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

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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)*

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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.

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Introduction

- EV is gaining market share in the US and around the world
  - Plug-in EV sales are expected o 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)*

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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

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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.
  - Maximize flow captured subject to budget constraint: flow capturing facility location models (FCLM) *(Hodgson,1990, Kuby &Lim,2005,2007, Lim & Kuby,2010)*
  - *Minimize cost while enforcing a recharing 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)*

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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?

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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.

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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: h 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)*

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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(α): $t_r = \alpha \frac{E}{P}$ (α=1.3)

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Model setting

- Consider long corridor with a maximum length of l, serving EV drivers traveling along one direction.
- Let λ 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 λl, and the total number of trips in the analysis period is $\lambda l f$.

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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

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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*

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Design Model

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

Subject to:

$$\left(\frac{l}{\beta\theta E} - 1\right)\frac{\alpha\theta E}{P} \le T_0$$

Design Model

Charging Station Cost

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

Subject to:

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

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Design Model

Battery Cost

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

Subject to:

$$(\frac{l}{\beta\theta E} - 1)\frac{\alpha\theta E}{P} \leq T_0$$

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:

$$\left(\frac{l}{\beta\theta E} - 1\right)\frac{\alpha\theta E}{P} \le T_0$$

Level of Service Constraint

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Analytical Solution

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

Solution 1: ${E_0}^* = c_3;\ {P_0}^* = \frac{c_2 c_3 - C_p}{c_1}$ (no charging station needed)

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

$c_1 \equiv n_0 C_s$: 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

$\eta \equiv \sqrt{\frac{c_3(T_0 c_2 + \alpha\theta c_1)}{\alpha\theta c_1 c_3 + T_0 C_p}}$: A constant

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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 (λ) makes it more desirable to have a smaller battery size and larger charging capacity.

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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

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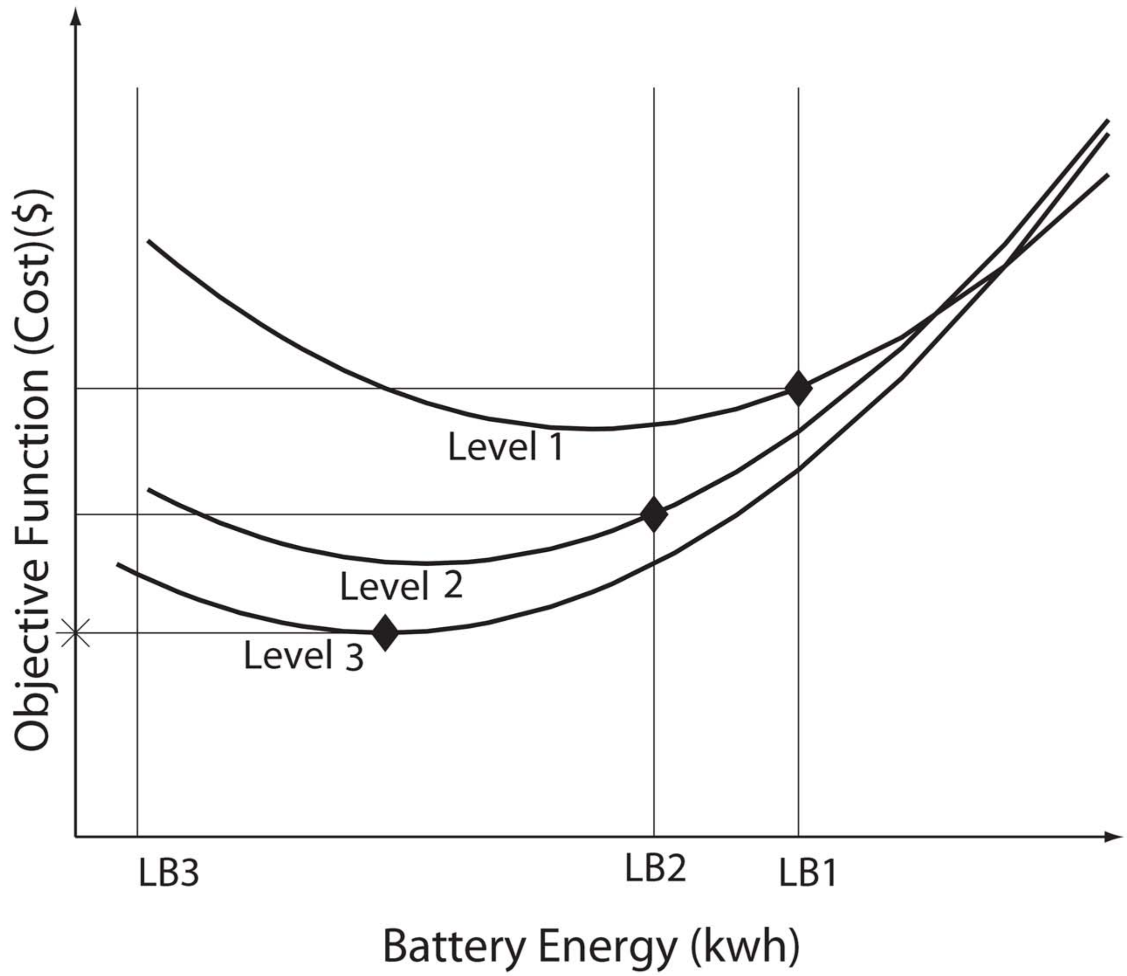
Discrete charging capacity

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

Subject to:

$$\frac{l}{\beta\theta} - \frac{T_0 P}{\alpha\theta} \le E \le \frac{l}{\beta\theta}$$

