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

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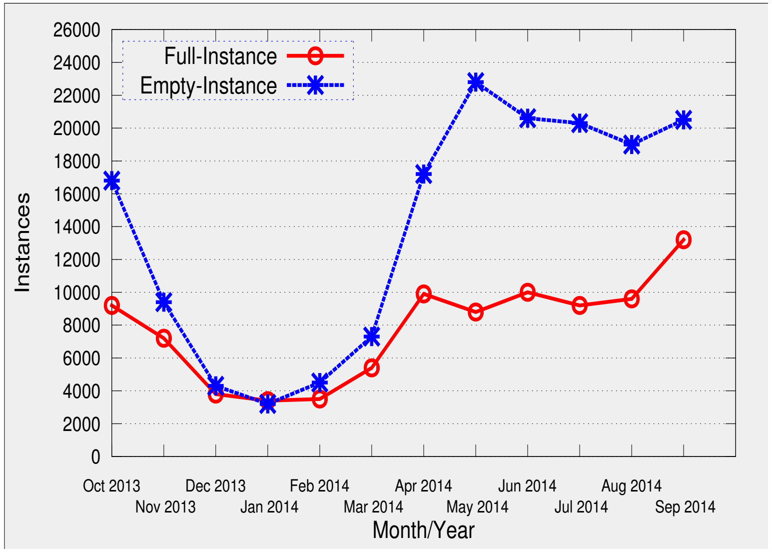
Motivation: Bike Sharing System

- **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.

World view of bike sharing systems

- **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.



Starvation/congestion in Capitalbikeshare

Background

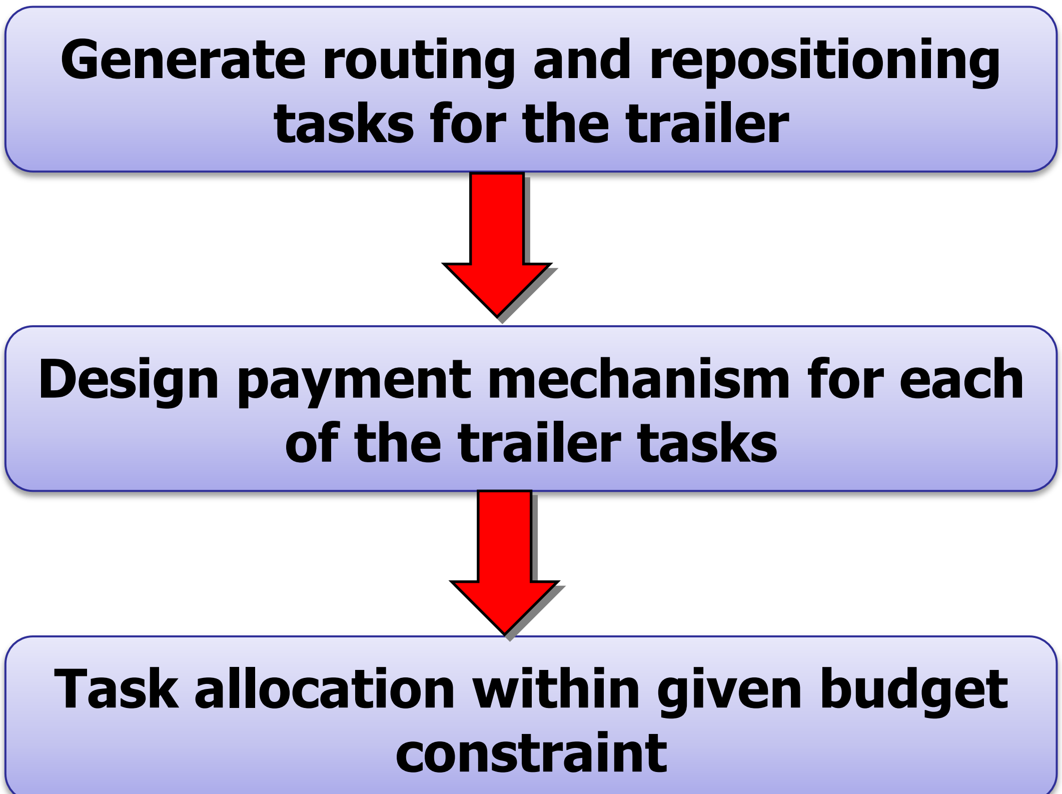
- Repositioning using trucks
  - Static Redeployment - once at the end of day
  - Dynamic Redeployment - matching of producer and consumer station
  - Problems with trucks for repositioning:
    - Incur substantial routing and labor costs
    - Increase carbon footprint
    - Limited number of trucks

