USC Viterbi
School of Engineering

METRANS SEMINAR

Cost-Sharing Mechanisms for Ride-Sharing

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MOTIVATION & BACKGROUND

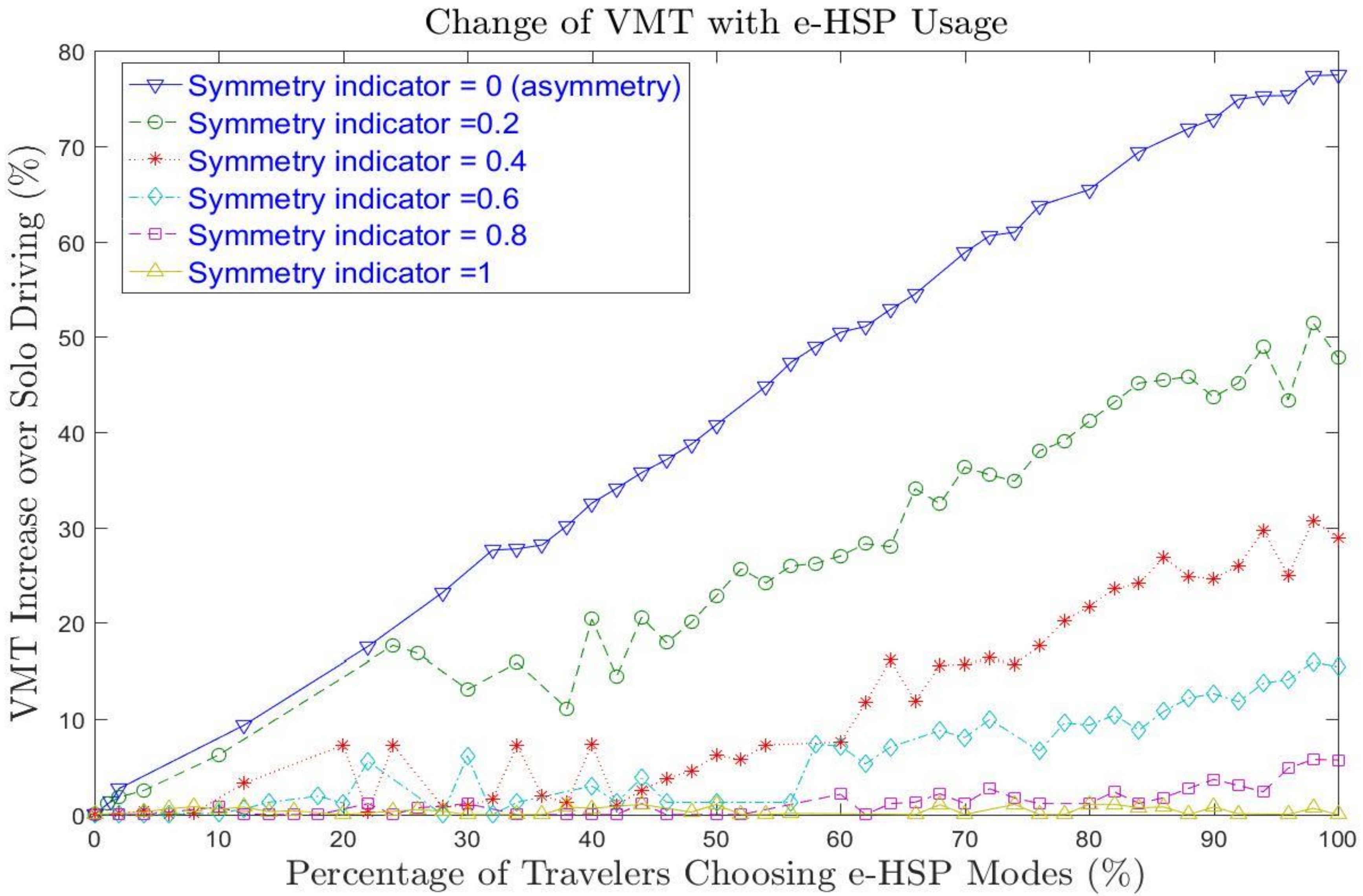
- According to the U.S. Department of Transportation more than 10% of the GDP is related to transportation activity
- The 2019 Urban Mobility report estimates the cost of congestion in the US to be on the order of $160 billion or $960 per commuter and 7 billion hours in delayed time
- There exists a significant amount of unused capacity in the transportation network
- Emerging information technologies have made available a wealth of real-time and dynamic data about traffic conditions
  - GPS systems both in vehicles/phones
  - interconnected data systems
  - on-board computers

