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SINGAPORE MANAGEMENT UNIVERSITY

Dynamic Redeployment to Counter Congestion/ Starvation in Vehicle Sharing Systems

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Motivation: Bike Sharing Systems

- Examples
  - Bike Sharing (Capital Bikeshare, Hubway, etc.): 747 active systems

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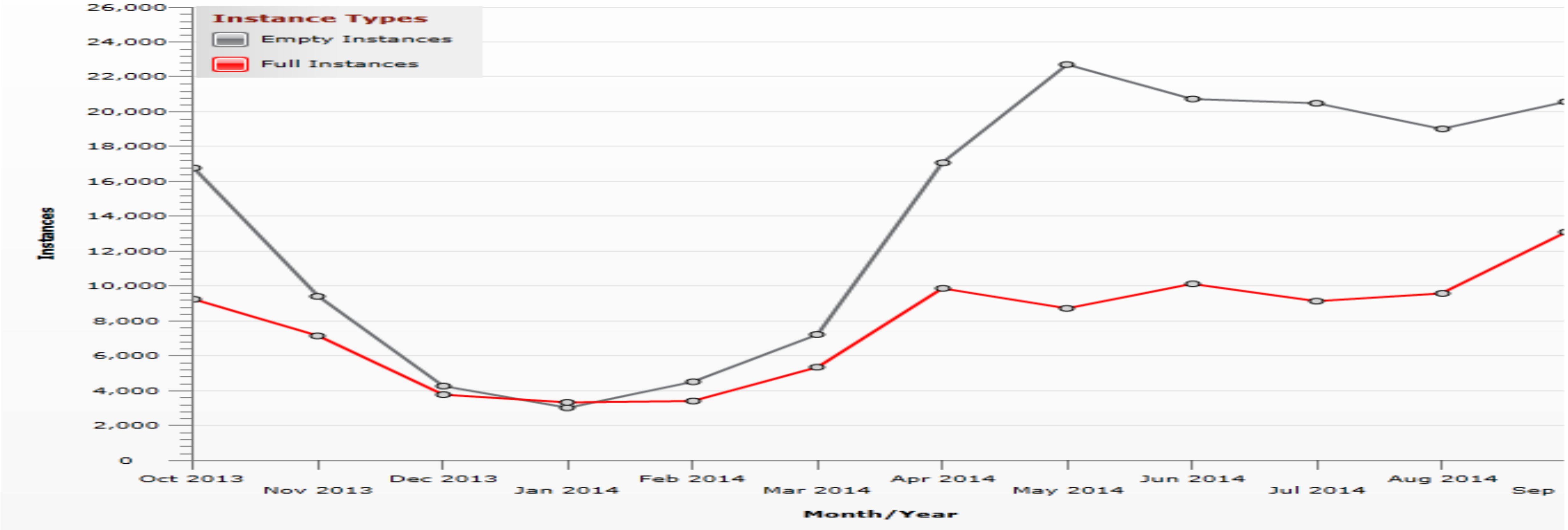
- **Alternative transportation to reduce carbon emissions and traffic congestion**

Motivation: Bike Sharing Systems



- Problem: Lost demand because of insufficient vehicles at right places/times
  - Increased use of private transportation and hence carbon emissions
  - Reduced revenue

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Related Work

- Static Redeployment (once at the end of day)
  - *Raviv and Kolka (2013), Raviv et al. (2013), Raidl et al. (2013)*
  - Issue - Stations are imbalanced during the day.

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- **Our Approach:**
  - MILP to jointly consider dynamic routing and redeployment problem **[DRRP]**
  - Lagrangian dual decomposition to improve the scalability.
  - Abstraction mechanism by grouping the nearby base stations to reduce the decision problems.

Challenge

- Input: A **DRRP** is compactly defined using following tuple

$$\left\langle \mathcal{S}, \mathcal{V}, \mathbf{C}^{\#}, \mathbf{C}^{*}, \mathbf{d}^{\#,0}, \mathbf{d}^{*,0}, \{\sigma_v^0\}, \mathbf{F}, \mathbf{R}, \mathbf{P} \right\rangle$$

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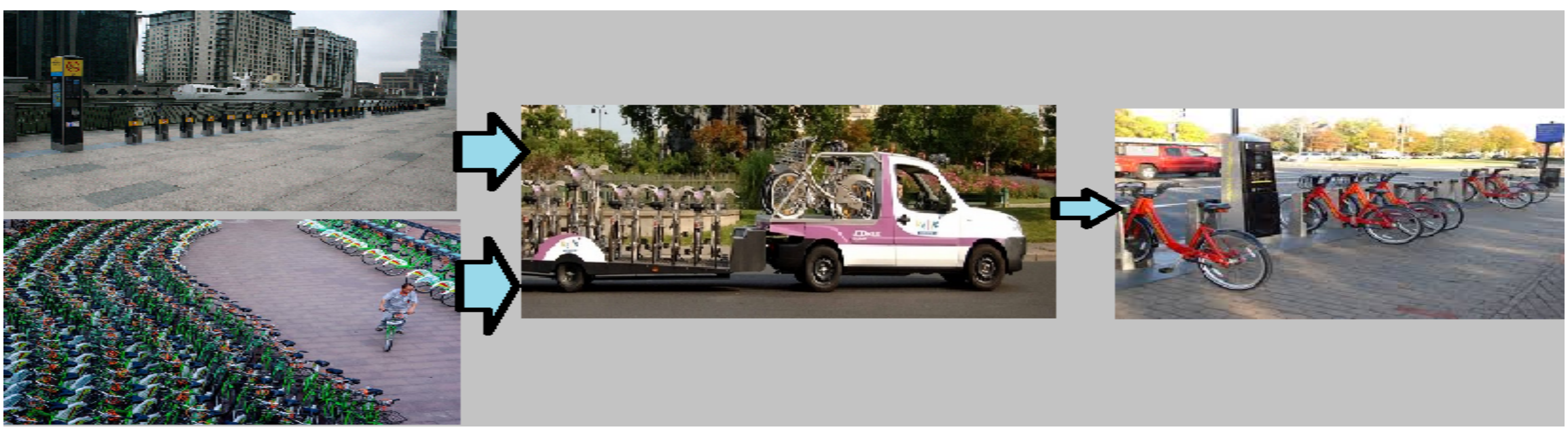
- Outputs:
  - Number of vehicles to be redeployed, **y**
  - Routes for carriers, **z** to make redeployments



