Incentivizing the Use of Bike Trailers for Dynamic Repositioning in Bike Sharing Systems

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Motivation: Bike Sharing System

- **Bike Sharing Systems**
  - 1,070 active systems all over the world.
  - Attractive alternative to private vehicles
  - Reduce traffic congestion, green house gas emission and air pollution.

- **Problem:** Starvation or congestion of bikes at stations
  - Increase usage of private vehicle and carbon emission.

- **Goal:** Repositioning of bikes during the day to address availability issues.

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Figure 2: Number of empty and full instances of stations in Capital Bikeshare Company

Due to a trivial reduction from existing Static Bicycle Repositioning Problem (SBRP) which is NP-Hard (Schuijbroek et al., 2013), DRRP is at least NP-Hard. Therefore, we focus on developing principled approximation methods. Our key contributions are as follows:

1. A mixed integer linear program (MILP) formulation to maximise profit for the bike sharing company that considers the trade off between:
   - Maximising served demand
   - Minimising cost incurred by vehicles

2. A dual decomposition mechanism to decompose the MILP into two components – one which computes repositioning solution for bikes and one that computes routing solutions for vehicles.
Background

- Repositioning using trucks
  - Static Redeployment - once at the end of day
  - Dynamic Redeployment - matching of producer and consumer station
- Problems with trucks for repositioning:
  - Incur substantial routing and labor costs
  - Increase carbon footprint
  - Limited number of trucks
Contributions

- Repositioning with bike-trailers – Moving beyond trucks

**Challenges:**

- Physical limitations of the routes for trailers.
- Limited budget: Employing staffs for trailer is not feasible.

**Overall Goal:**

- Develop a self-sufficient system of rebalancing using bike trailers
- Crowdsource repositioning tasks to customers within a given budget
Solution Approach

- Dynamic Routing and Repositioning Problem using Trailers (DRRPT)
  - Inputs: $\langle S, \mathcal{V}, C^#, C^*, D^#, 0, \{\sigma^0_v\}, P, F, B \rangle$
  - Outputs: Repositioning strategy for trailers & allocation of tasks

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**Solution Approach**

1. **Generate routing and repositioning tasks for the trailer**
2. **Design payment mechanism for each of the trailer tasks**
3. **Task allocation within given budget constraint**
Task Generation for Bike Trailers

\[
\min_{y^+, y^-} \sum_{k,s} L_k^s
\]

Minimise Lost demand over k scenarios

**Constraints:**

- Compute lost demand

\[
s.t. \quad L_k^s \geq \sum_{s'} F_{s,s'}^k - \left( d^# + \sum_v \left( y_{s,v}^- - y_{s,v}^- \right) \right), \forall k, s
\]

Lost Demand = 6 - 4 = 2
Task Generation for Bike Trailers

\[
\min_{y^+, y^-} \sum_{k,s} L^k_s 
\]

Constraints:
- Compute lost demand
- Trailer should pickup bikes from the neighbor of its origin station
Task Generation for Bike Trailers

\[
\min_{y^+, y^-} \sum_{k,s} L^k_s
\]

Minimise Lost demand over k scenarios

**Constraints:**

- Compute lost demand
- Trailer should pickup bikes from the neighbor of it origin station
- Trailer should drop-off exact number of bikes at its destination
  - While satisfies the physical limitation of the trailer routes
Solution Approach

1. Generate routing and repositioning tasks for the trailer
2. Design payment mechanism for each of the trailer tasks
3. Task allocation within given budget constraint
Mechanism Design

- Compute the value for task of trailer $v$

$$U(v) = \frac{\xi}{K} \sum_{k,s} \left[ \min \left( \max \left( \sum_{s'} F_{s,s'}^k - d^#, 0 \right), y_{s,v}^+ \right) - \min \left( \max \left( y_{s,v}^-, (d^# - \sum_{s'} F_{s,s'}^k), 0 \right), y_{s,v}^- \right) \right]$$

**Assumption:** Set of bidders for different tasks are pairwise disjoint

**Observation:** Tasks are primarily independent but coupled by the central budget constraint.
Mechanism Design

- Mechanism for single task $\nu$ ($N_\nu$ users bid for the task):
  - Collect the bids from user $i$, $C_i(\nu)$ privately
  - Make payment using standard VCG mechanism

$$
\lambda_i^*(\nu) = \begin{cases} 
1 & \text{if } i = \arg\max_{j \in N_\nu} [U(\nu) - C_j(\nu)] \\
0 & \text{Otherwise}
\end{cases}
$$

$$
P_i(\nu) = \lambda_i^*(\nu) \left[ \min_{i \neq j} C_j(\nu) \right]
$$

Second lowest bid

- Example:
  - $\lambda_1^*(\nu) = 1$ (highest bid)
  - $\lambda_2^*(\nu) = 0$ (lowest bid)
  - $\lambda_3^*(\nu) = 0$ (second lowest bid)

- Payments:
  - $P_1(\nu) = \lambda_1^*(\nu) \times \min C_j(\nu) = 1 \times \$12$
  - $P_2(\nu) = \lambda_2^*(\nu) \times \min C_j(\nu) = 0 \times \$12 = \$0$
  - $P_3(\nu) = \lambda_3^*(\nu) \times \min C_j(\nu) = 0 \times \$12 = \$0$

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Solution Approach

1. Generate routing and repositioning tasks for the trailer
2. Design payment mechanism for each of the trailer tasks
3. Task allocation within given budget constraint
Task Allocation within Budget Constraint

- Goal: Allocate a set of tasks $\mathcal{T} = \{1, \ldots, \mathcal{V}\}$, each having a valuation of $U(v)$ and payment of $P(v)$, within a central budget $B$.