Graphic illustration



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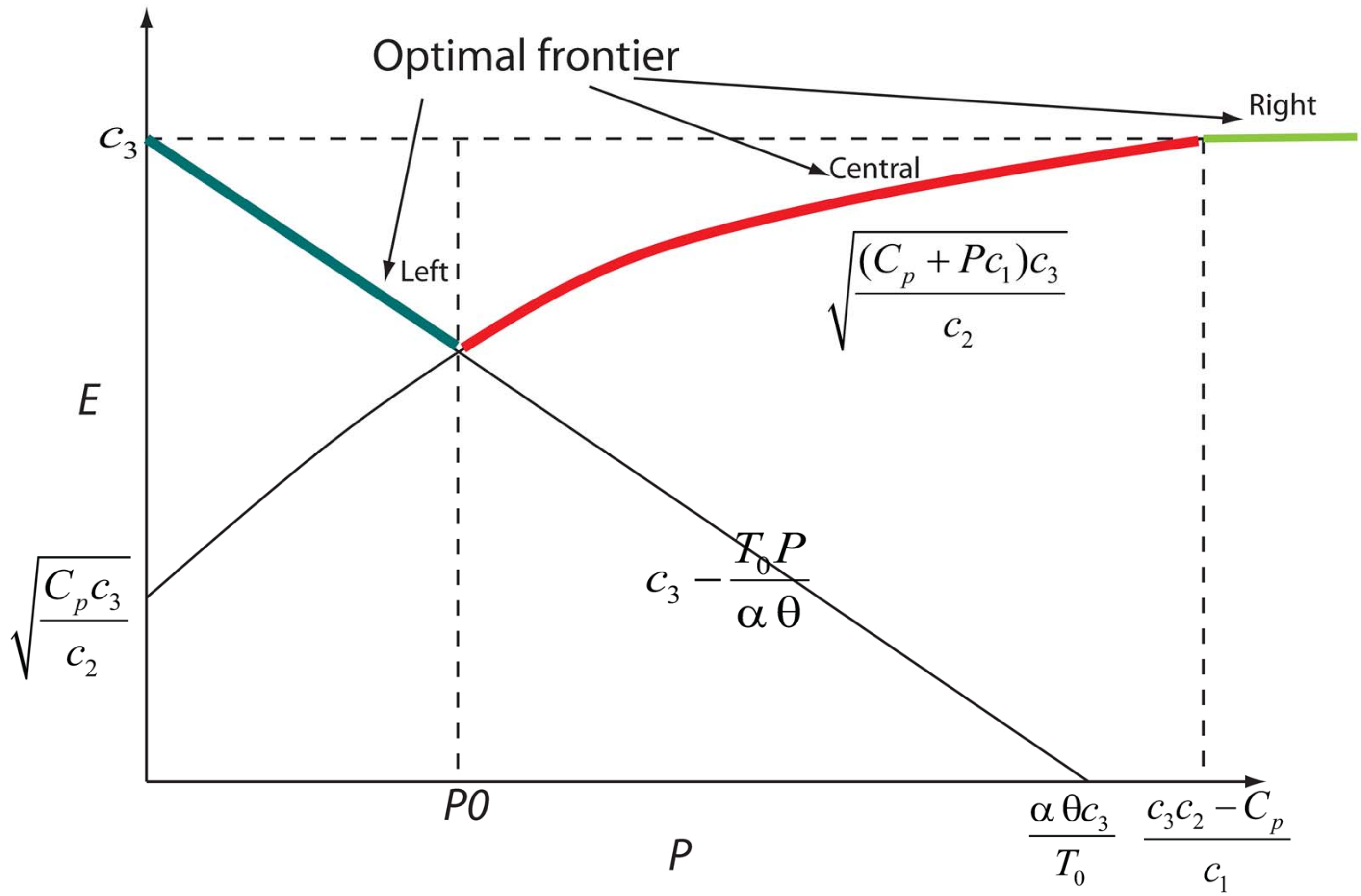
Special Cases

Discrete capacity for Charging Facility



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Battery swapping

$$\min\ z(P,E) = \left(C'_p + rP_3 n_o C_s\right)\left(\frac{l}{\beta\theta E} - 1\right) + n_b C_e E$$

Subject to:

$$\frac{\frac{l}{\beta\theta}}{\left(\frac{T_0}{t_e}+1\right)} \le E \le \frac{l}{\beta\theta}$$

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

P_3 - the power of level-3 charging

r – charger/battery ratio

t_e – time spent on swapping (estimated at 5 minutes)

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Special Cases

Battery Swapping

- $$\begin{cases} \sqrt{\frac{(C'_p + rP_3 c_1)c_3}{c_2(1-f)}} & \frac{c_3}{(\frac{T_0}{t_e}+1)} \le \sqrt{\frac{(C'_p + rP_3 c_1)c_3}{c_2(1-f)}} \le c_3 \\ \frac{c_3}{(\frac{T_0}{t_e}+1)} & \sqrt{\frac{(C'_p + rP_3 c_1)c_3}{c_2(1-f)}} < \frac{c_3}{(\frac{T_0}{t_e}+1)} \\ c_3 & \sqrt{\frac{(C'_p + rP_3 c_1)c_3}{c_2(1-f)}} > c_3 \end{cases}$$

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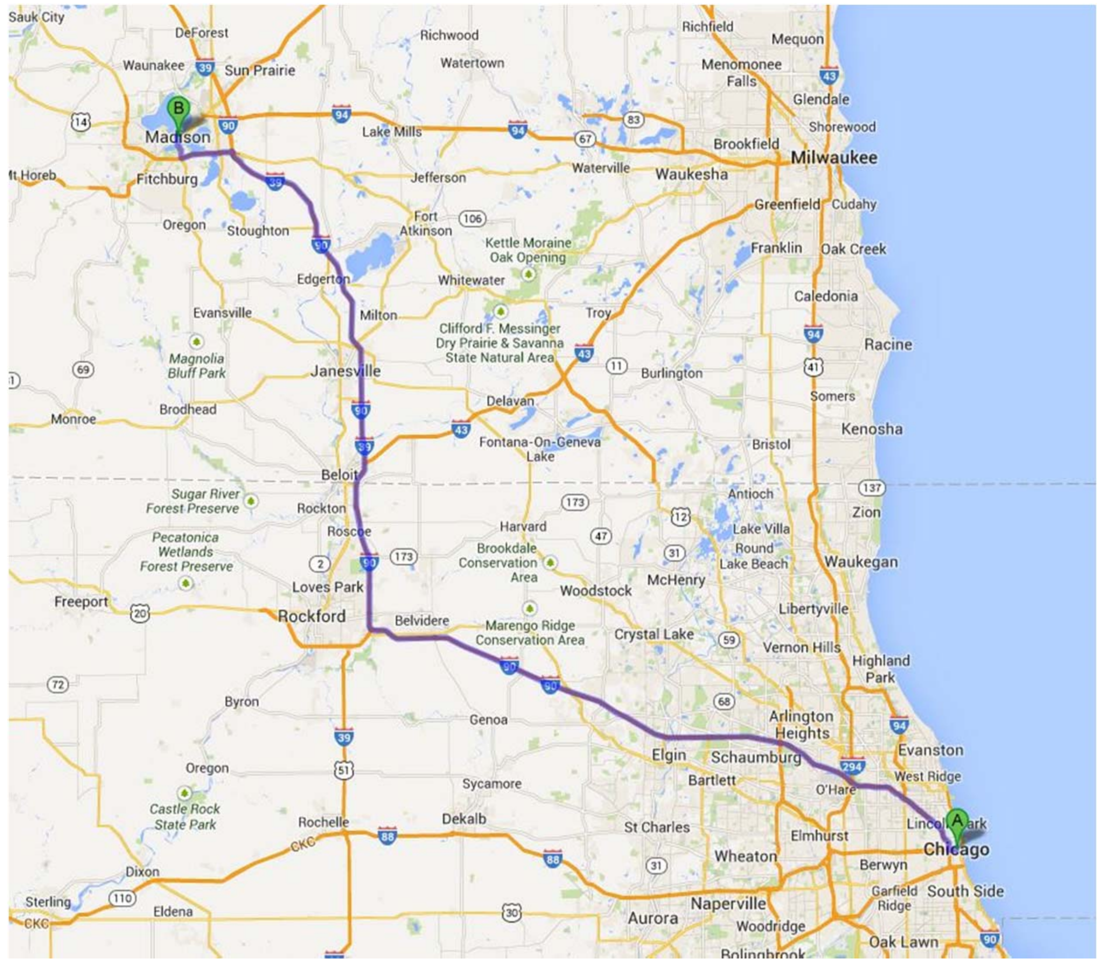
Case Study