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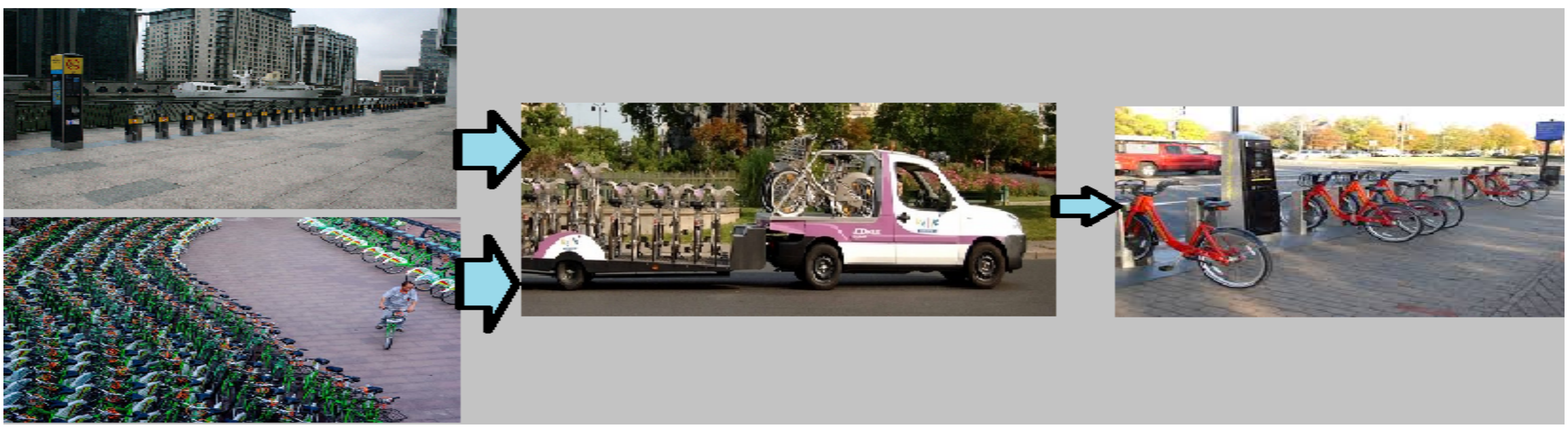
- **Objective: Maximize revenue (increasing satisfied demand + reducing carrier fuel costs)**



Approach: Linear Optimization

$$\min_{\mathbf{y}^+,\mathbf{y}^-,\mathbf{z}} - \sum_{t,k,s,s'} R^{t,k}_{s,s'} \cdot x^{t,k}_{s,s'} + \sum_{t,v,s,s'} P_{s,s'} \cdot z^{t}_{s,s',v}$$

Maximize revenue

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Maximize revenue

$$d^{\#,t}_s + \underbrace{\sum_{k,\hat{s}} x^{t-k,k}_{\hat{s},s} - \sum_{k,s'} x^{t,k}_{s,s'}}_{\text{Bikes inflow}} + \underbrace{\sum_{v} (y^{-,t}_{s,v} - y^{+,t}_{s,v})}_{\text{Redeployed bikes}} = d^{\#,t+1}_s, \ \forall t, s$$

Flow preservation of bikes at stations

Approach: Linear Optimization

$$\min_{\mathbf{y}^+,\mathbf{y}^-,\mathbf{z}} - \sum_{t,k,s,s'} R^{t,k}_{s,s'} \cdot x^{t,k}_{s,s'} + \sum_{t,v,s,s'} P_{s,s'} \cdot z^t_{s,s',v}$$

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Actual flow ∝ Observed Flow

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$$d^{*,t}_v + \sum_{s \in S} [(y^{+,t}_{s,v} - y^{-,t}_{s,v})] = d^{*,t+1}_v, \qquad \forall t, v$$

Flow preservation of vehicles in carriers

Approach: Linear Optimization

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Flow preservation of vehicles in carriers

$$\sum_{k \in \mathcal{S}} z^t_{s,k,v} - \sum_{k \in \mathcal{S}} z^{t-1}_{k,s,v} = \sigma^t_v(s), \qquad \forall t, s, v$$

$$\sum_{j \in \mathcal{S}, v \in \mathcal{V}} z^t_{s,j,v} \leq 1, \qquad \forall t, s$$

Enforcing right movement of carriers between stations

Approach: Linear Optimization

$$\min_{\mathbf{y}^+,\mathbf{y}^-,\mathbf{z}} -\sum_{t,k,s,s'} R^{t,k}_{s,s'} \cdot x^{t,k}_{s,s'} + \sum_{t,v,s,s'} P_{s,s'} \cdot z^t_{s,s',v}$$

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Enforcing right movement of carriers between stations

$$y^{+,t}_{s,v} + y^{-,t}_{s,v} \leq C^*_v \cdot \sum_{i \in \mathcal{S}} z^t_{s,i,v}, \qquad \forall t, s, v$$

Redeployment should respect the routing strategy

Key Idea 1: Lagrangian Dual Decomposition (LDD)

- Observation:
  - Minimal dependency between y (redeployment) and z (routing variables)

$$\min_{\mathbf{y},\mathbf{z}} - \sum_{t,k,s,s'} R^{t,k}_{s,s'} \cdot x^{t,k}_{s,s'} + \sum_{t,v,s,s'} P_{s,s'} \cdot z^{t}_{s,s',v}$$

$$\textbf{s.t. } d^{\#,t}_s + \sum_{k,\hat{s}} x^{t-k,k}_{\hat{s},s} - \sum_{k,s'} x^{t,k}_{s,s'} + \sum_{v} (\check{y}^t_{s,v} - \hat{y}^t_{s,v}) = d^{\#,t+1}_s, \ \forall t, s$$

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Redeployment

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Routing

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Key Idea 1: Lagrangian Dual Decomposition (LDD)

- Observation:
  - Minimal dependency between y (redeployment) and z (routing variables)
- Lagrangian Dual decomposition on joint constraints
  - Update price variable in the master function.