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: $\langle \mathcal{S}, \mathcal{V}, C^{\#}, C^{*}, D^{\#,0}, \{\sigma_v^0\}, P, \mathbf{F}, \mathbf{B} \rangle$
  - Outputs: Repositioning strategy for trailers & allocation of tasks



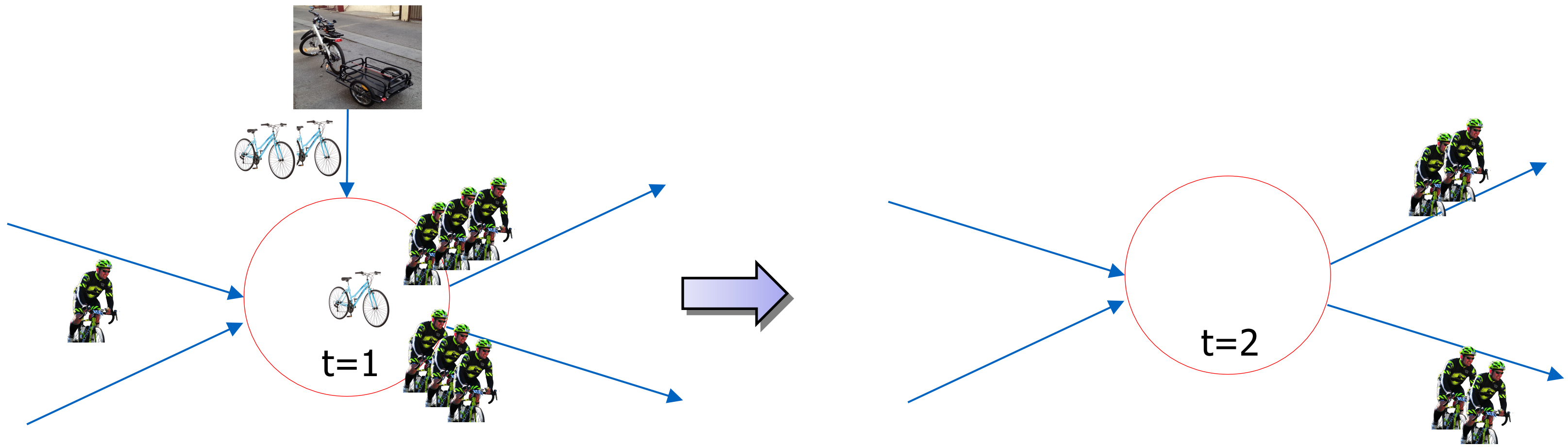
Task Generation for Bike Trailers

$$\min_{y^+,y^-} \sum_{k,s} L_s^k$$

Minimise Lost demand over k scenarios

- **Constraints:**
  - Compute lost demand

$$s.t. \quad L_s^k \geq \underbrace{\sum_{s'} F^k_{s,s'}}_{\text{Demand}} - \underbrace{\Big(d_s^{\#} + \sum_{v} (y^-_{s,v} - y^-_{s,v})\Big)}_{\text{Supply}}, \forall k, s$$



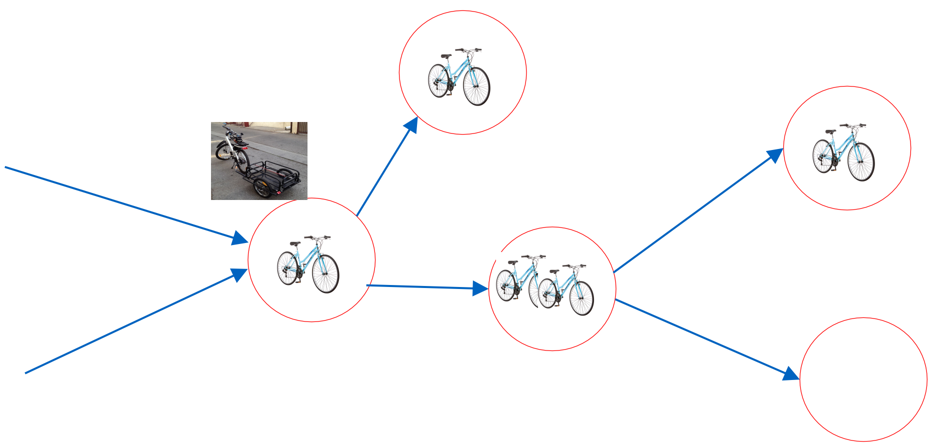
Lost Demand = 6-4 =2

Task Generation for Bike Trailers

$$\min_{y^+, y^-} \sum_{k,s} L_s^k$$

Minimise Lost demand over k scenarios

- **Constraints:**
  - Compute lost demand
  - Trailer should pickup bikes from the neighbor of it origin station

