Growing Charging Station Networks with Trajectory Data Analytics

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Growth of Electric Vehicles

Cumulative U.S. Plug-In Vehicle Sales

BEV, PHEV & EREV Since December 2010
New sales that month

Growth of Electric Vehicles

Top-selling light-duty plug-in electric vehicle global markets
(cumulative sales through December 2016 by country/region)

- China: 645,708
- Europe: 637,552
- United States: 570,187
- Japan: 147,488
- Norway: 135,276
- The Netherlands: 113,636
- France: 108,065
- United Kingdom: 91,627
- Germany: 84,754
Charging Station Deployment

- Electric Vehicles:
  - Green transportation:
    - Switching to EVs, 42% reduction in CO₂ emissions
  - Cost efficiency:
    - Fuel (electricity) costs are much lower
- Statistics in Shenzhen, China: (by 2013/11)

<table>
<thead>
<tr>
<th></th>
<th>Gasoline Car</th>
<th>Electric Car</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refueling Time</td>
<td>3~5 minutes</td>
<td>1.5~2 hours</td>
</tr>
<tr>
<td>Kilometers</td>
<td>Around 600km</td>
<td>Around 200km</td>
</tr>
<tr>
<td>Number of cars</td>
<td>2.5 million</td>
<td>2,000 (780 EV taxis)</td>
</tr>
<tr>
<td>Gas Stations</td>
<td></td>
<td>Charging Stations</td>
</tr>
<tr>
<td>Number of stations</td>
<td>270</td>
<td>25</td>
</tr>
<tr>
<td>Seeking time</td>
<td>minutes</td>
<td>4 minutes</td>
</tr>
<tr>
<td>Waiting time</td>
<td>1 minute</td>
<td>0 ~ 1.5 hours</td>
</tr>
</tbody>
</table>
Number of public electric vehicle charging stations and charging outlets in the U.S. as of February 2016 (in units)
Current Station Geo-Distribution

Challenges

How to deploy charging stations to meet the increasing needs?
Input Data Description

• **EV Trajectory Data:**
  • **Source:** EV taxi GPS in Shenzhen
  • **Duration:** November 1st–30th, 2013.
  • **Size:** 23,967,501 GPS records of 490 EV taxis
  • **Sampling Frequency:** 40 seconds.
  • **Format:** Taxi ID, time, latitude, longitude, load

• **Road Map and Charging Station Information:**
Optimal Charging Station Deployment (OCSD)
Stage 1: Road Map Griding

- Given a side length $s=0.01^\circ$
  - 1508 grids are obtained
  - 760 grids are strongly connected by road network
Stage 1: Road Map Gridding

Why gridding?

Reasons:

- Exact locations not applicable
- Identify good candidate regions in different granularities
- Simplify problem, easy implementation in practice

Aim:

- Estimate the average travel time between grids
- To compute the shortest grid paths
Stage 1: Road Map Griding

Adjacent average travel time matrix $T$.

$$T_{ij} = \sum_{k=1}^{v_{ij}} t_{ij}(k) / v_{ij},$$

Shortest path travel time matrix $C$:

- Giant strongly connected components $G \subseteq G_0$
- Dijkstra’s or Bellman-Ford algorithm
Stage 2: Extracting sub-trajectories

- Traveling sub-trajectory
- Seeking sub-trajectory
- Charging sub-trajectory
Stage 2: Extracting sub-trajectories

• Charging sub-trajectory
  - GPS records in same location at existing station

• Seeking sub-trajectory
  1. prior to charging sub-trajectory, there is a seeking sub-trajectory
  2. Start from dropping the last passenger before the next charging

• Traveling sub-trajectory
  - other un-labeled records
Stage 2: Extracting sub-trajectories

- The spatial distribution of seeking events:
Stage 3: Optimal Station Deployment

- Problem definition:
  - Given: $L$ existing stations, Seeking event set,
    $K$ new charging stations, $M$ new charging points
  - How to deploy: Minimize the average time of an EV to find and wait at a charging station

- Two Components:
  - Optimal Charging Station Placement (OCSP)
    - Goal: Minimize the average seeking time
  - Optimal Charging Point Assignment (OCPA)
    - Goal: Minimize the average utilization of charging points
      - (proportion of time each charging point is occupied)
Stage 3-I: OCSP

- K-median Problem with Initial medians
  - Assumption: Going to the nearest charging station
  - NP-Hard Problem
Stage 3-I: OCSP

• Formulation:

\[
\min \frac{1}{W} \sum_{g_i \in G} \sum_{g_j \in G} W_i X_{ij} C_{ij} \\
\text{s.t.: } \sum_{g_j \in G} X_{ij} = 1, \\
\sum_{g_j \in G} y_j \leq K + L, \\
X_{ij} \leq y_j, \\
y_i, y_j = \{0, 1\}, \\
y_j = 1, \\
\forall g_i \in G, \forall g_i, g_j \in G, \forall g_j \in G_L
\]

Notations

\(W_i\): number of seeking events in \(g_i\)

\(X_{ij}\): 0/1 indicator representing if seeking inside \(g_i\) to \(g_j\)

\(y_i\): if \(g_i\) has charging stations

• Approximation Alg:
  • (1) LP-Relaxation
  • (2) Rounding
Stage 3-II: OCPA

Formulation:

- Each charging station is an $M/M/(S_\ell + \hat{S}_\ell)$ queue.
- Arriving rate $\lambda_\ell$: average # of per hour seeking events
- Serving rate $\mu_\ell$: average # of per hour served EVs
- Charging point utilization

\[ \rho_\ell = \frac{\lambda_\ell}{((S_\ell + \hat{S}_\ell)\mu_\ell)} \]

minimize \[ \sum_{\ell=1}^{K+L} \frac{\lambda_\ell}{(S_\ell + \hat{S}_\ell)\mu_\ell} \]

subject to:

\[ \sum_{\ell=1}^{K+L} S_\ell = M \]

Optimal Solution:

\[ S_\ell = (M + \hat{M}) \frac{\lambda_\ell}{(\mu_\ell r)} - \hat{S}_\ell \]

with $\hat{M} = \sum_{\ell=1}^{K+L} \hat{S}_\ell$

\[ r = \sum_{\ell=1}^{L+K} \frac{\lambda_\ell}{\mu_\ell} \]
Stage 3-II: OCPA

Proof: The objective in eq.(7) can be rewritten as

$$
\min \sum_{\ell=1}^{K+L} \frac{1}{(S_\ell + \hat{S}_\ell) \mu_\ell / \lambda_\ell}
$$

Arithmetic-Harmonic Means Inequality [10] in eq.(9) holds

$$
\frac{a_1 + \cdots + a_n}{n} \geq \frac{1}{\frac{1}{a_1} + \cdots + \frac{1}{a_n}},
$$

where the equality holds if and only if $a_1 = \cdots = a_n$. We apply the inequality eq.(9) to eq.(8), and obtain

$$
\sum_{\ell=1}^{K+L} \frac{1}{(S_\ell + \hat{S}_\ell) \mu_\ell / \lambda_\ell} \geq \frac{(K + L)^2}{\sum_{\ell=1}^{K+L} (S_\ell + \hat{S}_\ell) \mu_\ell / \lambda_\ell},
$$

where the equality is attained with $S_\ell = (M + \hat{M}) r_\ell - \hat{S}_\ell$. ■
Evaluation

- Charging station placement
  - Baselines
    - Rand-SP: Random station placement
    - Top: Top seeking events
  - OCSP algorithm
- Charging point assignment
  - Baselines
    - Rand-PA: Random point assignment
    - Aver.: Average charging point assignment
  - OCPA algorithm
Average Seeking & Waiting Time

Average Seeking Time:

26%–94% reduction rate

Average Waiting Time:

2.5 to 25 times reduction
More evaluation
Current Geo-Distribution

- Ave Seeking Time: 213s
- Ave Waiting Time: 928s (15min)

Redeployment

- Ave Seeking Time: 110s
- Ave Waiting Time: 11s
Fig. 16. Geo-distributions of seeking events in three periods. The last subfigure presents the geo-distribution of rush-hour arrival rates in Nov. 2013.
Discussions

Charging Point Assignment using Rush-Hour Demands

- Long waiting time occur at rush hour
- using \( \lambda_{\ell}^{max} := \max_t \lambda_{\ell}^{(t)} \) as the maximum arriving rate

\[
\min_s \sum_{\ell=1}^{K+L} \frac{\lambda_{\ell}^{max}}{(S_{\ell} + \hat{S}_{\ell}) \mu_{\ell}} \quad \text{s.t.:} \quad \sum_{\ell=1}^{K+L} S_{\ell} = M.
\]

- Same results
Discussions

Time-Varying Seeking Policy

- Always go to the nearest charging station (assumption)
- linear combination of OCSP and OCPA
- trade-off parameter $\theta$

\[
\begin{align*}
\min & : \sum_{t=1}^{t_{max}} \sum_{g_j \in G} \left( \sum_{g_i \in G} \frac{W_i(t)}{W} X_{ij}^{(t)} C_{ij} + \frac{\theta \lambda_j^{(t)}}{(S_j + \hat{S}_j) \mu_j^{(t)}} \right) \\
\text{s.t.:} & \sum_{g_j \in G} X_{ij}^{(t)} = 1, \quad \forall g_i \in G, t \in [1, t_{max}] \\
& \sum_{g_j \in G} y_j \leq K + L, \\
& X_{ij}^{(t)} \leq y_j, \quad \forall g_i, g_j \in G, t \in [1, t_{max}] \\
& X_{ij}^{(t)}, y_j = \{0, 1\}, \quad \forall g_i, g_j \in G, t \in [1, t_{max}] \\
& y_j = 1, \quad \forall g_j \in G_L \\
& \sum_{g_j \in G} S_j = M, \quad \forall g_j \in G_L
\end{align*}
\]
Discussions

Time-Varying Seeking Policy
- Always go to the nearest charging station (assumption)
- Linear combination of OCSP and OCPA
- Trade-off parameter $\theta$

Result:
- Not much difference

Possible reason:
- Number of charging stations is far away of sufficient
- Primary concern is distance, stations are busy anyway
Conclusions

Contribution:

- Study how to deploy charging stations and charging points to minimize the time of whole charging activity.
- Develop a data-driven optimal charging stations deployment framework, including OCSP and OCPA.
- Evaluate the framework and the performance is great.

Also answers:

"Super or small stations"?

If there are sufficient charging points, small stations are preferred. if there are not, super stations is a wiser choice.
Questions?

For more information:

http://wpi.edu/~yli15/