OPPORTUNITIES for RIDE-SHARING

- Ride-sharing is a joint-trip of more than two participants that share a vehicle and requires coordination with respect to itineraries and time
- Unorganized ride-sharing
  - Family, colleagues, neighbors
  - Hitchhiking
  - Slugging
- Organized ride-sharing
  - Matching of driver and rider
  - Can require
    - Service operators
    - Matching agencies
    - Cost-sharing systems (Carma, Flinc)
    - Revenue maximizing systems (Uber, Lyft, DiDi, etc)

IMPACT of TNCs on CONGESTION

- Shifts mode from environmentally friendly modes
  - 2018 Schaller Report – survey of TNC users – 60% would have used public transit, biked, or walked and 40% would have used either a taxi or personal vehicle
  - 2019 University of Kentucky Report - more than half of the 62% increase in weekday traffic delays between 2010 and 2016 due to Uber and Lyft trips
- Causes extra deadhead miles to pickup customers – up to 20% of the trip in SF and 50% in NYC (LA Times, 2019)
- Overall, Schaller reports that TNCs have added 5.7 billion VMT annually in total for nine large metro areas
- Less time driving searching for parking and car ownership


Change of VMT with e-HSP Usage
▽ Symmetry indicator = 0 (asymmetry)
○ Symmetry indicator =0.2
✱ Symmetry indicator = 0.4
◇ Symmetry indicator =0.6
□ Symmetry indicator = 0.8
△ Symmetry indicator =1
VMT Increase over Solo Driving (%)
Percentage of Travelers Choosing e-HSP Modes (%)
0
10
20
30
40
50
60
70
80
90
100

RIDE-SHARING CHALLENGES & RESEARCH

EXAMPLES: High-dimensional Matching

Ride preferences have dimensions

- Type of vehicle
- Flexibility of route
- Gender
- Cost
- Travel time

Software assistants can help with

- How to balance different criteria
- Multiple rides for a trip
- Transfer points
- Which routes to take to maximize possibility of ride-sharing

RESEARCH AREAS

High-dimensional Matching

Trust and Reputation

Mechanism Design

Routing

Network Congestion Effects and Computational Planning Tools

RIDE-SHARING CHALLENGES & RESEARCH

EXAMPLES: Trust and Reputation

Implementation of large scale word of mouth systems (reputation systems)

- Used in Carma, Carpool World, Goloco
  - New users
  - Bias toward positive comments (retaliation threat)

Escrow Mechanisms

- Intermediary that forwards payment and collects feedback
- Issues with incentive compatability, efficiency.

Use of Social Networking Sites (SNS)

