l$, serving EV drivers traveling along one direction.
• Let $\lambda$ denote the density of the EVs (measured in vehicle per unit distance), and $f$ be the average frequency of the trips made by each EV for a given analysis period (typically a day).
• The total number of EV drivers is given as $\lambda l$, and the total number of trips in the analysis period is $\lambda l f$. 
Model assumptions

• All trips are concentrated at the two ends of the corridor.
• All EVs have the same range.
• Each station must have enough charging outlets to accommodate all trips.
• Stations are uniformly spaced based on the range of the EVs
Model objective

• Choose the energy capacity of each EV’s primary battery (denoted as $E$), and the power of the charging facilities (denoted as $P$) to minimize total cost.
• Cost of building a charging station is a function of $P$, the number of charging outlets $n_o$, and a fixed capital cost.
• The cost of each battery is a function of its energy capacity $E$
Design Model

\[
\min z(P, E) = (C_p + P n_o C_s) \left( \frac{l}{\beta \theta E} - 1 \right) + \lambda l C_e E
\]

Subject to:

\[
\left( \frac{l}{\beta \theta E} - 1 \right) \frac{\alpha \theta E}{P} \leq T_0
\]
Design Model

\[
\min z(P, E) = \left( C_p + P n_o C_s \right) \left( \frac{l}{\beta \theta E} - 1 \right) + \lambda \ell C_e E
\]

Subject to:

\[
\left( \frac{l}{\beta \theta E} - 1 \right) \frac{\alpha \theta E}{P} \leq T_0
\]
Design Model

\[
\min z(P, E) = (C_p + Pn_o C_s) \left( \frac{l}{\beta \theta E} - 1 \right) + \lambda l C_e E
\]

Subject to:

\[
\left( \frac{l}{\beta \theta E} - 1 \right) \frac{\alpha \theta E}{P} \leq T_0
\]
Design Model

\[
\min z(P, E) = (C_p + Pn_oC_s) \left( \frac{l}{\beta \theta E} - 1 \right) + \lambda l C_e E
\]

Subject to:

\[
\left( \frac{l}{\beta \theta E} - 1 \right) \frac{\alpha \theta E}{P} \leq T_0
\]

Level of Service Constraint
Analytical Solution

• The model is not convex, so multiple local optimums are possible.

Solution 1: $E_0^* = c_3; \quad P_0^* = \frac{c_2c_3 - C_p}{c_1}$ (no charging station needed)

Solution 2: $E_1^* = \frac{c_3}{\eta}; \quad P_1^* = \frac{c_3a\theta}{T_0} \left(1 - \frac{1}{\eta}\right)$ (charging stations will needed)

$c_1 \equiv n_0C_s$: variable cost of charging facility

$c_2 \equiv \lambda l C_e$: Unit cost to manufacture all batteries

$c_3 \equiv \frac{l}{\beta\theta}$: battery energy needed to travel the corridor without charging

$\eta \equiv \frac{c_3(T_0c_2 + a\theta c_1)}{\sqrt{a\theta c_1c_3 + T_0C_p}}$: A constant
Results from the analysis

- A higher battery construction cost leads to smaller battery and larger charging capacity. Conversely, a higher construction cost results in larger batteries and smaller charging capacity.
- A lower level of service requirement (i.e. larger $T_0$) reduces the optimal battery size
- The growth in the EV population ($\lambda$) makes it more desirable to have a smaller battery size and larger charging capacity.
Results from the analysis

• Higher long-distance trip frequency will lead to larger optimal battery size and reduce the capacity of charging facility.

• As long as the density of EV demand exceeds certain threshold (about 0.1 vehicle/mile), it is always beneficial to provide charging facilities.
Discrete charging capacity

\[
\min z(P, E) = (C_p + Pn_oC_s)\left(\frac{l}{\beta \theta E} - 1\right) + \lambda l C_e E
\]

Subject to:

\[
\frac{l}{\beta \theta} - \frac{T_0P}{\alpha \theta} \leq E \leq \frac{l}{\beta \theta}
\]
Graphic illustration

Objective Function (Cost) vs. Battery Energy (kwh)

Levels:
- Level 1
- Level 2
- Level 3

Labels:
- LB3
- LB2
- LB1
Special Cases
Discrete capacity for Charging Facility
Battery swapping

\[
\min z(P, E) = (C_p' + rP_3n_0C_s)\left(\frac{l}{\beta\theta E} - 1\right) + n_bC_eE
\]