$$\min_{\mathbf{y},\mathbf{z}} - \sum_{t,k,s,s'} R^{t,k}_{s,s'} \cdot x^{t,k}_{s,s'} + \sum_{t,v,s,s'} P_{s,s'} \cdot z^{t}_{s,s',v}$$

s.t. $d^{\#,t}_s + \sum_{k,\hat{s}} x^{t-k,k}_{\hat{s},s} - \sum_{k,s'} x^{t,k}_{s,s'} +$

$$\sum (\check{y}^t_{s,v} - \hat{y}^t_{s,v}) = d^{\#,t+1}_s, \quad \forall t, s$$

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Routing

$$\sum_{j \in \mathcal{S}, v \in \mathcal{V}} z^t_{s,j,v} \le 1, \qquad \forall t, s$$

$$\hat{y}^t + \check{y}^t_{v} \le C^* \cdot \sum z^t_{i,v} \qquad \forall t$$

Redeployment + Routing

Key Idea 1: Lagrangian Dual Decomposition (LDD)

- Observation:
  - Minimal dependency between y (redeployment) and z (routing variables)
- Lagrangian Dual decomposition on joint constraints
  - Update price variable in the master function.
  - **Primal extraction based on routing feasibility**
  - **Strong upper and lower bounds**

$$\min_{\mathbf{y},\mathbf{z}} - \sum_{t,k,s,s'} R^{t,k}_{s,s'} \cdot x^{t,k}_{s,s'} + \sum_{t,v,s,s'} P_{s,s'} \cdot z^{t}_{s,s',v}$$

Redeployment

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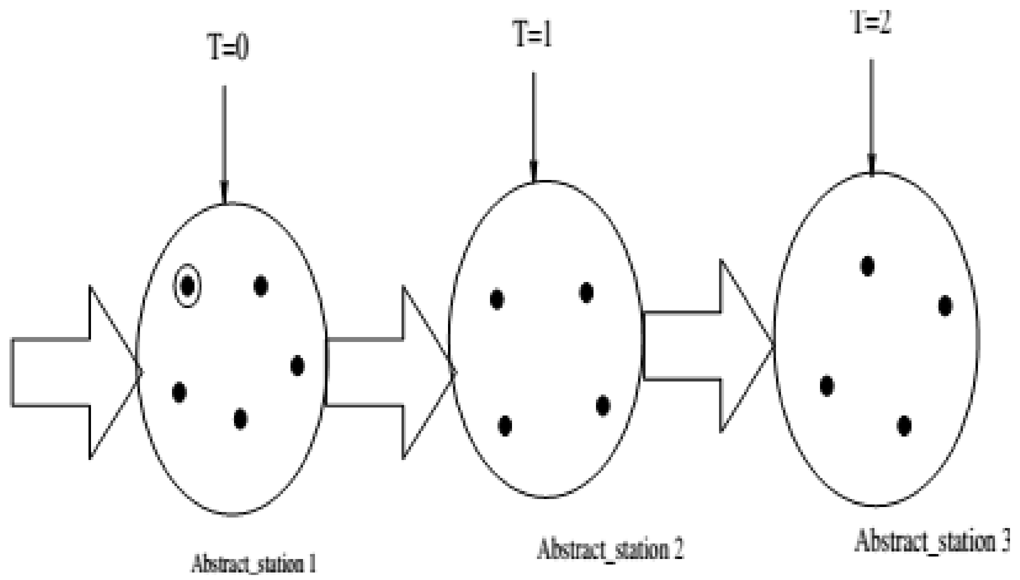
$$\hat{y}^t_{s,v} + \check{y}^t_{s,v} \leq C^* \cdot \sum_{i} z^t_{s,i,v} \quad \forall t, s, v$$

Key Idea 2: Abstraction



- Grouping of stations
  - Group base stations into abstract stations
  - Solve abstract problem using LDD