- Get to know the driver/rider
- ZimRide, Carma, Carticipate

RESEARCH AREAS

High-dimensional Matching

Trust and Reputation

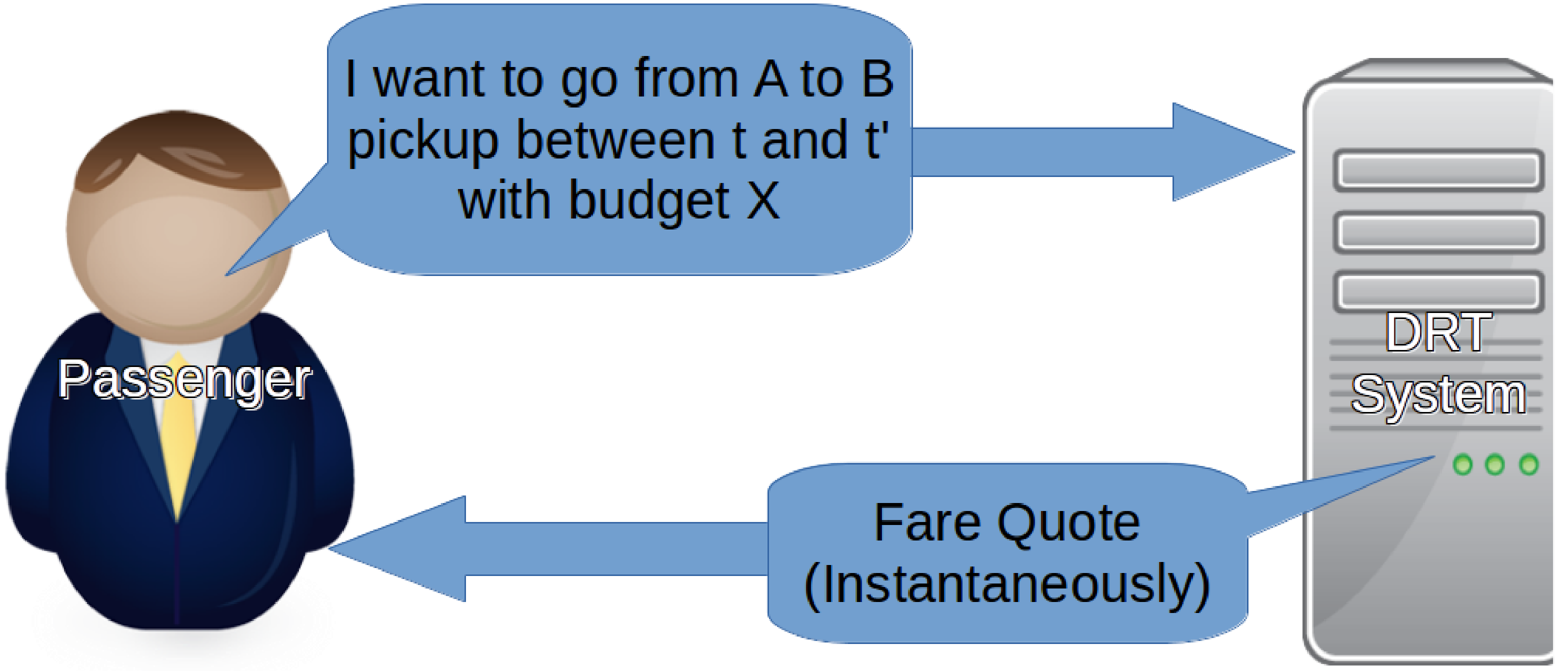
Mechanism Design

Routing

Network Congestion Effects and Computational Planning Tools

OUR SETTING

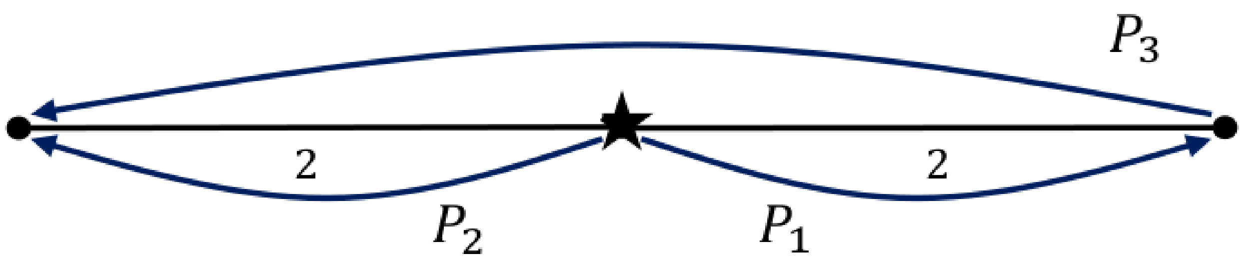
- Share the ride costs fairly and without any subsidies.
- Make sure passengers have no reason to drop out after accepting their fare quote.
- Motivate passengers to submit requests early. This allows the system to maximize serviced passengers.



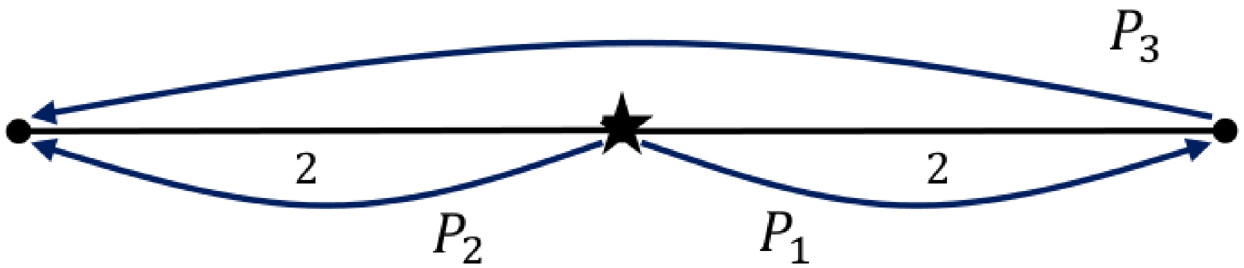
I want to go from A to B pickup between t and t' with budget X