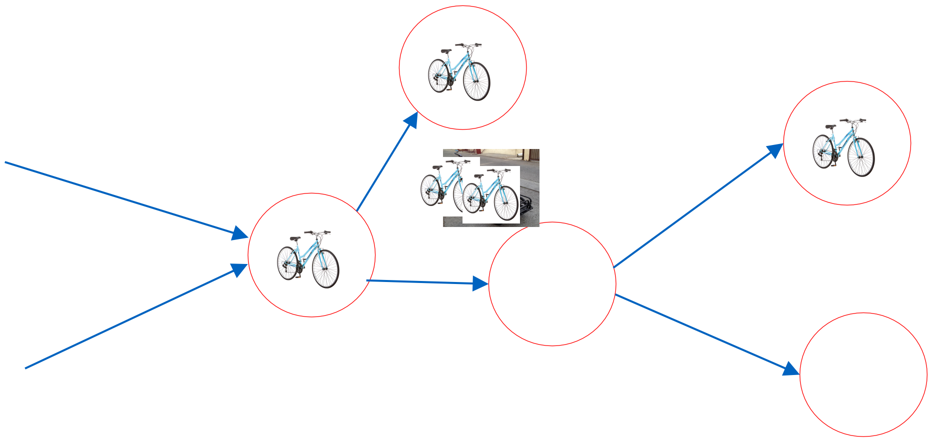


Task Generation for Bike Trailers

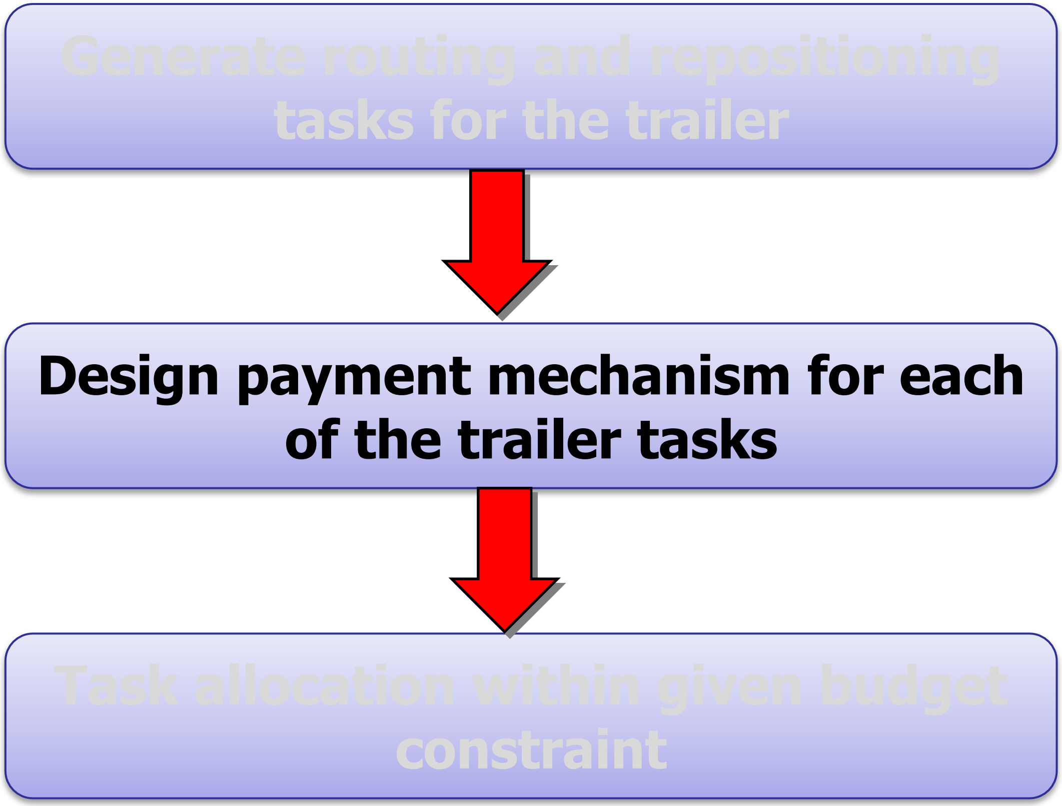
$$\min_{y^+,y^-} \sum_{k,s} L_s^k$$

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



Mechanism Design

- Compute the value for task of trailer *v*

Unit value of LD — Lost Demand

$$U(v) = \frac{\xi}{K}\sum_{k,s}\Big[\underbrace{\min\big(\max(\sum_{s'} F^k_{s,s'} - d^{\#}_s, 0), y^{+}_{s,v}\big)}_{\text{Lost Demand Saved}} - \underbrace{\min\big(\max(y^{-}_{s,v} - (d^{\#}_s - \sum_{s'} F^k_{s,s'}), 0), y^{-}_{s,v}\big)}_{\text{Lost Demand Created}}\Big]$$