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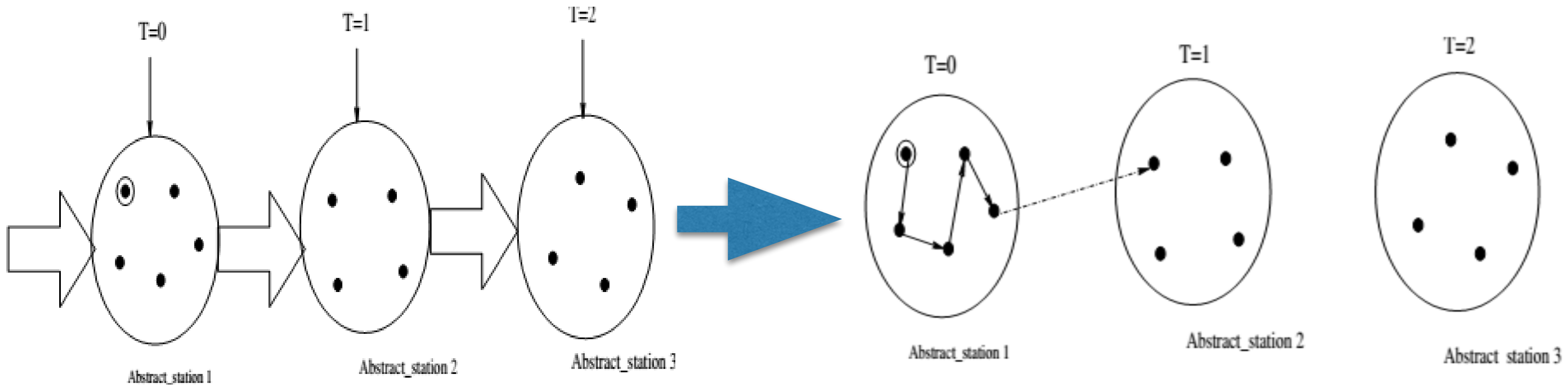
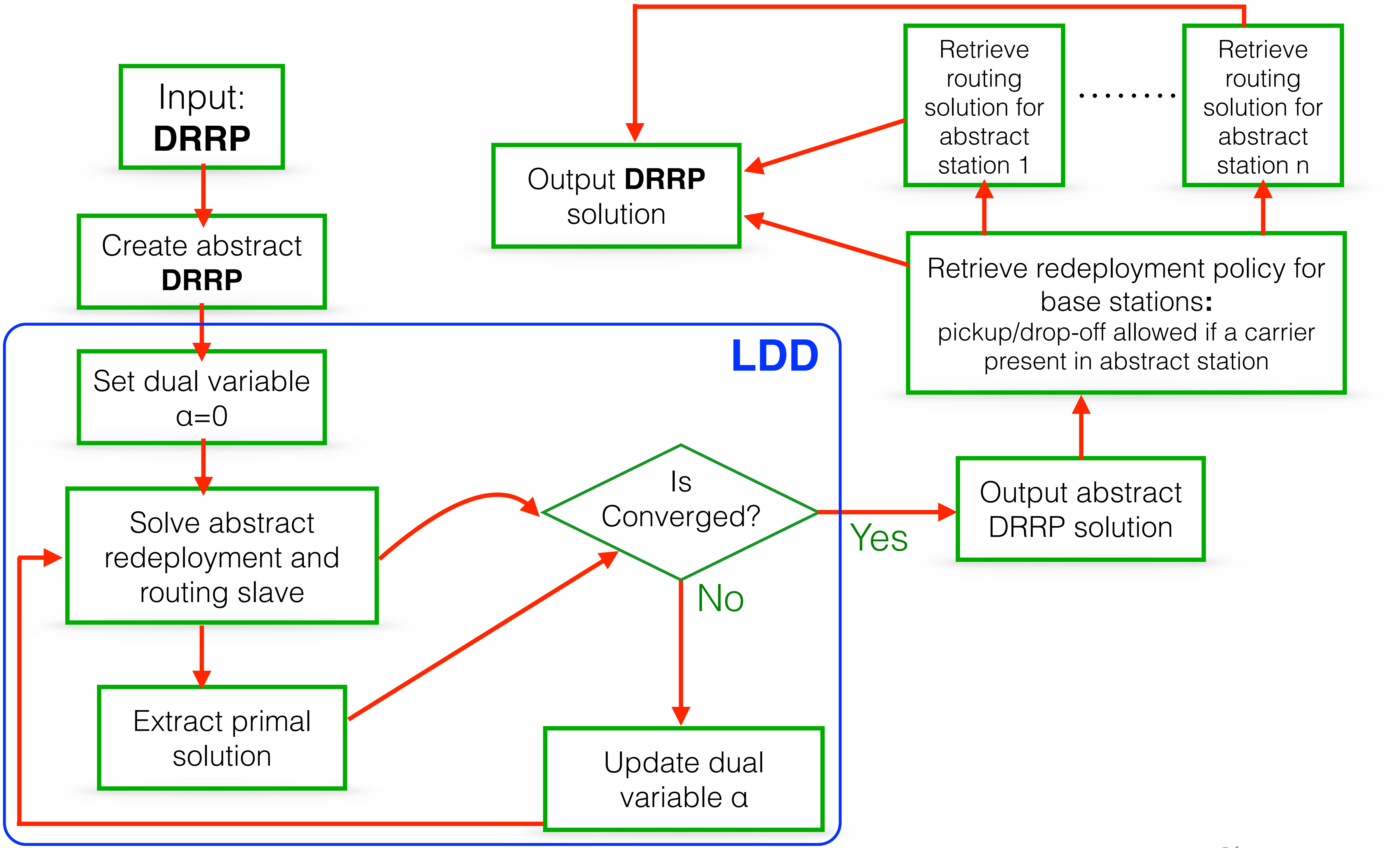


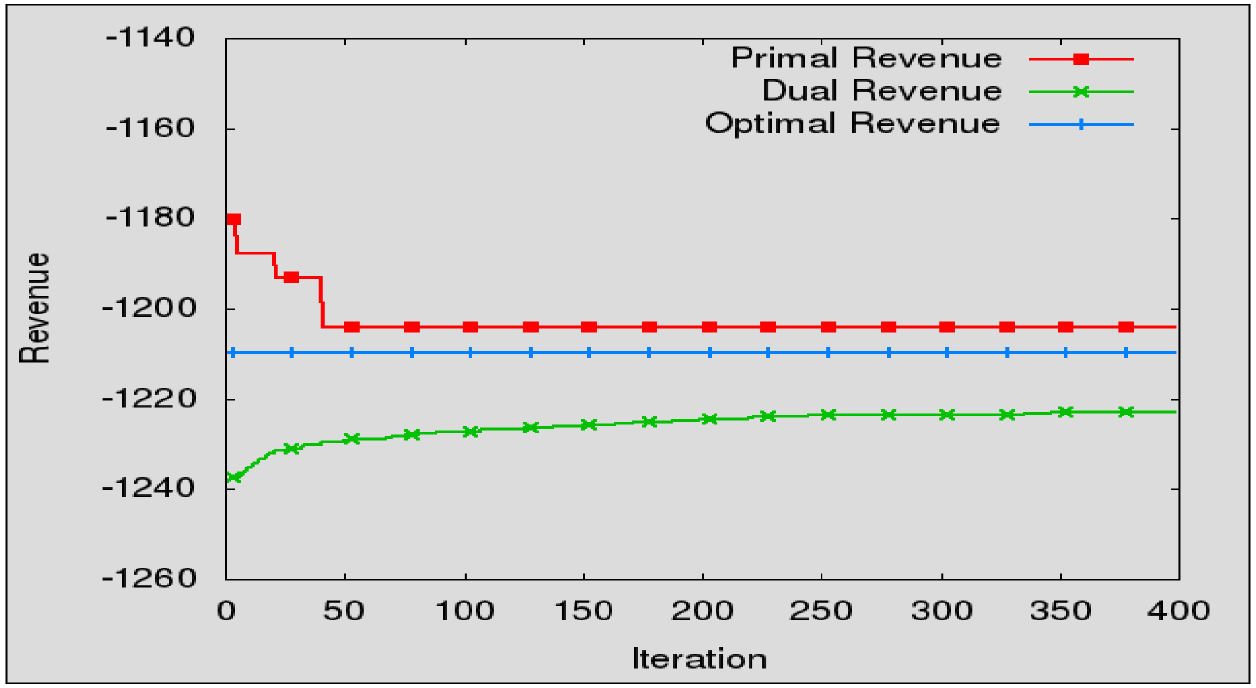
- Grouping of stations
  - Group base stations into abstract stations
  - Solve abstract problem using LDD
- Retrieve redeployment and routing strategy from solution to the abstract problem
  - Involves solving an optimization problem