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



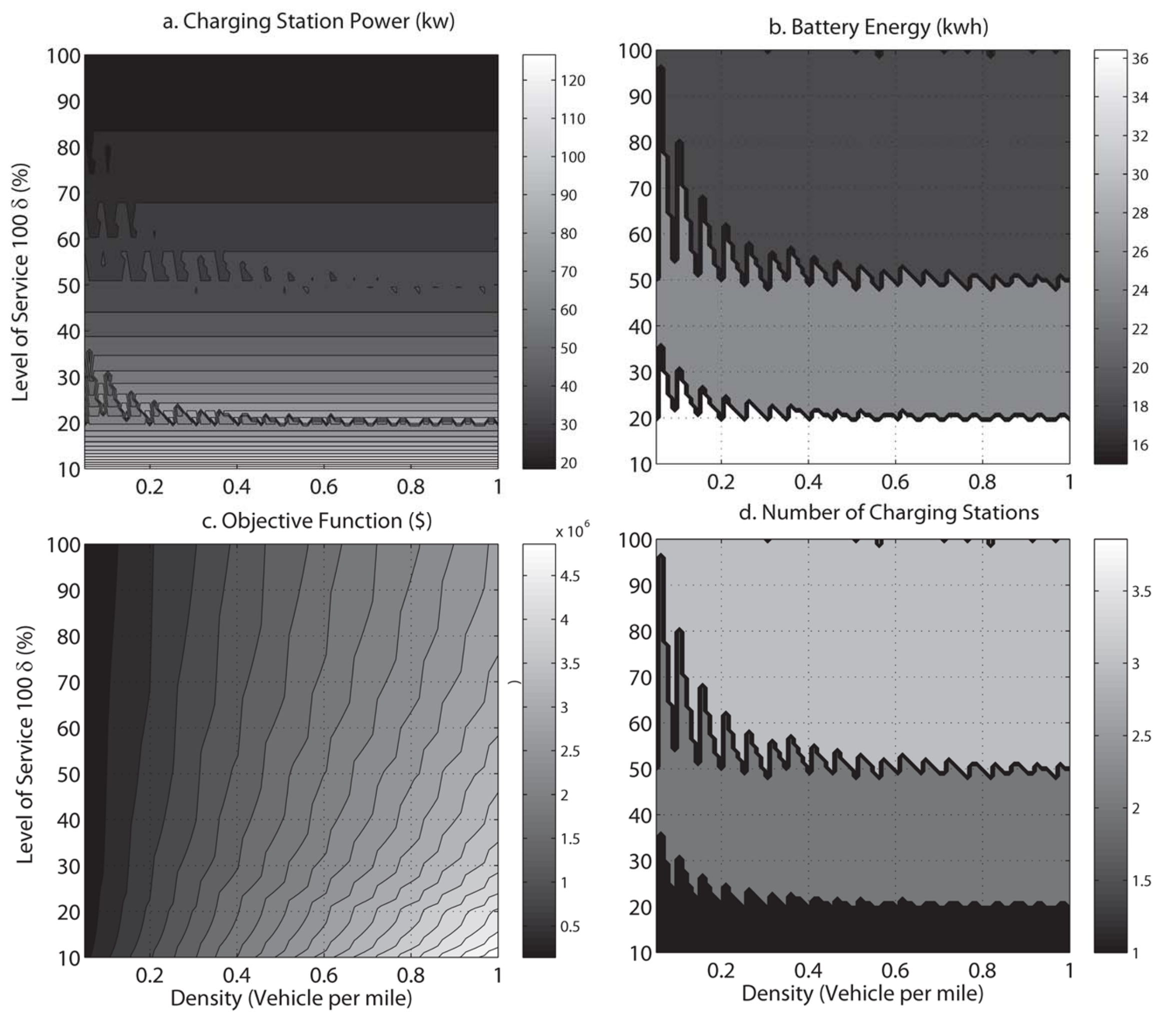
Case Study

Baseline model

Level of service 100δ	Total travel time (hr)	Energy E (kwh)	Battery range (mile)	Charging Power P (kW)	Number of charging stations m
0%	2.7	75.0	187.50	0	0
5%	2.9	37.5	93.75	286.0	1
15%	3.1	37.5	93.75	95.3	1
25%	3.4	25.0	62.50	76.3	2
50%	4.1	25.0	62.50	38.1	2
85%	5.0	18.7	46.87	25.2	3
100%	5.5	18.7	46.87	21.4	3

Case Study

Sensitivity of Demand (Baseline model)



