Bicycle-Sharing System Expansion: Station Re-Deployment through Crowd Planning

Jiawei Zhang\textsuperscript{1}, Xiao Pan\textsuperscript{2}, Moyin Li\textsuperscript{1}, Philip S. Yu\textsuperscript{1,3}

\textsuperscript{1}University of Illinois at Chicago, Chicago, IL, USA
\textsuperscript{2}Shijiazhuang Tiedao University, Shijiazhuang, Hebei, China
\textsuperscript{3}Institute for Data Science, Tsinghua University, Beijing, China
Big cities need public bicycle-sharing systems to alleviate traffic congestion.

Amount of space required to transport the same number of passengers by car, bus, or bicycle.


(Des Moines, Iowa - August 2010)
Bicycle-sharing systems are launched in many big cities and keep expanding.
Problem Studied: Bicycle-sharing system expansion via crowdsourcing

Expansion Plan

Crowd Suggestions

Divvy

SUGGEST A LOCATION
Bicycle-sharing system expansion actions

• Actions performed in expansion
  • Stations
    • *add* new stations
    • *remove* existing stations,
    • *move* existing stations to a new place (remove it first, and add it again)
  • Bikes
    • *add* new bike docks
    • *remove* existing bike docks
Bicycle-sharing system expansion objective

- Prior to expansion: service provider determines the target expansion size (# stations $K$, # bikes $C$)
- Expansion objective
  - maximize the usage convenience for customers
  - minimize the cost involved in the expansion
Bicycle-sharing system expansion objective

- Prior to expansion: service provider determines the target expansion size (number of stations $K$, number of bikes $C$)

- Expansion objective
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Objective Optimization Function

$$\begin{align*}
S_F^* &= \arg \max_{S_F} \text{convenience}(S_F) - \beta \cdot \text{cost}(S_F) \\
\text{s.t. } |S_F| &= K, \sum_{s \in S_F} \text{capacity}(s) = C
\end{align*}$$

optimal stations and bikes after expansion
Proposed Method: CrowdPlanning

- CrowdPlanning: two-phase planning method

- **Step 1**: Station Planning (i.e., station location determination)
  - usage convenience
    - current station convenience: historical trips
    - future station convenience: crowd suggestions
  - cost in adding/removing/adjusting bike stations
Proposed Method: CrowdPlanning

• CrowdPlanning: two-phase planning method

• **Step 1: Station Planning (i.e., station location determination)**
  • usage convenience
    • current station convenience: historical trips
    • future station convenience: crowd suggestions
  • cost in adding/removing/adjusting bike stations

• **Step 2: Station Capacity Planning (i.e., bike assignment)**
  • usage convenience
    • current bike number: historical trips
    • future bike number: crowd suggestions
  • cost in adding/removing bikes from existing stations
Step 1: Station Planning

- Usage convenience based on crowd suggestions

\[
\text{convenience}_{c}(S_F) = \sum_{g_i \in G} y(g_i)
\]

\[
s.t. \; y(g_i) \geq y(g_j) \quad \text{if} \quad |\Gamma_{H}(g_i)| \geq |\Gamma_{H}(g_j)| \quad \forall g_i, g_j \in G
\]

\{0, 1\} has stations in the cell

crowd suggestions at the cell

service region grid cells
Step 1: Station Planning

- Usage convenience based on historical trip records
  - frequently used existing stations are more likely to be preserved in the expansion
Step 1: Station Planning

- Usage convenience based on historical trip records
  - frequently used existing stations are more likely to be preserved in the expansion
  - existing station preserving probability

\[ P(g_i) = \frac{e^{k|\Gamma_T(g_i)|}}{1 + e^{k|\Gamma_T(g_i)|}} \]  

\( P(g_i) \) is monotone

# trips start/end at the cell
Step 1: Station Planning

- Usage convenience based on **historical trip records**
  - frequently used existing stations are more likely to be preserved in the expansion
  - existing station preserving probability

\[
P(g_i) = \frac{e^{k|\Gamma T(g_i)|}}{1 + e^{k|\Gamma T(g_i)|}}
\]