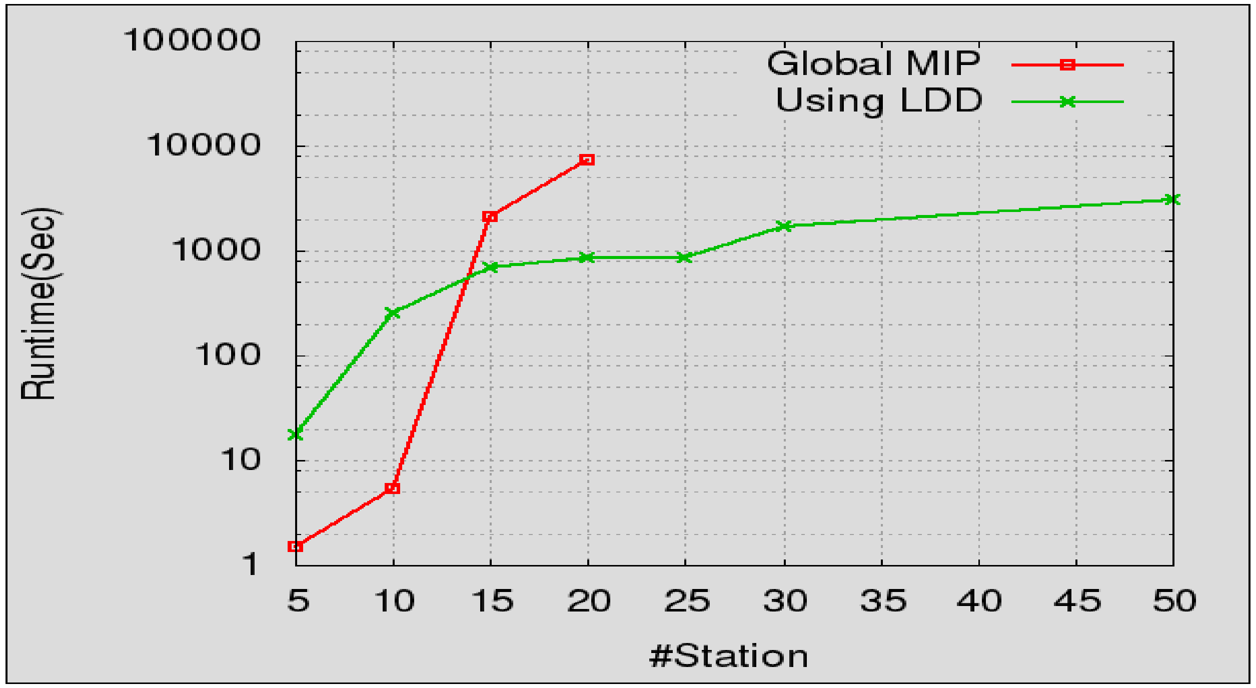
LDD+Abstraction



Experimental Results

- One synthetic data set and two real data sets:
  - Capital Bikeshare (305 stations, 6 carriers)
  - Hubway (95 stations, 4 carriers)
- Strategy of redeployment and routing for the entire day (30 minute decisions)
- Obtain strategy from part of the datasets and execute on another part





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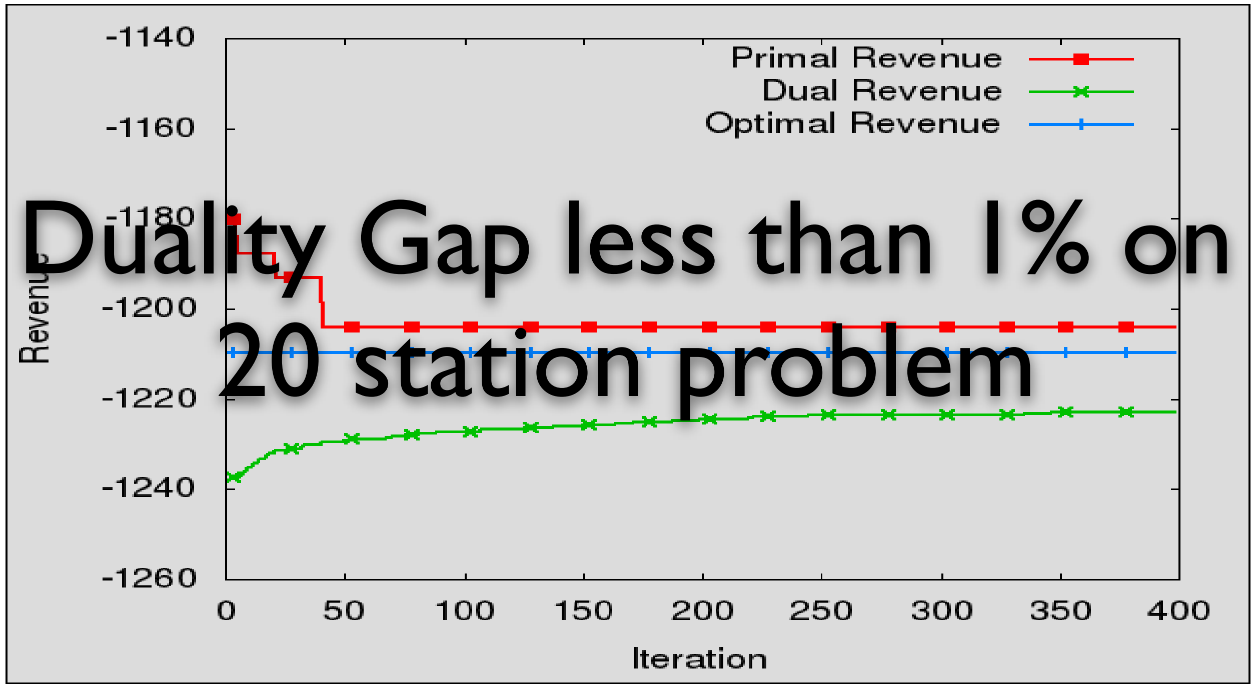
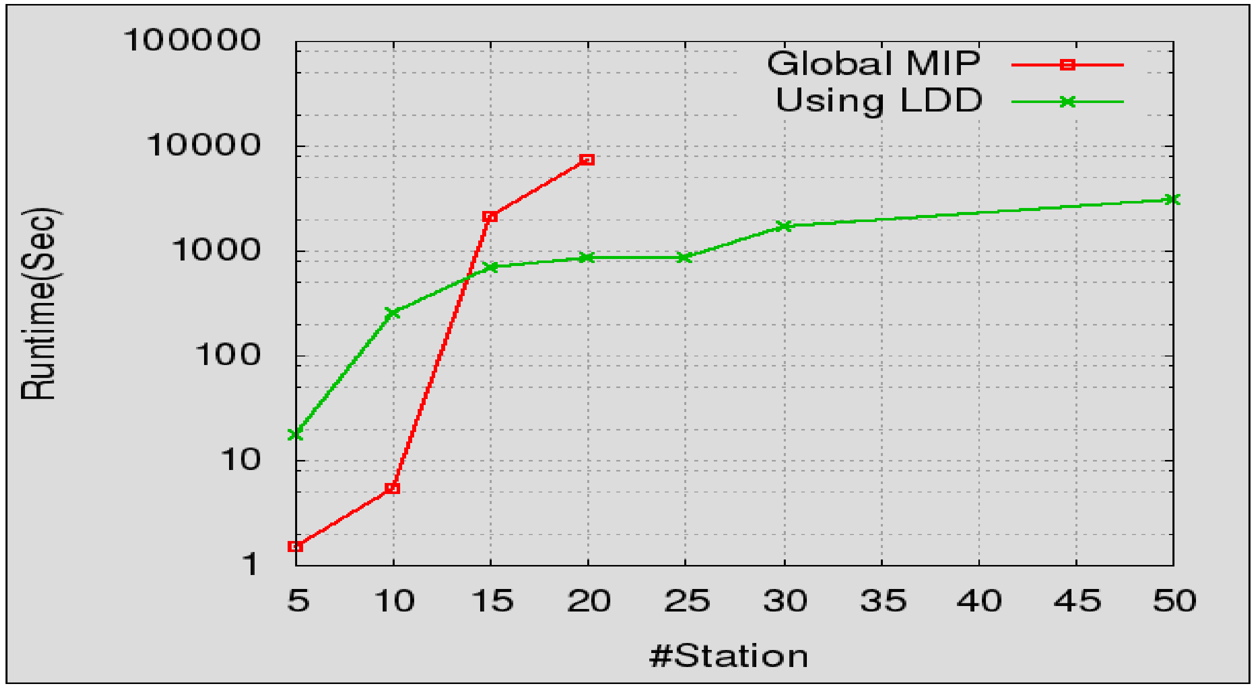