#Scenarios

Assumption: Set of bidders for different tasks are pairwise disjoint

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

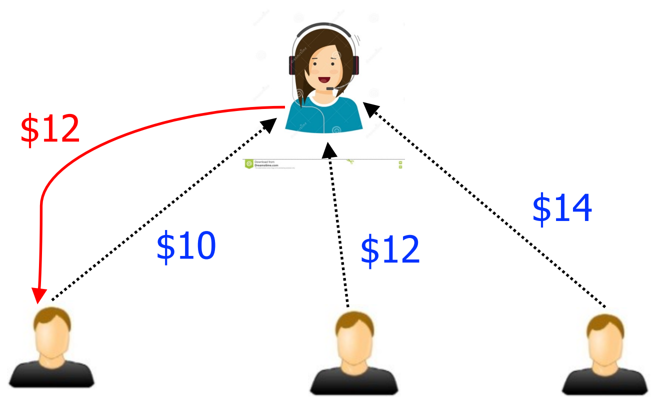
Mechanism Design

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

$$\lambda_i^*(v) = \begin{cases} 1 & \textbf{if } i = \text{argmax}_{j \in N_v} [U(v) - C_j(v)] \\ 0 & \textbf{Otherwise} \end{cases}$$

$$P_i(v) = \lambda_i^*(v) \boxed{[\min_{i \neq j} C_j(v)]}$$

Second lowest bid



Solution Approach

Generate routing and repositioning tasks for the trailer

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Design payment mechanism for each of the trailer tasks

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Task allocation within given budget constraint

Task Allocation within Budget Constraint

- Goal: Allocate a set of tasks $\mathcal{T} = \{1, ..., \mathcal{V}\}$, 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.

$$\max_x \sum_{v \in \mathcal{T}} x(v) \cdot U(v)$$

Maximise the total valuation of center

$$s.t. \quad \sum_{v \in \mathcal{T}} x(v) \cdot P(v) \leq B$$

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

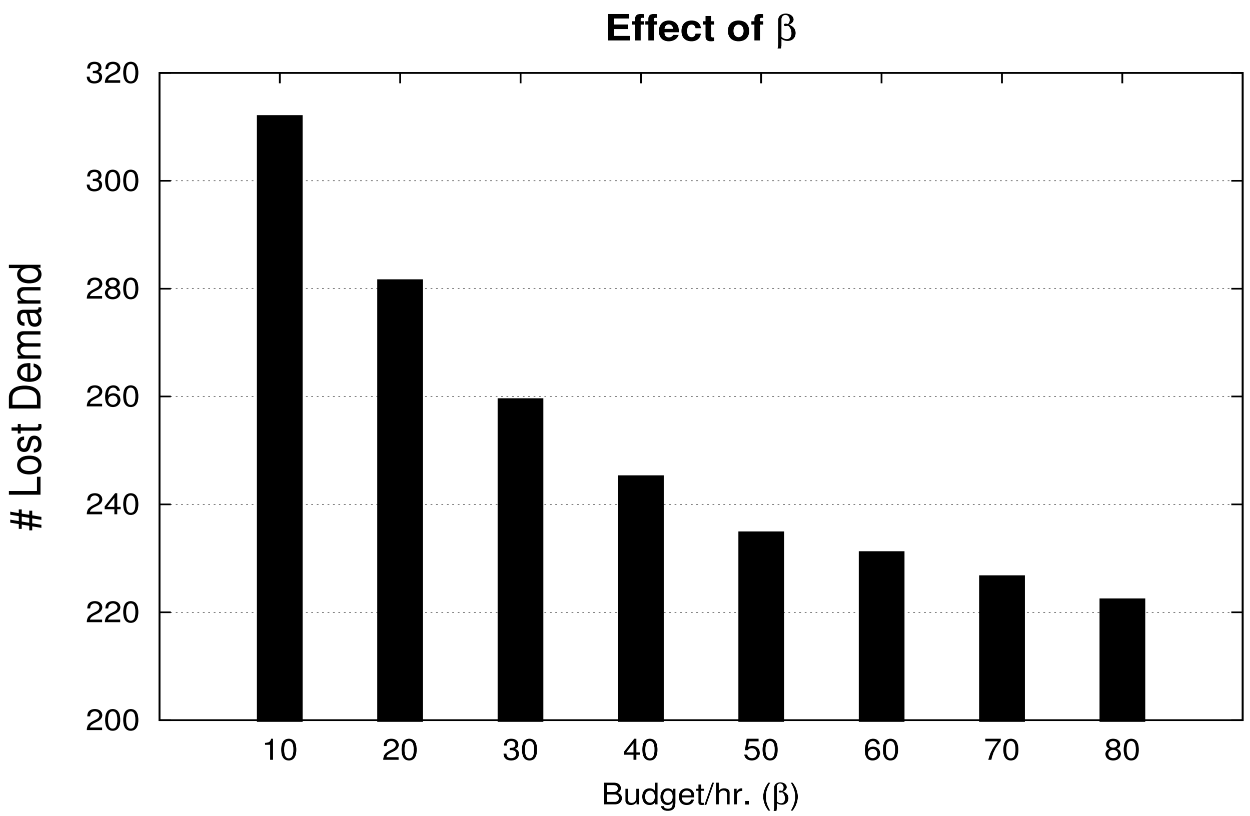
- Effect of bidding parameters on lost demand (LD)
  - Hourly Budget
  - % of users interested in bidding
  - Ratio of lower and upper bounds of bid (α)