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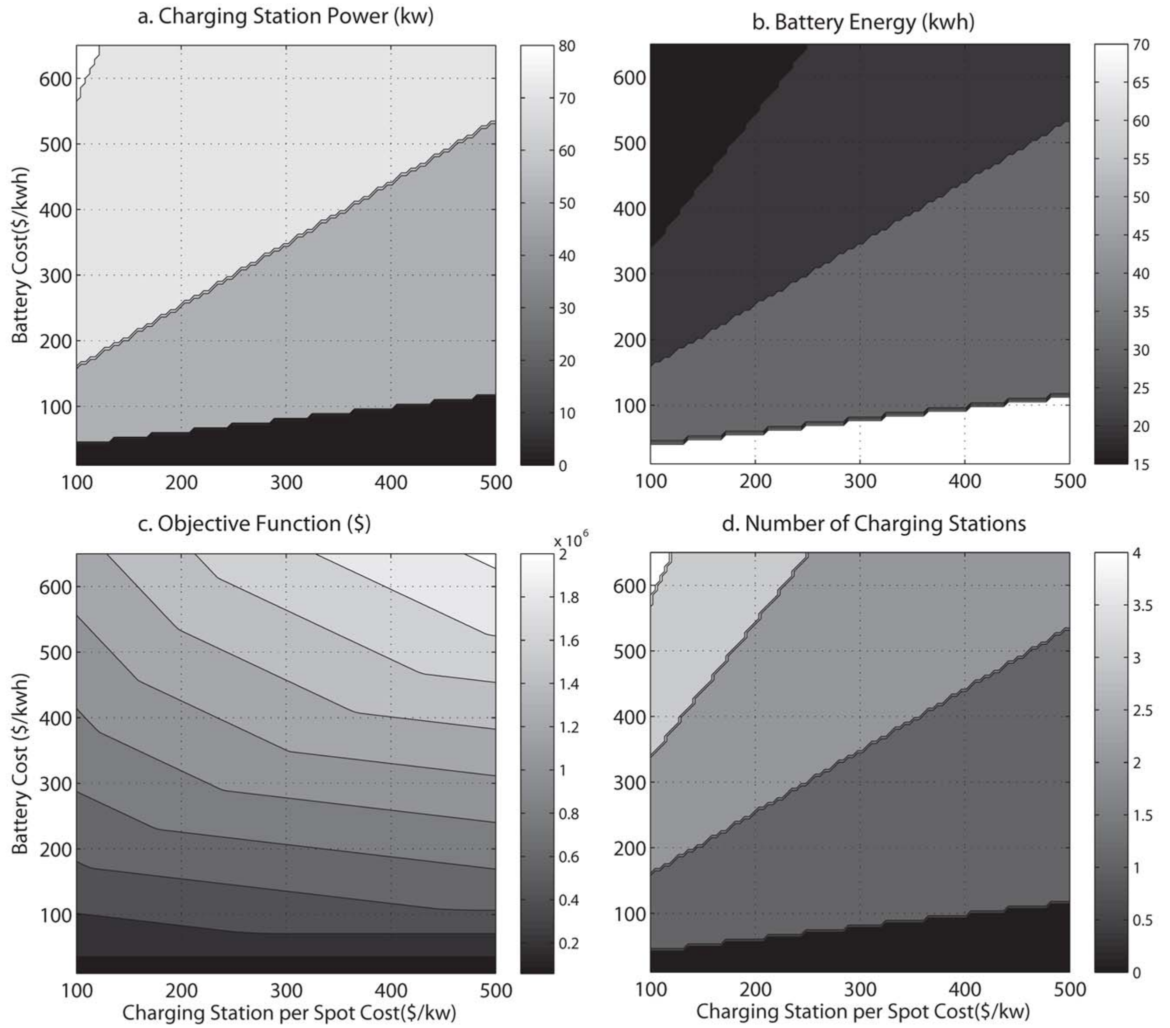
Case Study

Sensitivity of Technology (Baseline model)



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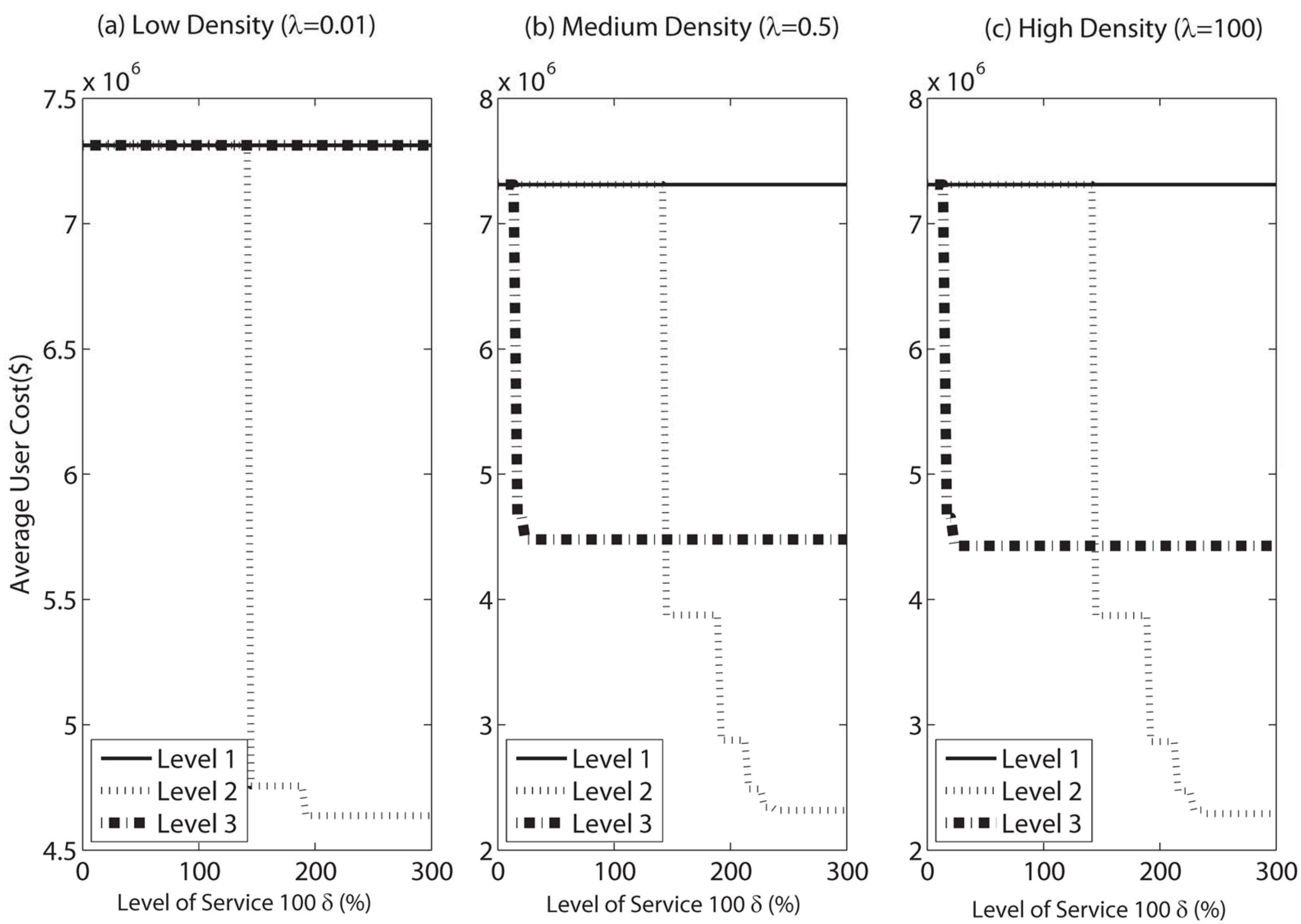
Case Study