- historical trip usage based convenience

\[
\text{convenience}_u(S_F) = \sum_{g_i \in G} y(g_i) \cdot P(g_i)
\]
Step 1: Station Planning

- Station deployment costs

\[
\text{cost}(g_i) = \begin{cases} 
\text{cost}^+_s, & \text{if } \bar{y}(g_i) = 0, y(g_i) = 1; \\
\text{cost}^-_s, & \text{if } \bar{y}(g_i) = 1, y(g_i) = 0; \\
0, & \text{otherwise.}
\end{cases}
\]

- No station before expansion
- One station after expansion
- No changes, no cost
Step 1: Station Planning

- Station deployment costs
  - Station adding cost

\[
\text{cost}(g_i) = \begin{cases} 
\text{cost}_s^+, & \text{if } \bar{y}(g_i) = 0, y(g_i) = 1; \\
\text{cost}_s^-, & \text{if } \bar{y}(g_i) = 1, y(g_i) = 0; \\
0, & \text{otherwise.}
\end{cases}
\]

- Overall station deployment cost

\[
\text{cost}(S_F) = \text{cost}(G) = \sum_{g_i \in G} \text{cost}(g_i) = \sum_{g_i \in G} \max\{y(g_i) - \bar{y}(g_i), 0\} \cdot \text{cost}_s^+ + \max\{\bar{y}(g_i) - y(g_i), 0\} \cdot \text{cost}_s^-.
\]
Step 1: Station Planning

- Station deployment objective function

\[
\gamma^* = \arg \max_{\gamma} \text{convenience}(S_F) - \beta \cdot \text{cost}(S_F)
\]

\[
= \arg \max_{\gamma} \sum_{g_i \in G} \left( y(g_i) + \alpha \cdot y(g_i) \cdot P(g_i) - \beta \cdot (\max\{y(g_i) - \bar{y}(g_i), 0\} \cdot \text{cost}_{s}^+ + \max\{\bar{y}(g_i) - y(g_i), 0\} \cdot \text{cost}_{s}^-) \right)
\]

\[
\sum_{g_k \in G} y(g_k) = K; y(g_k) \in \{0, 1\}, \forall g_k \in G.
\]

- Convenience terms
- Cost term
- Quantity constraint
Step 2: Bike Planning

• Bike assignment planning

  • more bikes assigned to stations with more suggestions
    \[ c(g_i) \geq c(g_j) \] if \( |\Gamma_H(g_i)| \geq |\Gamma_H(g_j)|, \forall g_i, g_j \in \tilde{G} \),

  • more bikes assigned to stations with more historical usages
    \[ c(g_i) \geq c(g_j), \text{ if } |\Gamma_T(g_i)| \geq |\Gamma_T(g_j)|, \forall g_i, g_j \in \tilde{G}. \]

  • construction cost should be as low as possible

    \[
    \text{cost}(g_i) = \begin{cases} 
    \text{cost}_d^+ \cdot (c(g_i) - \bar{c}(g_i)), & \text{if } \bar{y}(g_i) = y(g_i) = 1, c(g_i) \geq \bar{c}(g_i); \\
    \text{cost}_d^- \cdot (\bar{c}(g_i) - c(g_i)), & \text{if } \bar{y}(g_i) = y(g_i) = 1, \bar{c}(g_i) \geq c(g_i); \\
    0, & \text{otherwise.}
    \end{cases}
    \]

    \[
    \text{cost}(\tilde{G}) = \sum_{g_i \in \tilde{G}} \text{cost}(g_i)
    = \sum_{g_i \in \tilde{G}} \bar{y}(g_i) \cdot y(g_i) \cdot (\text{cost}_d^+ \cdot \max\{c(g_i) - \bar{c}(g_i), 0\} + \text{cost}_d^- \cdot \max\{\bar{c}(g_i) - c(g_i), 0\}).
    \]
Step 2: Bike Planning