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

Runtime performance.

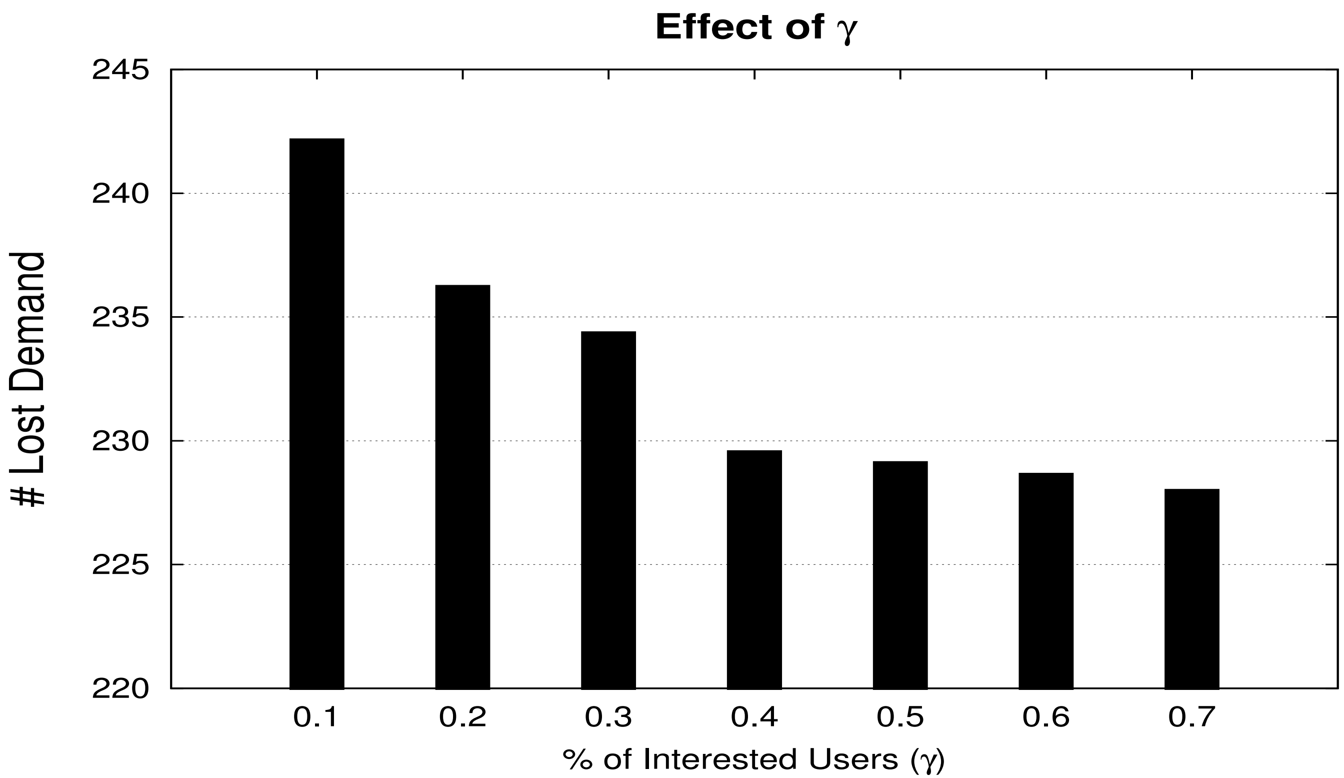
Experimental Results

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



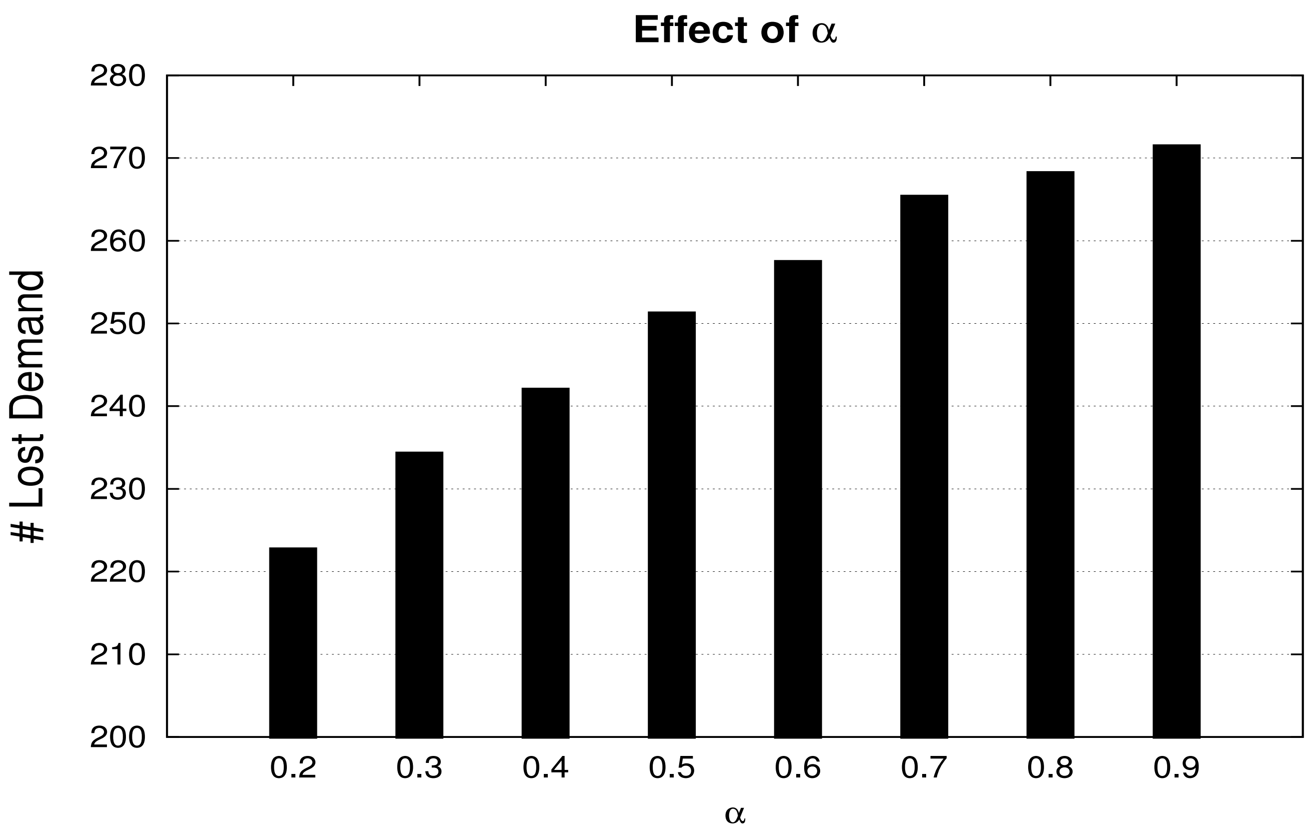
Experimental Results

