Service Region Design for Urban Electric Vehicle Sharing Systems

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Outline

• Background
• Service Region Design Problem
  – Mathematical Modeling
• Case Study: Car2Go@San Diego
• Conclusion
Booming Sharing Economy

• How was your last vacation?
  – How long were you away?
  – What did you do with your house?
    • Airbnb hosts in SF: US$160 per night
  – Your car?
    • RelayRides users: US$250-1000 per month
  – ......

• Emerging market
  – Uber: $40 billion valuation
  – Airbnb: $13 billion
Shared Mobility Systems

- Platforms that allow users to access mobility means without ownership via sharing
- Prevalent business models:

![Diagram showing different modes of shared mobility systems including RelayRides, Uber, Lyft, Enterprise, zipcar, and CAR2GO.]
Modes of Car Sharing

**ZipCar**

- Specified locations
- Stations
- Round trips

**Car2Go**

- Any street parking
- Service region
- Round trips and One-way trips
One-Way Car Sharing: Benefits

- Substantial demand for one-way trips

- Natural complement for public transit
  - In Brooklyn NY, busiest stop near G line subway stations
Car Sharing and Sustainability

- Clean energy in transportation
  - Accounts for 70% of US oil use, 28% of GHG emissions
  - Electric, hybrid, fuel cell vehicles......

- Car sharing
  - Reduces 0.23 cars per household
  - 23mpg (own) → 33mpg (sharing)

- Electric vehicle goals
  - US: 1 million by 2015 (26% reached)
  - China: 5 million by 2020 (1.5% reached)
Buying vs. Sharing Electric Vehicles

• Characteristics of EVs
  – High fixed costs (US$10,000 above gasoline counterpart)
  – Low variable costs (US$4 vs. US$12 per 100 miles)
  – Long recharging times
  – Resale anxiety [Lim et al. 2015]

• Benefits of EV sharing
  – Sharing of fixed costs (pooling)
  – Charging managed by company

• Challenges of EV sharing
  – Lower utilization due to charging times
Our Objective

• Develop analytics solution for service region design of one-way car sharing (with EVs), integrating:
  – Adoption behavior & associated planning uncertainty
  – Operational characteristics under imbalanced demand

• Calibrate models to real data, with:
  – Operations data from Car2Go San Diego
  – Various data sources, e.g., US Department of Transportation & Department of Energy
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• Motivation

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• Conclusion
Fundamental Trade-off: More vs. Less Coverage

- More imbalanced demand
- Larger fleet size
- Higher setup (infrastructure) cost
- More travel needs covered
- Higher value of covering other locations

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Service Region Design for EV Sharing Systems
Service Region Design

\[
\begin{align*}
\text{max} & \quad \sum_{i \in I} fQ_i q_i(\mathbf{x}) - \sum_{i \in I} g_i x_i + \Theta(x_i, q_i(\mathbf{x}), \alpha) \\
\text{subject to} & \quad x_i \in \{0, 1\}\quad \forall i \in I
\end{align*}
\]

- Membership revenue
- Fixed costs
- Operational profit

\[
\begin{align*}
x_1 &= 1 \\
x_2 &= 1 \\
x_3 &= 0 \\
x_4 &= 0 \\
x_5 &= 0 \\
x_6 &= 0 \\
x_{10} &= 0
\end{align*}
\]
Repositioning and Charging

- Closed networks are hard to analyze due to dependence of arrivals & departures.
- Fixed population mean (FPM) approximation → Open network [Whitt, MS]

Closed Queueing Network
Repositioning and Charging

- Closed networks are hard to analyze due to dependence of arrivals & departures
- Fixed population mean (FPM) approximation → Open network [Whitt, MS]

Open Queueing Network
Operational Profit Model

- Departure to charging station in region $i$: $\lambda_i = \sum_{j \in J} \mu_j q_j P_{ji} P_c$

- Calculate fleet size via fixed population mean (FPM) approximation.

$$\sum_{j \in I} \sum_{i \in I} t_{ij} \Lambda_i P_{ij} + \sum_{i \in I} L_i x_i + \sum_{i \in I} \lambda_i t_c + \sum_{i \in I} \sum_{m \in I} \sum_{j \in I} \tau_{mj} \phi_{imj} \leq N$$

  - EVs serving customers
  - EVs waiting
  - EVs in charging
  - EVs in repositioning

- Operational profit

$$\Theta(x_i, q_i, \alpha) = \sum_{j \in I} \sum_{i \in I} r t_{ij} \Lambda_i P_{ij} - \sum_{i \in I} c t_c \lambda_i - \sum_{i \in I} \sum_{j \in I} \sum_{m \in I} \eta \tau_{jm} \phi_{ijm} - hN$$