Subject to:

\[
\frac{l}{\beta\theta} \left(\frac{T_0}{t_e} + 1\right) \leq E \leq \frac{l}{\beta\theta}
\]

\[
n_b \equiv \lambda l + \left(\frac{l}{\beta\theta E} - 1\right) \lambda l f: \text{number of batteries}
\]

\[
P_3 - \text{the power of level-3 charging}
\]

\[
r - \text{charger/battery ratio}
\]

\[
t_e - \text{time spent on swapping (estimated at 5 minutes)}
\]
Special Cases
Battery Swapping

\[
\begin{align*}
\sqrt{\frac{(C'_p + r P_3 c_1) c_3}{c_2 (1-f)}} & \\
\frac{c_3}{\left(\frac{T_0}{t_e} + 1\right)} & \\
\end{align*}
\]

\[
\begin{align*}
\frac{c_3}{\left(\frac{T_0}{t_e} + 1\right)} & \leq \sqrt{\frac{(C'_p + r P_3 c_1) c_3}{c_2 (1-f)}} & \leq c_3 \\
\sqrt{\frac{(C'_p + r P_3 c_1) c_3}{c_2 (1-f)}} & < \frac{c_3}{\left(\frac{T_0}{t_e} + 1\right)} \\
\sqrt{\frac{(C'_p + r P_3 c_1) c_3}{c_2 (1-f)}} & > c_3
\end{align*}
\]
Case Study

- Chicago, IL- Madison, WI
- 150 miles
- 75 EVs
- Range anxiety (0.8)
- Once a week
## Case Study

### Baseline model

<table>
<thead>
<tr>
<th>Level service 100(\delta)</th>
<th>Total travel time (hr)</th>
<th>Energy (kwh)</th>
<th>(E)</th>
<th>Battery range (mile)</th>
<th>Charging Power (kW)</th>
<th>(P)</th>
<th>Number of charging stations (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>2.7</td>
<td>75.0</td>
<td></td>
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<td>0</td>
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<tr>
<td>5%</td>
<td>2.9</td>
<td>37.5</td>
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<td>93.75</td>
<td>286.0</td>
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<td>1</td>
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<tr>
<td>15%</td>
<td>3.1</td>
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<td>93.75</td>
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<td>76.3</td>
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<td>50%</td>
<td>4.1</td>
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<td>62.50</td>
<td>38.1</td>
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<tr>
<td>85%</td>
<td>5.0</td>
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<td>100%</td>
<td>5.5</td>
<td>18.7</td>
<td></td>
<td>46.87</td>
<td>21.4</td>
<td>3</td>
<td>3</td>
</tr>
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</table>
Case Study
Sensitivity of Demand (Baseline model)
Case Study
Sensitivity of Technology (Baseline model)

Graphs:
- a. Charging Station Power (kw)
- b. Battery Energy (kwh)
- c. Objective Function ($)
- d. Number of Charging Stations

(NOTE: The graphs show the relationship between cost and charging station power, battery energy, objective function, and number of charging stations.)
Case Study
Discrete capacity for Charging Facility

(a) Low Density ($\lambda=0.01$)
(b) Medium Density ($\lambda=0.5$)
(c) High Density ($\lambda=100$)
Case Study
Battery Swapping
Findings

• Level 2 charging is socially optimal for very low EV market penetrate rates.

• Level 3 charging is needed to achieve a reasonable level of service.

• The optimal solution is more sensitive to the cost of battery than to the cost of chargers.

• Battery swapping enables the use of smaller batteries and to achieve higher level of service.

• Charging could be a socially optimal solution for modest levels of service.
Future study

• Consider more realistic arriving pattern of EVs at charging and/or swapping stations.
• More realistic charging cost and battery cost functions.
• Network wide application with multiple corridors between different origin destination pairs.
• Hybrid models that consider both point and O-D flows.
The presentation is based on
Yu (Marco) Nie, Mehrnaz Ghamami, A corridor-centric approach to planning electric vehicle charging infrastructure, Transportation Research Part B: Methodological, Available online 19 September 2013, ISSN 0191-2615,

Thank You
Questions?
## Case Study

### Parameters values

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l$</td>
<td>Corridor length</td>
<td>mile</td>
<td>150</td>
</tr>
<tr>
<td>$f$</td>
<td>Average trip frequency</td>
<td>trip/day</td>
<td>0.13</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>EV fleet density</td>
<td>vehicle/mile</td>
<td>0.5</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>Energy Efficiency (Converting energy/Power ratio to charging time)</td>
<td>-</td>
<td>1.3</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Battery performance</td>
<td>mile/kwh</td>
<td>2.5</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Delay tolerance</td>
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<td>15%</td>
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<tr>
<td>$A_0$</td>
<td>Minimum construction area</td>
<td>sqf</td>
<td>2000</td>
</tr>
<tr>
<td>$a_0$</td>
<td>Per spot construction area</td>
<td>sqf</td>
<td>300</td>
</tr>
<tr>
<td>$C_a$</td>
<td>Unit construction cost for new stations (charging or swapping)</td>
<td>$/sqf</td>
<td>104</td>
</tr>
<tr>
<td></td>
<td>Unit construction cost for existing charging stations</td>
<td>$/sqf</td>
<td>20</td>
</tr>
<tr>
<td>$C_e$</td>
<td>Unit manufacturing cost of battery</td>
<td>$/kwh</td>
<td>650</td>
</tr>
<tr>
<td>$C_s$</td>
<td>Per spot construction cost of charging outlet</td>
<td>$/kw</td>
<td>500</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Range tolerance (Confident range)</td>
<td>-</td>
<td>0.8</td>
</tr>
</tbody>
</table>
## Case Study
### Energy Efficiency