Duality Gap less than 1% on 20 station problem



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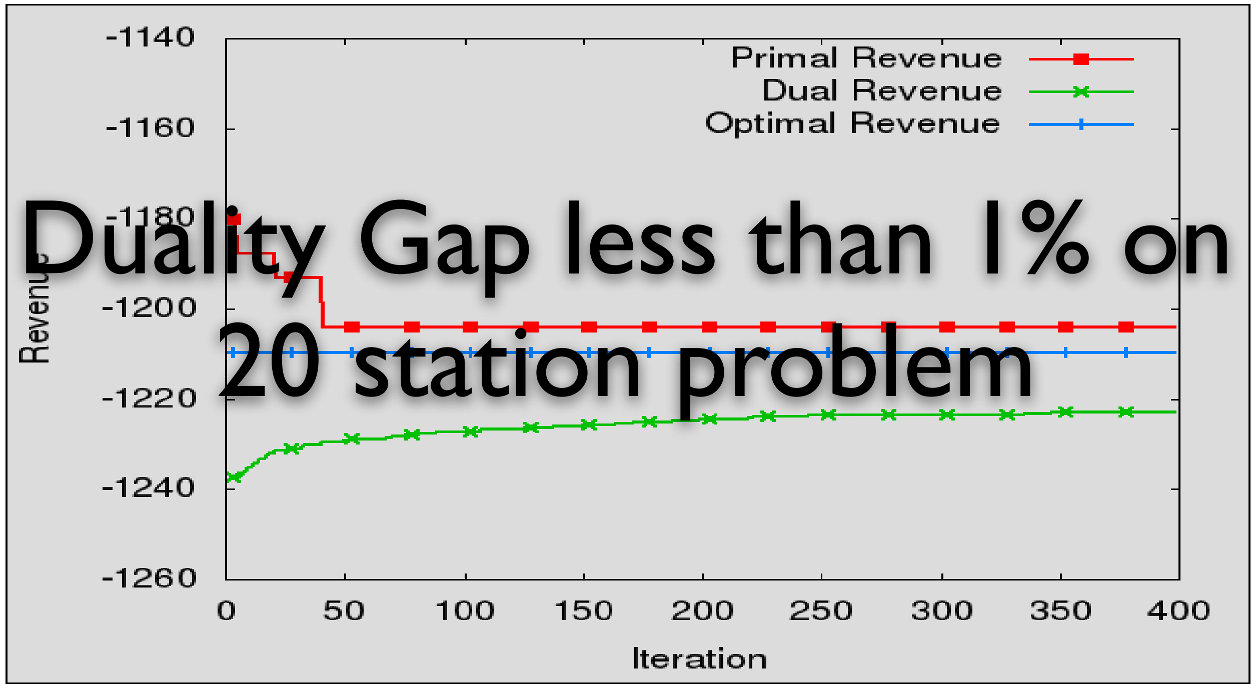