Discrete capacity for Charging Facility



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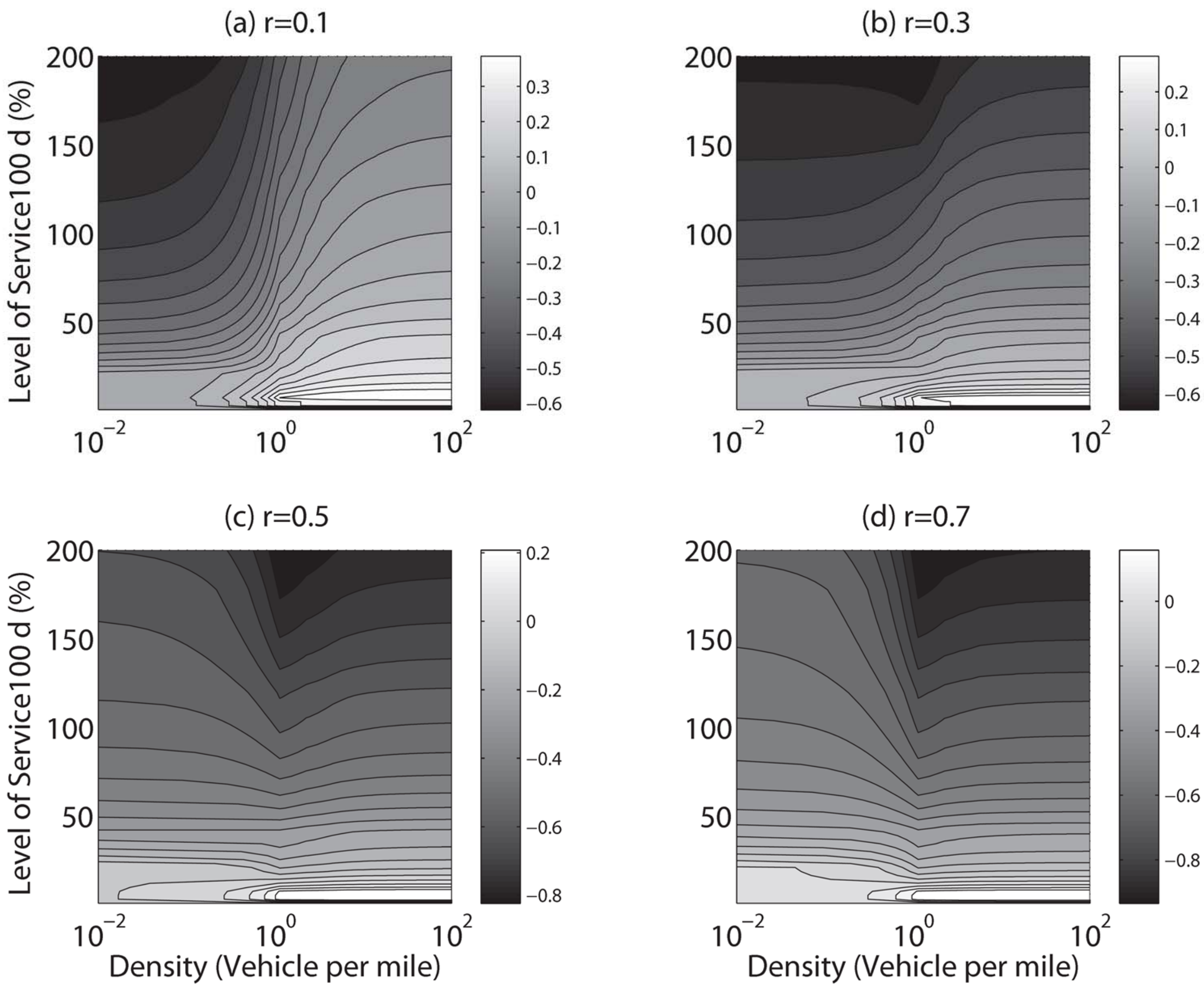
Case Study

Battery Swapping



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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.

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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?

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Case Study

Parameters values

Parameter	Description	Unit	Value
l	Corridor length	$mile$	150
f	Average trip frequency	$\frac{trip}{day}$	0.13
λ	EV fleet density	$\frac{vehicle}{mile}$	0.5
α	Energy Efficiency (Converting energy/Power ratio to charging time)	-	1.3
β	Battery performance	$\frac{mile}{kwh}$	2.5
δ	Delay tolerance	-	15%
A_0	Minimum construction area	sqf	2000
a_0	Per spot construction area	sqf	300
C_a	Unit construction cost for new stations (charging or swapping)	$\frac{\$}{sqf}$	104
	Unit construction cost for existing charging stations	$\frac{\$}{sqf}$	20
C_e	Unit manufacturing cost of battery	$\frac{\$}{kwh}$	650
C_s	Per spot construction cost of charging outlet	$\frac{\$}{kw}$	500
θ	Range tolerance (Confident range)	-	0.8

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Energy Efficiency

Vehicle Type	E (kWh)	I (amp)	v (V)	P(kW)	E/P (h)	t_r (h)	α
BMW Mini E	35	12	110	1.32	27	26.00	0.98
		32	240	7.68	5	4.50	0.99
		48	240	11.52	3	3.00	1.00
Chevy Volt	16	12	120	1.44	11	10.00	0.90
		20	240	4.8	3	4.00	1.20
Ford Focus EV	23	20	230	4.6	5	7.00	1.40
Mitsubishi iMiEV	16	12	110	1.32	12	12.50	1.03
		20	220	4.4	4	7.00	1.93
		60	480	28.8	0.6	2.50	4.50
Nissan LEAF	24	20	220	4.4	5	8.00	1.47
		60	480	28.8	0.8	0.60	0.72
Volvo C30	24	16	230	3.7	7	8.00	1.23
Toyota PRIUS	1.34	12	110	1.32	1.0	3.00	2.96
		20	200	4	0.3	1.67	4.98

I - electric current; E - battery energy; V - electric potential; P - power.