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



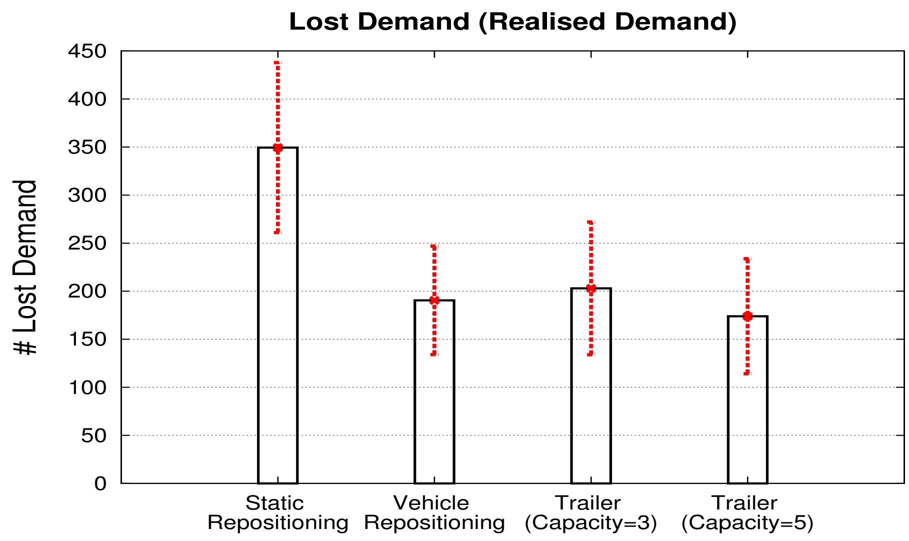
Experimental Results

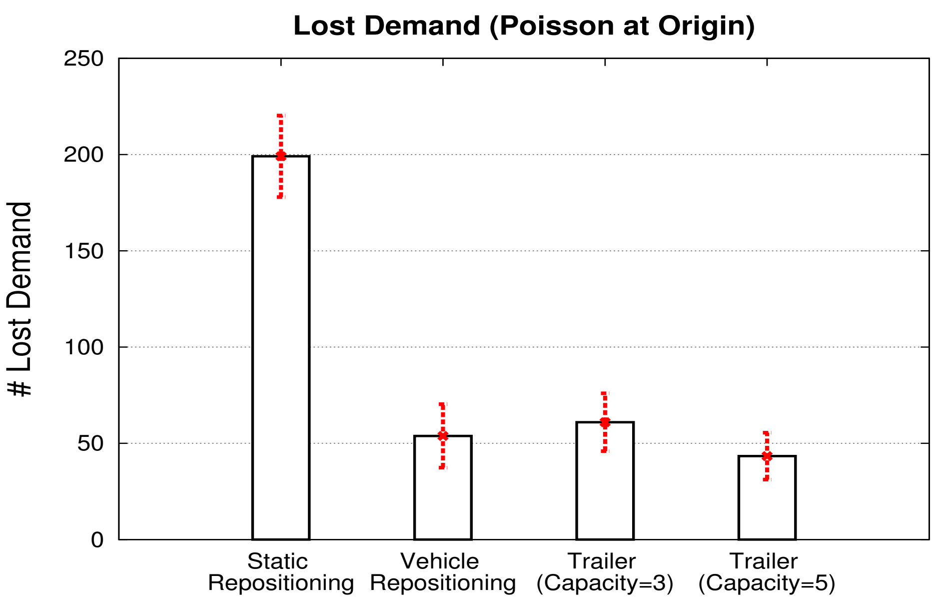
- Effect of bidding parameters on lost demand (LD)
  - Ratio of lower and upper bounds of bid (α): LD increases monotonically with α