  - Usage-based revenue
  - Charging cost
  - Repositioning cost
  - EV investment
Fundamental Trade-off: More vs. Less Coverage

- More imbalanced demand
- Larger fleet size
- Higher setup (infrastructure) cost

- More travel needs covered
- Higher value of covering other locations
Customer Adoption

Utility of serving dest. $j$ for a cust. in $i$

Aspiration level

\[ \sum_{j \in I} a_{ij} x_j \geq b \]

Binary coverage decision variable

\[ \sum_{j \in I} a_{ij} x_j \leq b \]
Customer Adoption

• Adoption decision for an individual customer in region $i$:

$$1\left( \sum_{j \in I} a_{ij} x_j \geq b \right)$$

• $a_{ij}$ is heterogeneous among customers and uncertain to planner

• Adoption rate of customers in region $i$:

$$q_i = \mathbb{E}\left[1\left( \sum_{j \in I} a_{ij} x_j \geq b \right)\right]$$

$$= \text{Prob}\left( \sum_{j \in I} a_{ij} x_j \geq b \right)$$
Customer Adoption

- $a_{ij}$ depends on travel pattern of customers
  - Highly heterogeneous within population
  - Uncertain to planner

- "One-shot" decision problem

- Estimations for $a_{ij}$ using limited data
  - Operational data from other cities
  - Pilot testing data
  - Travel survey data

Robustness is Crucial
Distributionally-Robust Optimization

Enlarged ambiguity set where true distribution may reside within

Data

Consider worst case in ambiguity set

Statistical estimation

Not perfectly reliable

Optimization
Robust Optimization

- Worst case of customer adoption rate in region $i$:

$$q_i \leq \inf_{\rho \in \mathcal{P}} \text{Prob} \left( \sum_{j \in I} a_{ij} x_j \geq b \right)$$

Given mean, covariance of nonnegative $a_{ij}$

Copositive Cone Constraints

Semi-definite Constraints

Copositive Cone

$$\mathcal{CO}_n := \{ A \in S_n | \forall \mathbf{v} \in \mathbb{R}_+^n, \mathbf{v}^T A \mathbf{v} \geq 0 \}$$

Second-order Cone Constraints
Integrated Formulation

\[
\max_{q_i, x_i, N} \sum_{i \in I} fQ_i q_i - \sum_{i \in I} g_i x_i + \sum_{j \in I} \sum_{i \in I} r_{t_{ij}} \Lambda_i P_{ij} - \sum_{i \in I} c_t \lambda_i - \sum_{i \in I} \sum_{j \in I} \sum_{m \in I} \eta \tau_{jm} \phi_{ijm} - hN
\]

s.t.

\[q_i \leq \inf \text{Prob} (\sum_{j \in I} a_{ij} x_j \geq b), \forall i \in I\]

\[q_i \leq x_i, \forall i \in I\]

\[\Lambda_i = \lambda_i + \sum_{j \in I} \Lambda_j P_{ji} (1 - P_c) - \sum_{j \in I} \sum_{l \in I} \phi_{jil} + \sum_{j \in I} \sum_{m \in I} \phi_{jmi}, \forall i \in I\]

\[\sum_{l \in I} \phi_{jil} \leq \Lambda_j P_{ji} (1 - P_c), \forall i \in I, j \in I\]

\[\Lambda_i \geq \alpha \mu_i q_i, \forall i \in I\]

\[\Lambda_i \leq \mu_i q_i, \forall i \in I\]

\[\lambda_i = \sum_{j \in J} \mu_j q_j P_{ji} P_c, \forall i \in I\]

\[\sum_{j \in I} \sum_{i \in I} t_{ij} \Lambda_i P_{ij} + \sum_{i \in I} L_i x_i + \sum_{i \in I} \lambda_i t_c + \sum_{i \in I} \sum_{m \in I} \sum_{j \in J} \tau_{m} \phi_{imj} \leq N\]

\[\Lambda_i \geq 0, \forall i \in I\]

\[\phi_{ikj} \geq 0, \forall i \in I, k \in I, j \in I\]

\[x_i \in \{0, 1\}, \forall i \in I\]
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Car2Go@San Diego
Operations Data from Car2Go Website

- 1-month time-stamp record of idle EVs at 5-minute level.
- Time, location, battery levels and charging status.
- 25,875 trips with 379 EVs identified.