Fare Quote (Instantaneously)

AN EXAMPLE



	k=1	k=2	k=3
Distance	2	2	4
Total Cost	20	60	60
Marginal Cost	20	40	0
Shared Cost	?	?	?



	k=1	k=2	k=3
Distance	2	2	4
Total Cost	20	60	60
Marginal Cost	20	40	0
Fixed-Fare	10	10	10
Incremental	20	40	0
Proportional	15	15	30

DESIRABLE PROPERTIES

ONLINE FAIRNESS

The costs per distance unit are monotonically nonincreasing (in passengers' arrival order).

EX-POST INCENTIVE COMPATIBILITY

The best strategy of every passenger is to arrive truthfully (provided that all other passengers arrive truthfully and none change whether they accept).

IMMEDIATE RESPONSE

The passengers' costs are monotonically nonincreasing (in time).

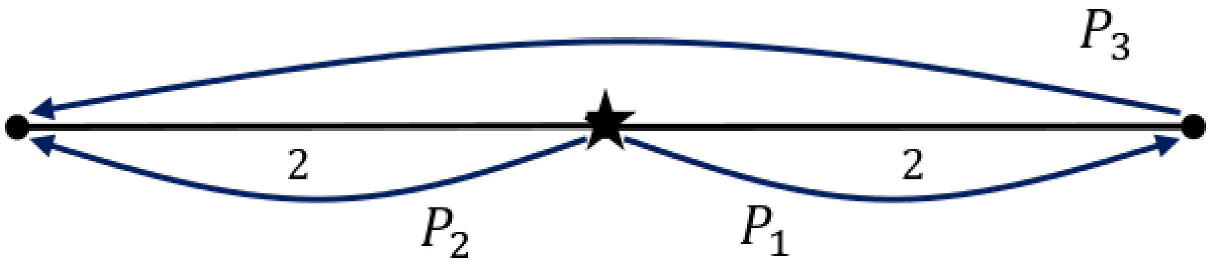
BUDGET BALANCE

The total cost is shared by all (serviced) passengers.

INDIVIDUAL RATIONALITY

The shared costs of passengers who accepted their initial quotes should never exceed their willingness-to-pay-level.

DESIRABLE PROPERTIES



	k=1	k=2	k=3
Distance	2	2	4
Total Cost	20	60	60
Marginal Cost	20	40	0
Fixed-Fare	10	10	10
Incremental	20	40	0
Proportional	15	15	30

- ✗ Budget balance (e.g., Fixed-Fare)
- ✗ Immediate response (e.g., Proportional)
- ✗ Online fairness (e.g., Incremental)

POCS MECHANISM

- Proportional Online Cost-Sharing is a mechanism that provides low fare quotes to passengers directly after they submit ride requests and calculates their actual fares directly before their rides.

- POCS calculates shared-costs by:

$$cost^t_{\pi(k)} := \alpha_{\pi(k)} \min_{k \leq j \leq t} \max_{1 \leq i \leq j} \underbrace{\frac{\sum_{l=i}^{j} mc_{\pi(l)}}{\sum_{l=i}^{j} \alpha_{\pi(l)}}}_{ccpa_{\pi(i,j)}}$$

- POCS is a mix of
  - marginal cost-sharing (with respect to coalitions)
  - proportional cost-sharing (with respect to passengers within a coalition)

STATIC RIDE-SHARING MECHANISM DESIGN

THE FRAMEWORK

Total Cost = **Driver’s Direct Cost F** + **Total Detour Cost**

Total Shared Cost = **Shared Cost of F** + **Shared Cost of the Total Detour**

Shared Cost of F:

- Any sub-mechanism
- Propose 3 mechanisms

Shared Cost of the Total Detour:

- Any sub-mechanism
- Use POCS for now

- New Properties Identified
  - –Reduced Burden for the First Passenger Property. In the initial quote for the first passenger, its shared cost of the driver’s direct cost < F.
  - –Fairness in Sharing Driver’s Cost Property. The final share of the driver’s direct cost paid by the passengers should be proportional to their demand.
- The Ride-Sharing Mechanism Framework (RSMF) constrains the sub-mechanisms for sharing the cost of F to satisfy the new properties.