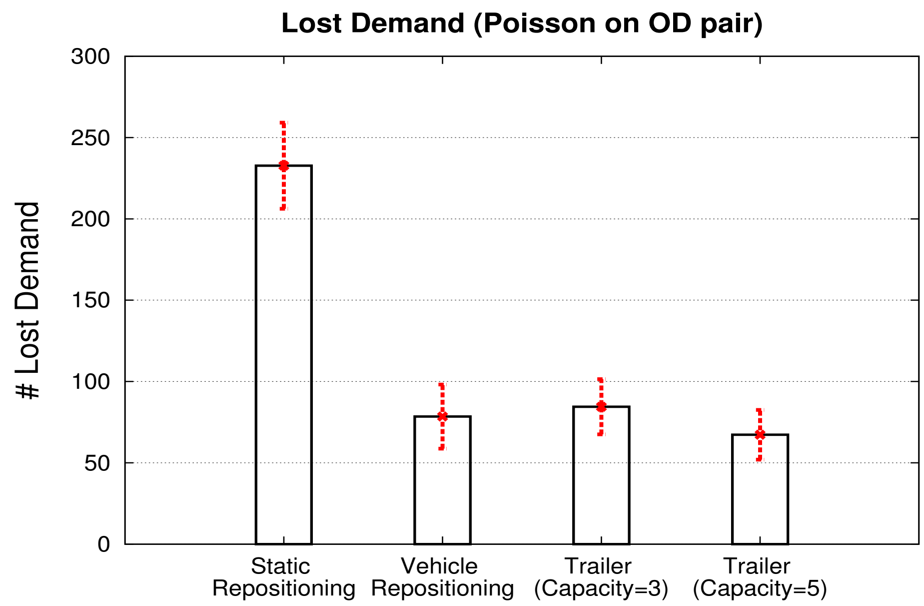


Experimental Results

- 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

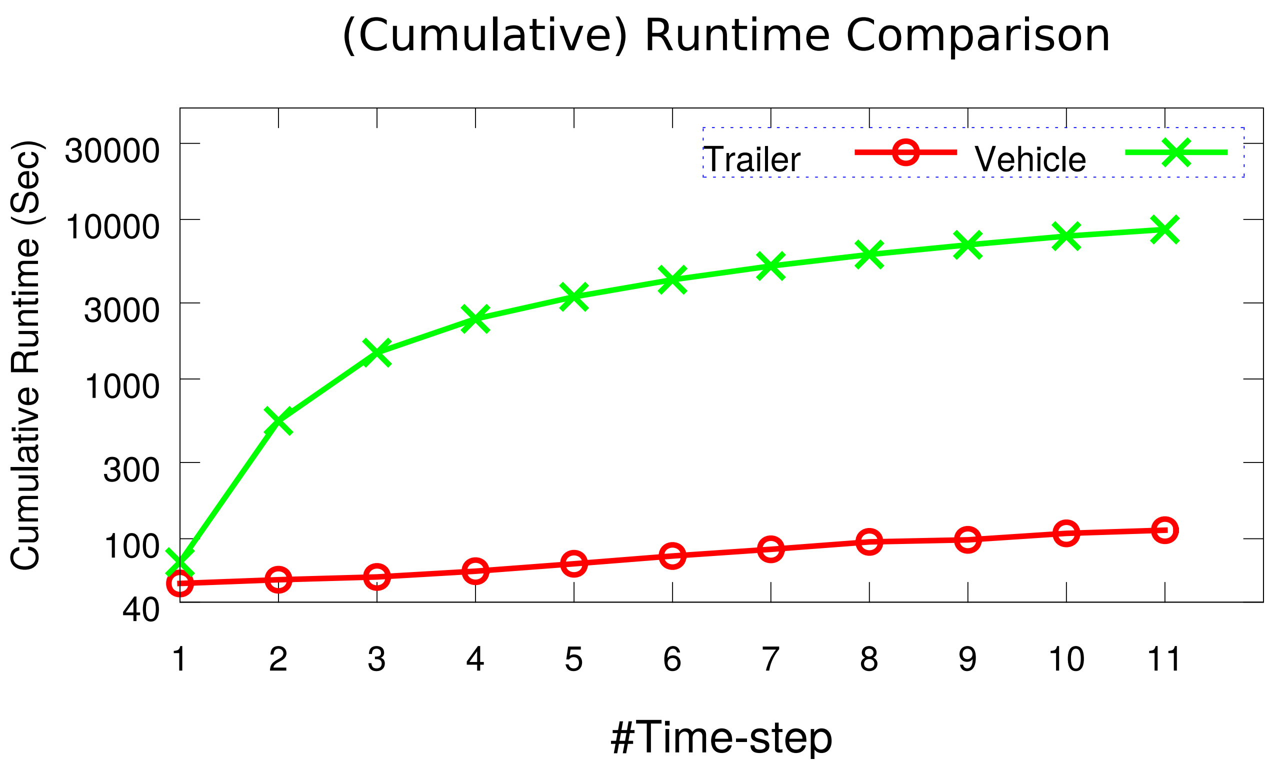






Experimental Results

- **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



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 crowdsource 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

$$\min_{\boldsymbol{y}} \sum_{s,k} L_s^k$$

Minimize total lost demand

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

Compute lost demand

$$y_{s,v}^+ \leq b_{s,v}^+ \cdot \min(d_s^{\#,t}, C_v^*), \quad \forall s, v$$

$$\sum_v y_{s,v}^+ \leq d_s^{\#,t}, \quad \forall s$$

Pickup restrictions by a trailer from a station

$$\sum_v y_{s,v}^- \leq C_s^{\#} - d_s^{\#,t}, \quad \forall s$$

$$y_{s,v}^- = b_{s,v}^- \cdot \sum_s y_{s,v}^+, \quad \forall s, v$$

Drop-off restrictions by a trailer at a station

$$(b_{s,v}^+ + b_{s',v}^- - 1) \cdot P_{s,s'} \leq P_{max} \quad \forall s, v$$

Physical limitations of trailer route

$$\sum_s b_{s,v}^+ = 1, \quad \forall v$$

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

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

Trailer should pick up from one station and drop-off at other station

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