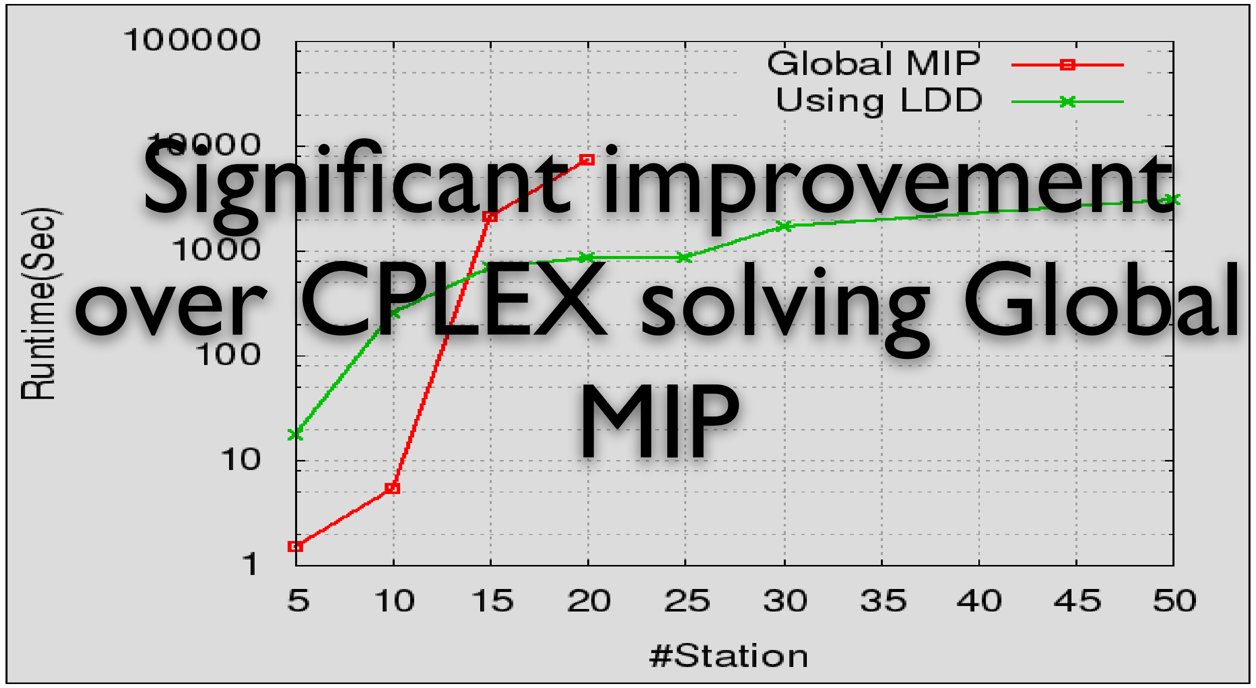

Experimental Results on Real Datasets

- Comparison with current practice (abstraction + LDD)
  - Demand follows poisson with mean observed flow
  - CapitalBikeshare Data:
    - Revenue increased by 3%
    - Lost demand reduced by up to 33.76%

	Whole day (5am-12am)		Peak period (5am-12pm)	
	Revenue gain	**Lost demand reduction**	**Revenue gain**	**Lost demand reduction**
Mean	3.47 %	22.72 %	7.74 %	30.58 %
Mon	2.33 %	22.46 %	4.48 %	25.55 %
Tue	3.07 %	28.56 %	7.86 %	37.10 %
Wed	3.30 %	31.16 %	8.95 %	44.88 %
Thu	2.86 %	33.76 %	6.04 %	35.97 %
Fri	2.51 %	27.37 %	4.50 %	28.15 %
Sat	3.87 %	23.61 %	4.33 %	24.30 %
Sun	3.01 %	26.00 %	4.04 %	36.51 %

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  - **Robust to small changes in mean demand**

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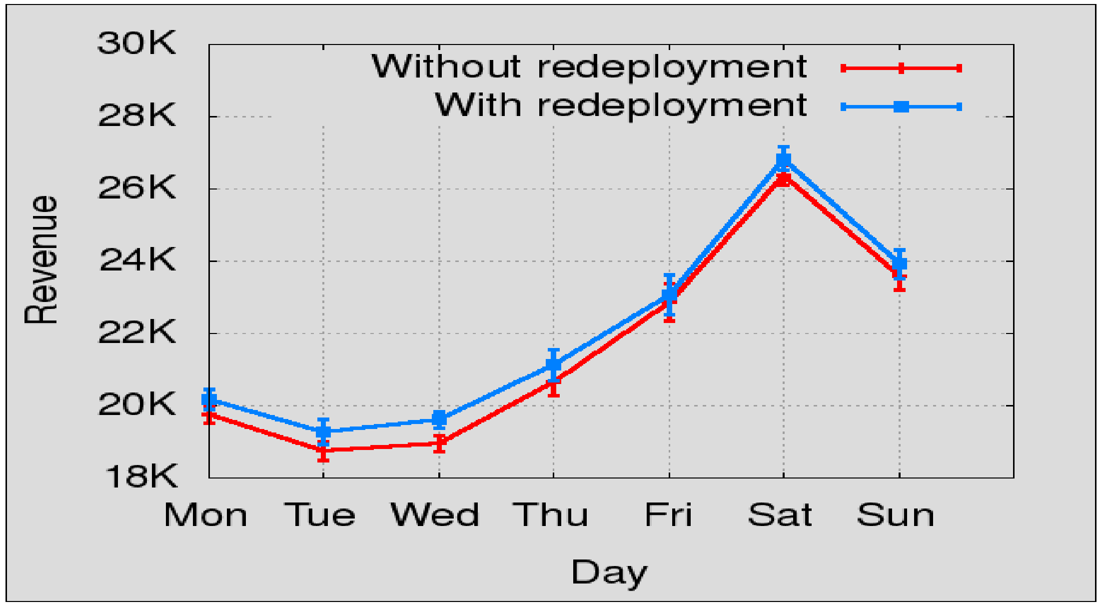
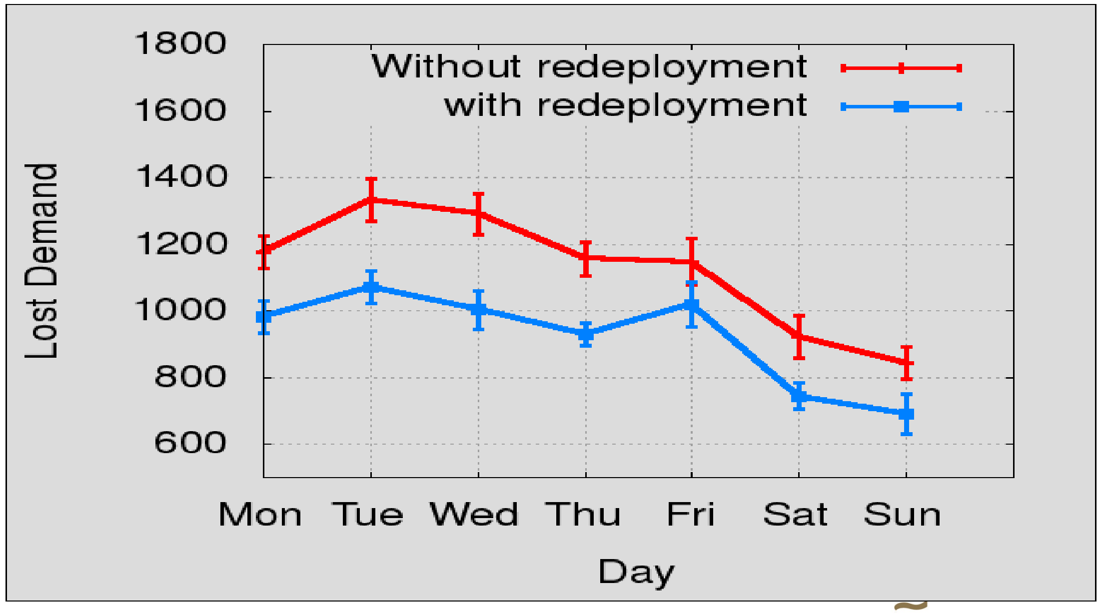
Sat	3.87 %	23.61 %	4.33 %	24.30 %
Sun	3.01 %	26.00 %	4.04 %	36.51 %