STATIC RIDE-SHARING MECHANISM DESIGN

THE MECHANISM IN DETAIL DRIVER-OUT-OF-COALITION

Total Shared Cost = **Shared Cost of F** + **Shared Cost of the Total Detour**

HOW TO SHARE THE COST F

- Share proportionally to passengers' demand
- Driver is out of the coalition in sharing F

- Pros:
  - all five original desirable properties are satisfied
  - Fairness in Sharing Driver's Cost property holds
- Cons:
  - fails to reduce the burden of the 1st passenger

Proposition 2:
they contradict with each other under certain circumstances

STATIC RIDE-SHARING MECHANISM DESIGN

THE MECHANISM IN DETAIL DRIVER-IN-COALITION

Total Shared Cost = **Shared Cost of F** + **Shared Cost of the Total Detour**

HOW TO SHARE THE COST F

- Share proportionally to passengers' demand
- Driver is in the coalition in sharing F

- Pros:
  - all five original desirable properties are satisfied
  - Fairness in Sharing Driver's Cost property holds
  - Reduced Burden for the First Passenger property holds
- Cons:
  - the driver's cost is not fully recovered

STATIC RIDE-SHARING MECHANISM DESIGN

THE MECHANISM IN DETAIL PASSENGERS PREDICTING

Total Shared Cost = **Shared Cost of F** + **Shared Cost of the Total Detour**

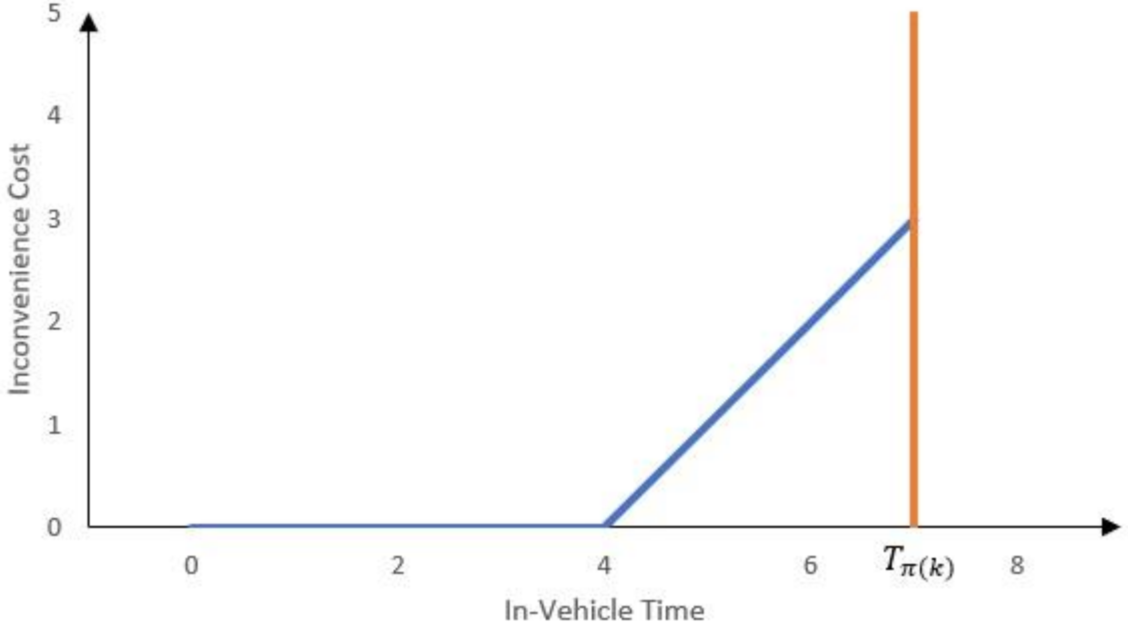
HOW TO SHARE THE COST F

- Predict the total number of passengers by adapting a robust optimization method (Bandi et al. 2015, 2018)
- A passenger's share of the driver's direct cost $= F \times \frac{passenger's\ demand}{total\ demand\ of\ the\ estimated\ passengers}$

- Pros:
  - four of the five original desirable properties are satisfied
  - Fairness in Sharing Driver's Cost property holds
  - Reduced Burden for the First Passenger property holds
- Cons:
  - the Budget Balance property is lost (increase prediction accuracy can mitigate this issue)