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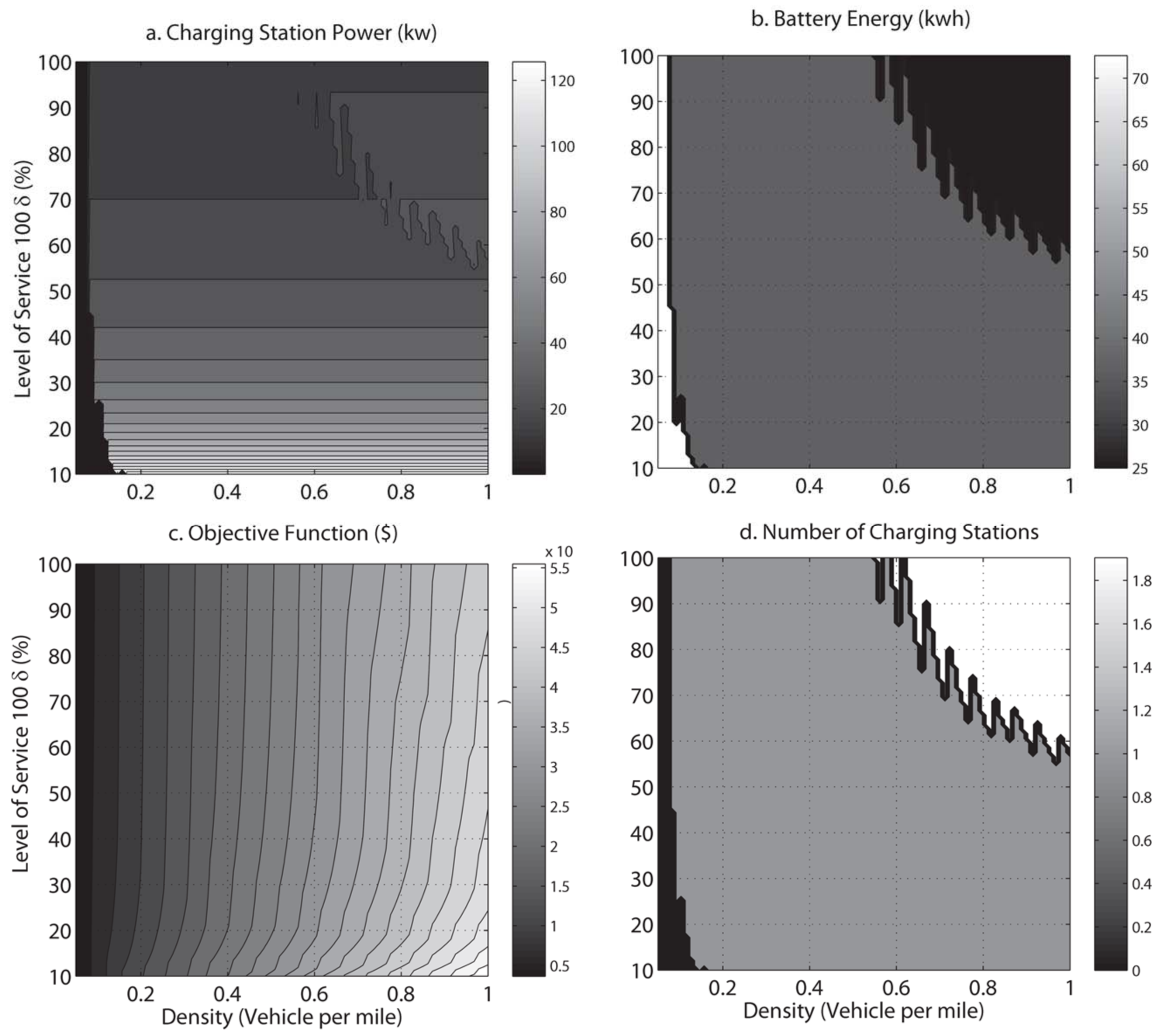
Case Study

Station construction cost



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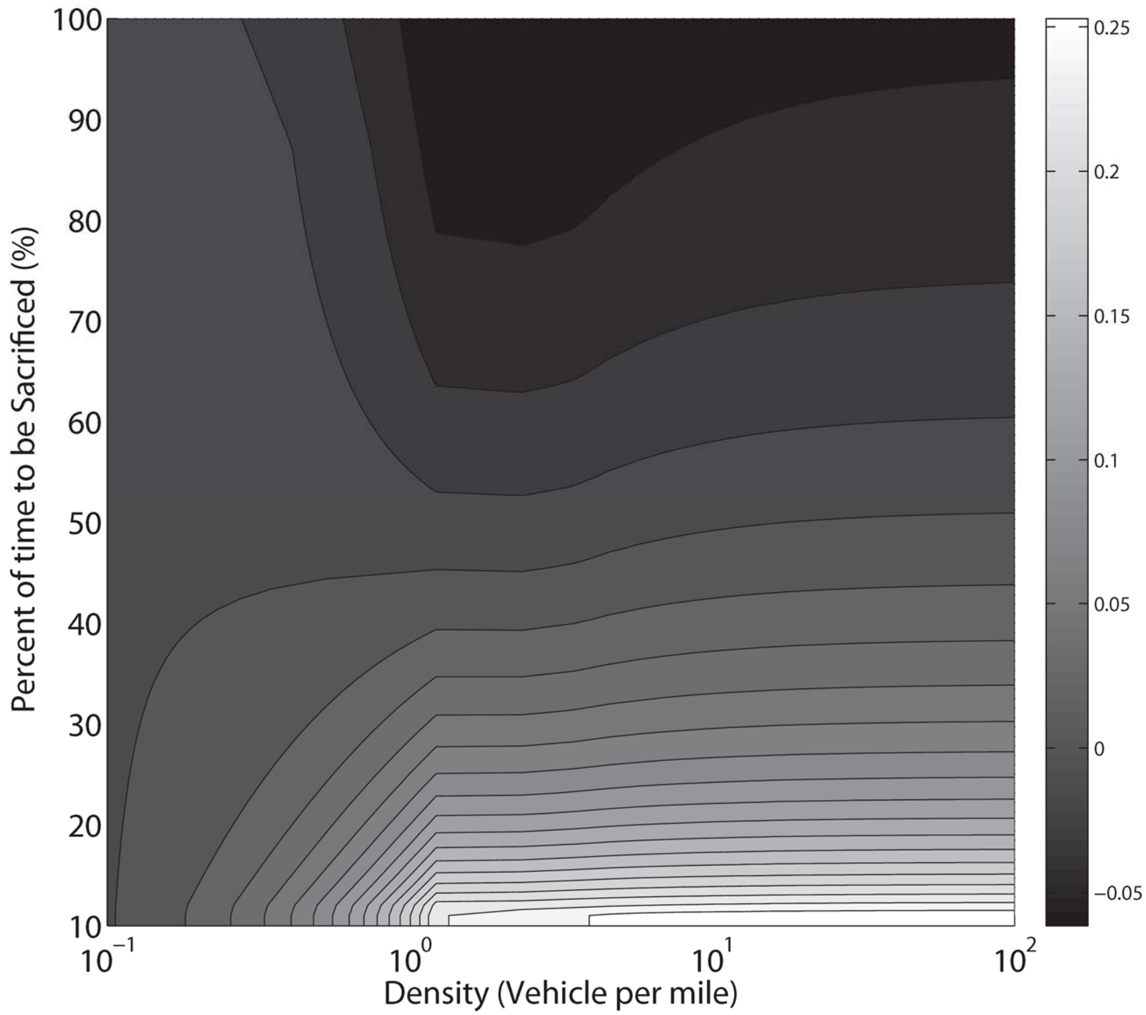
Case Study