- Exactly equivalent to binary knapsack problem
  - $x(v)$: Set to 1 if task $v$ is allocated the payment and 0 otherwise.

\[
\begin{align*}
\max_x & \quad \sum_{v \in \mathcal{T}} x(v) \cdot U(v) \\
\text{s.t.} & \quad \sum_{v \in \mathcal{T}} x(v) \cdot P(v) \leq B
\end{align*}
\]

Maximise the total valuation of center

Ensure that the total payment is bounded by the central budget

**Proposition:** The mechanism for task allocation for the trailers in bike sharing system is incentive compatible (IC) and truthful.
Experimental Setup

- **Dataset:**
  - Hubway (95 base stations & 3 vehicles)
    - 1 quarter of trip history data
    - Planning period: 6AM-12PM (each decision epoch is 30 minutes)

- **Demand Scenarios:**
  - Real-world data for 60 weekdays (Training/Testing: 20/40)
  - Demand follows Poission at origin station (Training/Testing: 30/70)
  - Demand follows Poission for each OD pair (Training/Testing: 30/70)

- **Evaluation Metrics:** Average lost demand over testing scenarios

- **Benchmark approaches:**
  - Static repositioning: Redeployment at the end of day
  - Online repositioning using truck: Adapted from Ghosh et. al., 2016
Experimental Results

- Effect of bidding parameters on lost demand (LD)
  - Hourly Budget
  - % of users interested in bidding
  - Ratio of lower and upper bounds of bid (α)

- Performance comparison with the benchmark approaches
  - Reduction in expected lost demand over three sets of demand scenarios.

Runtime performance.
Experimental Results

- Effect of bidding parameters on lost demand (LD)
  - Hourly Budget: LD decreases as the budget increases
Experimental Results

- Effect of bidding parameters on lost demand (LD)
  - % of users interested in bidding: LD decreases as number of bids increases.
Experimental Results

- Effect of bidding parameters on lost demand (LD)
  - Ratio of lower and upper bounds of bid ($\alpha$): LD increases monotonically with $\alpha$

![Effect of $\alpha$]

Effect of $\alpha$

- # Lost Demand
- $\alpha$ values: 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9
- LD increases monotonically with $\alpha$
Experimental Results

- **Performance comparison**
  - 10 trailers with capacity 3 reduces the lost demand by 41%
  - 10 trailers with capacity 5 perform better than repositioning with 3 vehicles
Experimental Results

- **Runtime Comparison:**
  - Runtime for the repositioning problem of trucks is around 15 minutes for each decision epoch.
  - Tasks for the trailers can be generated within a minute

(Cumulative) Runtime Comparison

![Cumulative Runtime Comparison Graph](graph.png)
Summary

- Dynamic Routing & Repositioning Problem using Bike-Trailers
  - Self-sustaining and green mode of repositioning
  - We propose a unique combination of optimization and mechanism design to crowdsourse the trailer tasks.
  - Experimental results show that trailers can replace the trucks.

- Future Direction:
  - Develop mechanism by considering the uncertainties in completion time of the trailer tasks.
  - Jointly consider the repositioning problem of trucks and trailers while considering the central budget constraints.
Q & A

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Supplementary Slides
### Task Generation: DRRPT

**Objective:**

\[
\min_y \sum_{s,k} L_s^k
\]

**Subject to:**

\[
L_s^k \geq \sum_{s'} F_{s,s'}^k - (d_s^{\#}, t + \sum_v (y_{s,v}^- - y_{s,v}^+)) \quad \forall k, s
\]

1. **Pickup restrictions by a trailer from a station:**
   \[
y_{s,v}^+ \leq b_{s,v}^+ \cdot \min(d_s^{\#}, t, C_v^*), \quad \forall s, v
\]

2. **Drop-off restrictions by a trailer at a station:**
   \[
   \sum_v y_{s,v}^- \leq C_s^\#, - d_s^{\#}, t, \quad \forall s
   \]

3. **Physical limitations of trailer route:**
   \[
   (b_{s,v}^+ + b_{s',v}^- - 1) \cdot P_{s,s'} \leq P_{max} \quad \forall s, v
   \]

4. **Trailer should pick up from one station and drop-off at other station:**
   \[
   \sum_s b_{s,v}^+ = 1, \quad \forall v
   \]

   \[
   \sum_{s \notin G_v} b_{s,v}^+ = 0, \quad \forall v
   \]

   \[
   \sum_s b_{s,v}^- = 1, \quad \forall v
   \]

5. **Variables:**

   \[
   b_{s,v}^+, b_{s,v}^- \in \{0, 1\}, \quad 0 \leq y_{s,v}^+, y_{s,v}^- \leq C_v^*, \quad L_s^k \geq 0
   \]