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>$E$ (kWh)</th>
<th>$I$ (amp)</th>
<th>$V$ (V)</th>
<th>$P$ (kW)</th>
<th>$E/P$ (h)</th>
<th>$t_r$ (h)</th>
<th>$\alpha$</th>
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<td>BMW Mini E</td>
<td>35</td>
<td>12</td>
<td>110</td>
<td>1.32</td>
<td>27</td>
<td>26.00</td>
<td>0.98</td>
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<tr>
<td></td>
<td></td>
<td>32</td>
<td>240</td>
<td>7.68</td>
<td>5</td>
<td>4.50</td>
<td>0.99</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48</td>
<td>240</td>
<td>11.52</td>
<td>3</td>
<td>3.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Chevy Volt</td>
<td>16</td>
<td>12</td>
<td>120</td>
<td>1.44</td>
<td>11</td>
<td>10.00</td>
<td>0.90</td>
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<td></td>
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<td>20</td>
<td>240</td>
<td>4.8</td>
<td>3</td>
<td>4.00</td>
<td>1.20</td>
</tr>
<tr>
<td>Ford Focus EV</td>
<td>23</td>
<td>20</td>
<td>230</td>
<td>4.6</td>
<td>5</td>
<td>7.00</td>
<td>1.40</td>
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<tr>
<td>Mitsubishi iMiEV</td>
<td>16</td>
<td>12</td>
<td>110</td>
<td>1.32</td>
<td>12</td>
<td>12.50</td>
<td>1.03</td>
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<td>220</td>
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<td>7.00</td>
<td>1.93</td>
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<td></td>
<td></td>
<td>60</td>
<td>480</td>
<td>28.8</td>
<td>0.6</td>
<td>2.50</td>
<td>4.50</td>
</tr>
<tr>
<td>Nissan LEAF</td>
<td>24</td>
<td>20</td>
<td>220</td>
<td>4.4</td>
<td>5</td>
<td>8.00</td>
<td>1.47</td>
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<td></td>
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<td>60</td>
<td>480</td>
<td>28.8</td>
<td>0.8</td>
<td>0.60</td>
<td>0.72</td>
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<tr>
<td>Volvo C30</td>
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<td>16</td>
<td>230</td>
<td>3.7</td>
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<td>8.00</td>
<td>1.23</td>
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<tr>
<td>Toyota PRIUS</td>
<td>1.34</td>
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<td>110</td>
<td>1.32</td>
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<td>3.00</td>
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<td>200</td>
<td>4</td>
<td>0.3</td>
<td>1.67</td>
<td>4.98</td>
</tr>
</tbody>
</table>

$I$ - electric current; $E$ - battery energy; $V$ - electric potential; $P$ - power.
Case Study
Station construction cost
Case Study
Station construction cost
Case Study
Energy Efficiency

(a) Box plots for determining battery charging efficiency

(b) Recharging efficiency changes with power
Case Study
Battery Performance

Tested six different types of vehicles in urban versus highway driving under various conditions (e.g. headlight setting, auxiliary loads, and A/C).

On average an EV can travel 2.5 miles for each kWh (kilo Watt hour) of energy.

Case Study

Power Cost Relation

![Graph showing the cost of building charging stations versus charging station power (kw).]
Case Study
Power Cost Relation

Ref: Cluzed, C. and Douglas, C. (2012), Cost and performance of EV batteries, element energy, The Committee on Climate Change
Case Study
Construction cost

The per spot cost of building a charging station excluding the acquisition cost of the charger varies widely depending on installation area, electric circuit, etc.

Construction cost is calculated based on the cost for building a gas station, including construction, contract and architectural fees.

- unit construction cost 104(\$/sqf). (Reed Construction Data, 2008)
- The average construction area of a gas station is about 4000(sqf). (LoopNetData, 2012)
  2000(sqf) fixed area and 300(sqf) area for each charging spot
- The per spot cost of building a charging station excluding the acquisition cost of the charger is $6000. (NREL, 2012)
  300(sqf) for each charging spot and per unit area cost 20(\$/sqf)