- Bike assignment planning
  - objective function

\[
\min_{\{c_{g_i}\}_{g_i \in \tilde{G}}} \sum_{g_i \in \tilde{G}} \bar{y}(g_i) \cdot y(g_i) \cdot (\text{cost}_d^+ \cdot \max\{c(g_i) - \bar{c}(g_i), 0\}) \\
+ \text{cost}_d^- \cdot \max\{\bar{c}(g_i) - c(g_i), 0\})
\]

s.t. \( c(g_i) \geq c(g_j), \text{ if } |\Gamma_H(g_i)| \geq |\Gamma_H(g_j)|, \forall g_i, g_j \in \tilde{G}, \)
\( c(g_i) \geq c(g_j), \text{ if } |\Gamma_T(g_i)| \geq |\Gamma_T(g_j)|, \forall g_i, g_j \in \tilde{G}, \)
\[ \sum_{g_i \in \tilde{G}} c(g_i) = C; c(g_i) \in \mathbb{N}^+, \forall g_i \in \tilde{G}. \]
Chicago Divvy bicycle sharing system Dataset

- Divvy and crowd suggestion Datasets

<table>
<thead>
<tr>
<th>Table 1: The Divvy Datasets</th>
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<td>datasets</td>
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<tr>
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<tr>
<td>2013 Q3-Q4</td>
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<tr>
<td>2014 Q1-Q2</td>
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<tr>
<td>2014 Q3-Q4</td>
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<tr>
<td>2015 Q1-Q2</td>
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<tr>
<td>2015 Q3-Q4</td>
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</tbody>
</table>

- 179,610 bike trips per month in the past two years

- Station number increases to 474 due to the system expansion at early 2015

<table>
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<tr>
<th>Table 2: Crowd Suggestion Dataset</th>
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<tr>
<td>datasets</td>
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<td>---------</td>
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<tr>
<td>Crowd Suggestion</td>
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Chicago Divvy bicycle sharing system Dataset

- **Settings:**
  - stations after the expansion as the station redeployment ground truth.
  - Trips and suggestions received before the end of 2014 Q4 as the known information
Chicago Divvy bicycle sharing system Dataset

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  • stations after the expansion as the station redeployment ground truth.
  • Trips and suggestions received before the end of 2014 Q4 as the known information

• Comparison Methods
  • CrowdPlanning: method proposed in this paper
  • CP-NoDens: no density constraints is considered
  • CP-NoCost: no construction cost is considered
  • IMILP: existing method for station deployment only, no capacity assignment
  • OSD: extension of existing method with construction costs
  • Random: random station and bike planning
Chicago Divvy bicycle sharing system Dataset

• Settings:
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  • *OSD*: extension of existing method without construction costs
  • *Random*: random station and bike planning

• Evaluation Metrics:
  • Accuracy, Precision, Recall for station deployment
  • MSE, MAE, R2 for capacity assignment
Experiment Results

• Station Deployment Result

Figure 4: Station deployment result evaluated by Accuracy, Precision and Recall.

• Bike Capacity Assignment Result

Figure 5: Local station capacity assignment result evaluated by MSE, MAE and $R^2$. 
Summary

- **Problem Studied**: bicycle-sharing system expansion with crowd planning
  - *station redeployment*: add new stations and remove/adjust existing stations
  - *station capacity assignment*: add/remove bikes from existing bike stations

- **Proposed Method**:
  - *convenience maximization*
    - convenience of *existing* stations/bikes based on historical trip records
    - convenience of *new* stations/bikes based on crowd suggestions
  - *cost minimization*
    - cost introduced in add/removing stations and bikes
Related Works: Bicycle Sharing Systems

Bicycle-Sharing System Analysis and Trip Prediction
MDM’ 16

Bicycle-Sharing System Expansion
SIGSPATIAL’ 16

Bicycle-Sharing System Trip Route Planning
IEEE CIC’ 16

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More Opportunities
Bicycle-Sharing System Expansion: Station Re-Deployment through Crowd Planning

Q & A

Jiawei Zhang¹, Xiao Pan², Moyin Li¹, and Philip S. Yu¹
jzhan9@uic.edu· smallpx@gmail.com· mli60@uic.edu· psyu@cs.uic.edu