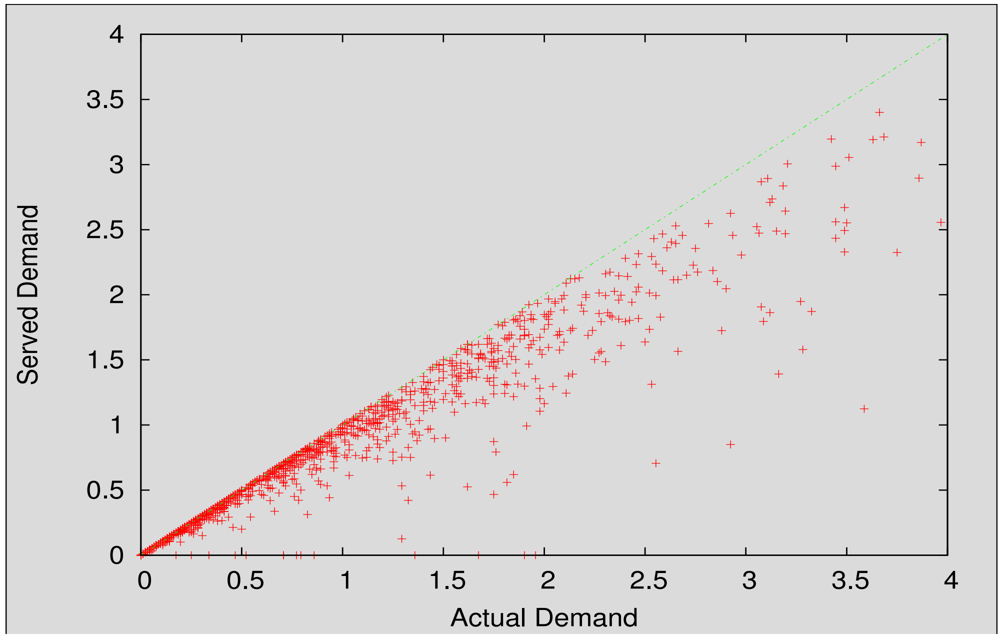
Experimental Results on Real Datasets (2)

- Hubway Data:
  - Revenue increased by 5%
  - Lost demand reduced by 60% on average

	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Revenue Gain (%)	3.94	5.93	4.45	5.90	6.27	2.20	3.15
Lost Demand Reduction(%)	42.6	60.7	58.5	54.7	77.2	69.8	74.0

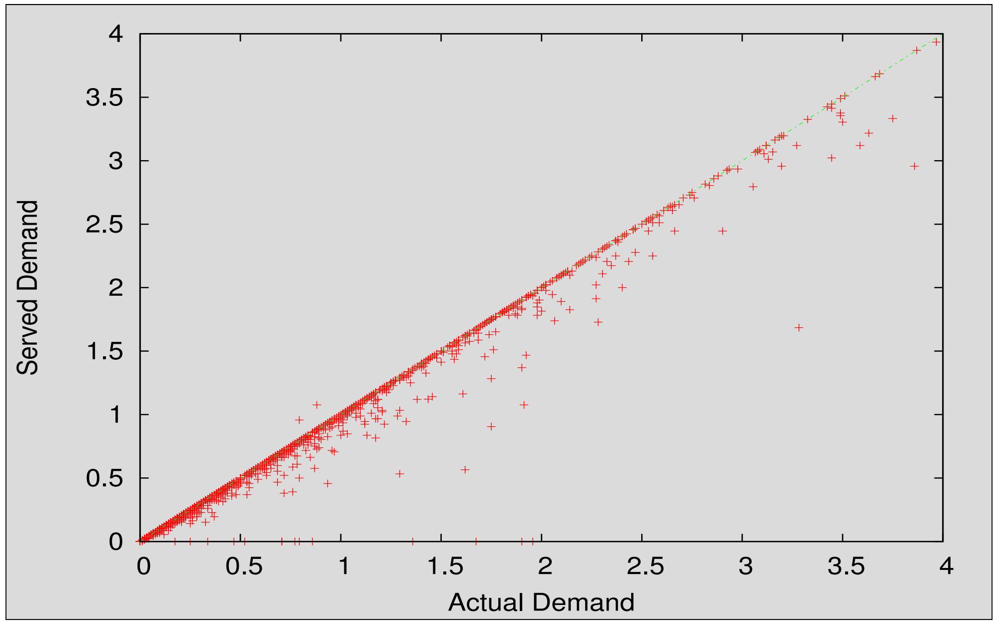
Experimental Results on Real Datasets (2)

- Hubway Data:
  - Revenue increased by 5%
  - Lost demand reduced by 60% on average
- Better matching of demand and supply
  - Ideally all the points should lie on the identity line



Matching without redeployment

	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Revenue Gain (%)	3.94	5.93	4.45	5.90	6.27	2.20	3.15
Lost Demand Reduction(%)	42.6	60.7	58.5	54.7	77.2	69.8	74.0



Matching using our redeployment

Summary

- Dynamic redeployment of bikes
  - Important large-scale problem with relevance to many cities
  - Two techniques (Decomposition, Abstraction) to improve scalability and provide near-optimal solutions
  - Reduces lost demand by over 20% on both datasets
  - Robust to small changes in demand

Questions???

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