Station construction cost



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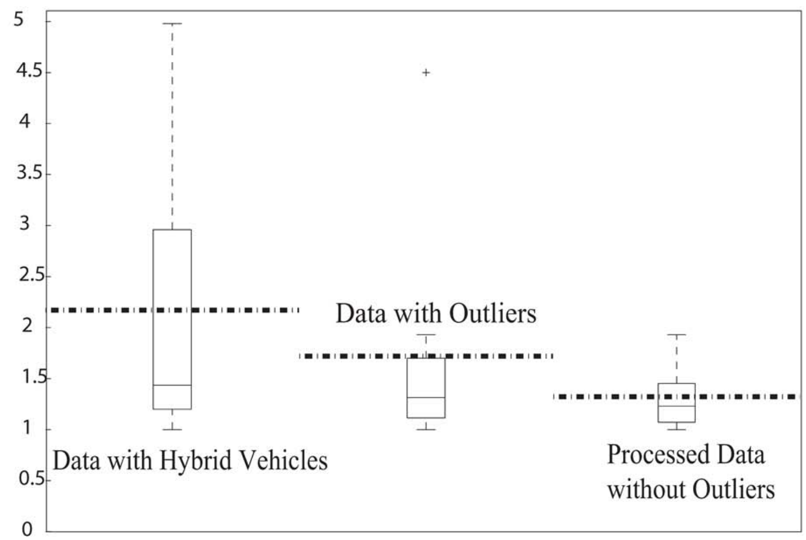
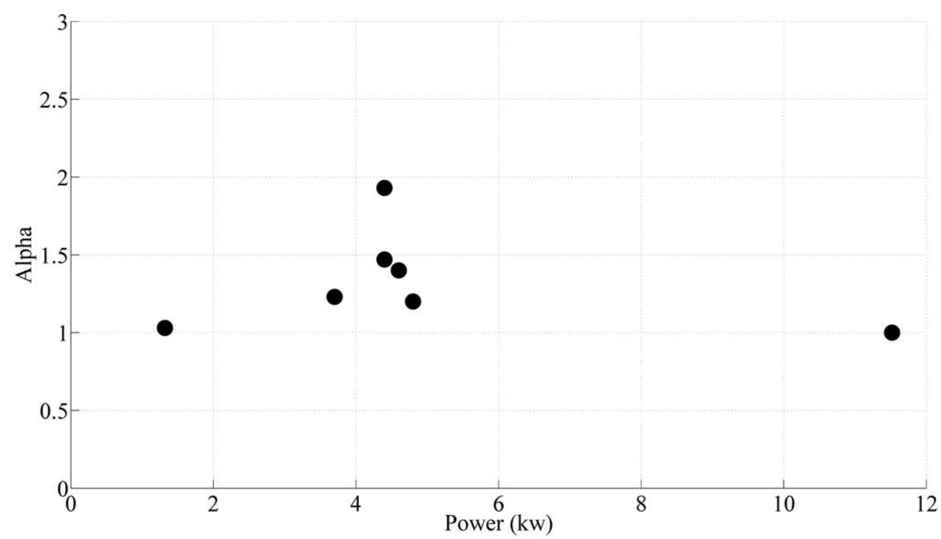
Case Study

Energy Efficiency



(a) Box plots for determining battery charging efficiency



(b) Recharging efficiency changes with power

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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.

U.S. Department of Energy (Electric Vehicle Operation Program, 1999)