![Example screenshot of Car2Go data](image.png)

<table>
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<tr>
<th>Name</th>
<th>Address</th>
<th>TimeGMT+8</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Fuel</th>
<th>Charging Status</th>
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</table>
Other Data Sets

- 2010 American Community Survey and ArcGIS
  - Census data at zip code level with population and income.
  - Travel distances and times between regions based on road network.

- 2010 California Household Travel Survey (CHTS)
  - Households, persons and places tables with age, income, zip codes and travel modes.
  - 1999 sample working population with 5,335 trips by car.

- EV charging station data from U.S. Department of Energy
  - Location, zip code, charger number and charging network (“Blink”)

<table>
<thead>
<tr>
<th>Mode</th>
<th>2010-2012 Mode Share</th>
<th>2000 Mode Share</th>
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</thead>
<tbody>
<tr>
<td>Auto/Van/Truck Driver</td>
<td>49.3%</td>
<td>60.2%</td>
</tr>
<tr>
<td>Auto/Van/Truck Passenger</td>
<td>25.9%</td>
<td>25.9%</td>
</tr>
<tr>
<td>Walk Trips</td>
<td>16.0%</td>
<td>8.4%</td>
</tr>
<tr>
<td>Public Transportation Trips</td>
<td>4.4%</td>
<td>2.2%</td>
</tr>
<tr>
<td>Bicycle Trips</td>
<td>1.5%</td>
<td>0.9%</td>
</tr>
<tr>
<td>Private Transportation Trips</td>
<td>0.6%</td>
<td></td>
</tr>
<tr>
<td>School Bus Trips</td>
<td>0.6%</td>
<td></td>
</tr>
<tr>
<td>Carpool/Vanpool</td>
<td>0.6%</td>
<td></td>
</tr>
<tr>
<td>All Other</td>
<td>0.5%</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100.0%</strong></td>
<td><strong>100.0%</strong></td>
</tr>
</tbody>
</table>
Integrating Model and Data

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Service Region Design for EV Sharing Systems

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DOE: charging stations density

Car2go data & ACS: gravity model estimation for moments

CHTS: clustering mode choice patterns

From other data sources & Car2go policy:
- Charging frequency, battery capacity, charging times
- Per-minute prices, membership fees, charging costs
- Fleet cost
- .......

Car2go data & GIS network: trip & repositioning durations

$$\max \sum_{i \in I} fQ_iq_i - \sum_{i \in I} g_ix_i + \sum_{j \in I} \sum_{i \in I} rt_{ij} \Lambda_i P_{ij} - \sum_{i \in I} ct_i \lambda_i - \sum_{i \in I} \sum_{m \in I} \sum_{j \in I} \eta \tau_{jm} \phi_{ijm} - hN$$

subject to

$$q_i \leq \inf \text{Prob}(\sum_{j \in I} \hat{a}_{ij} x_J \geq b), \forall i \in I$$

$$P_c - \sum_{j \in I} \sum_{l \in I} \phi_{jl} \leq P_c, \forall i \in I, j \in I$$

$$\sum_{j \in I} \sum_{i \in I} t_{ij} \Lambda_i P_{ij} + \sum_{i \in I} L_i x_i + \sum_{i \in I} \lambda_i t_c + \sum_{i \in I} \sum_{m \in I} \sum_{j \in I} \tau_{mj} \phi_{imj} \leq N$$
Optimal Service Region

Current Facts
Selected Zip codes: 18
Pop coverage: 32.57%
Fleet size: 379 EVs

Optimal Solution
Selected Zip codes: 33
Pop coverage: 52.96%
Fleet size: 485 EVs

With Clustering
Selected Zip codes: 38
Pop coverage: 58.72%
Fleet size: 540 EVs
Observation 1. Supporting customers’ travel needs with zero emission, deploying EV sharing service with 485 EVs gains similar CO2 emission savings from replacing 2312 gasoline cars with EV ownership.
Implications of Charging Technology Advances

**Observation 2.** Improvement in charging technology from status quo brings significant benefit with expanded service region. For fixed service region, faster charging reduces the fleet size, e.g. EVs at charging stations. However, there exists diminishing marginal benefits in service region design.
One-way vs. Round-trip

Observation 3. One-way systems shows more profits with higher adoption rates than round-trip systems by serving more destinations.
Conclusion

- Car sharing: emerging business model in sharing economy
  - Potential for sustainable development with EVs

- Service region design problem
  - Adoption behavior
  - Operational characteristics

- Analytics solution: Computationally-efficient robust formulation integrated with data

- Design questions
  - Expansion opportunities
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Questions?