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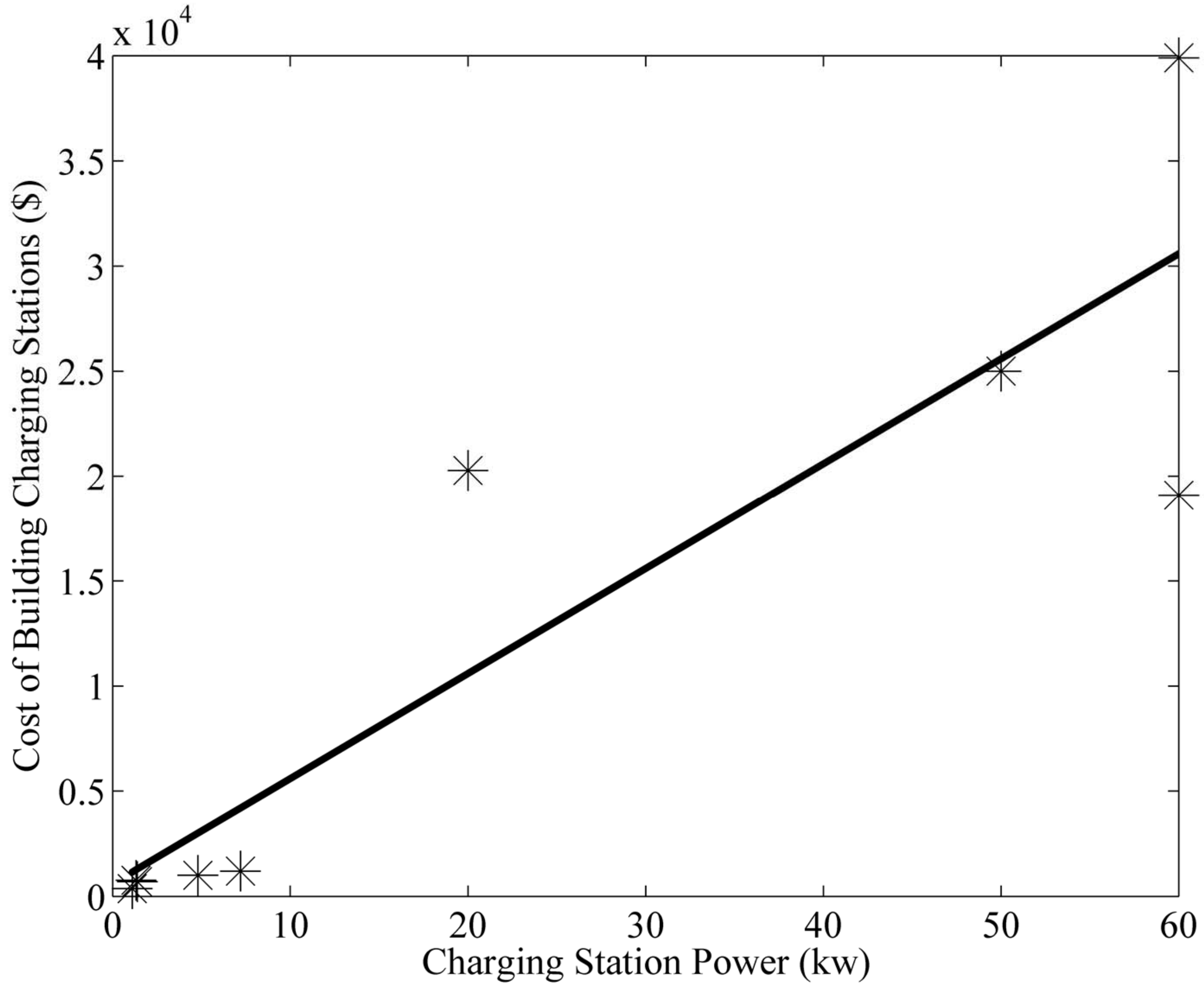
Power Cost Relation



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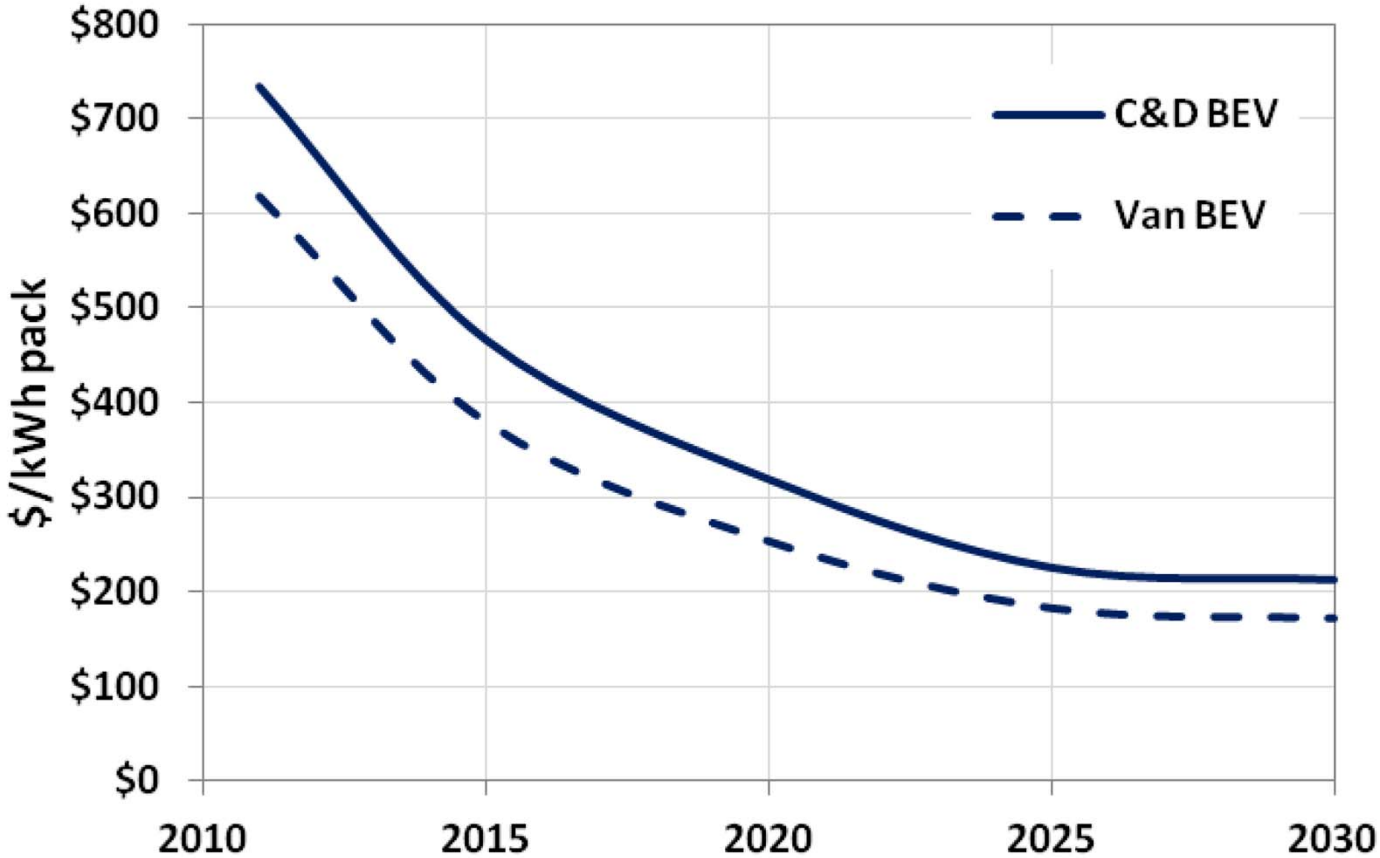
Power Cost Relation



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

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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*)

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