STATIC RIDE-SHARING MECHANISM DESIGN

RIDE-SHARING with TIME CONSTRAINTS



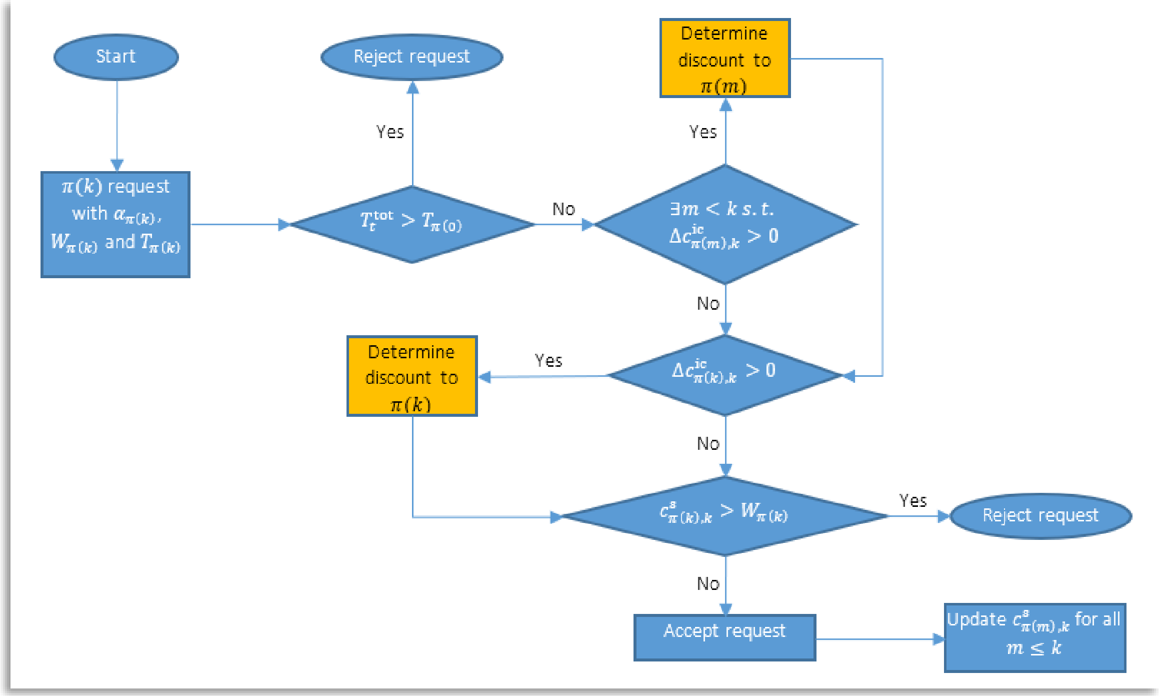
WHAT'S DIFFERENT?

- Drivers and passengers have a limit of how much time they want to spend in the vehicle.
- We use an inconvenience cost function to measure delays past their time window

STATIC RIDE-SHARING MECHANISM DESIGN

RIDE-SHARING with TIME CONSTRAINTS

Total Shared Cost = **Shared Cost of F** + **Shared Cost of the Total Detour** + **DISCOUNT COMPONENT**



Process Flow Diagram

Discounts are received whenever inconveniences occur

How to determine the discount amount?

STATIC RIDE-SHARING MECHANISM DESIGN

RIDE-SHARING with TIME CONSTRAINTS

Basic Discount

The new passenger is responsible for all inconvenience costs of previous passengers

- Pros:
  - three of the five original desirable properties are satisfied
  - Fairness in Sharing Driver's Cost property holds
  - Reduced Burden for the First Passenger property holds
  - Passengers are not responsible for the inconveniences costs that are not caused by themselves
- Cons:
  - the Online Fairness property is lost
  - the Ex-Post Incentive Compatibility property is lost

Inconvenience Cost Based Discount

Passengers form coalitions to share the inconvenience costs

- Pros:
  - four of the five original desirable properties are satisfied
  - Fairness in Sharing Driver's Cost property holds
  - Reduced Burden for the First Passenger property holds
- Cons:
  - the Online Fairness property is lost
  - passengers with high tolerance for time may not get any discounts while being responsible for part of the total inconvenience cost
  - requires more memory and time in simulation

EXPERIMENT RESULT

MECHANISM WITHOUT DISCOUNT

SETTINGS

- Randomly generated data set on 40*40 grid
- Each replication has 1 vehicle and 4 passengers
- Cost per mile is $1
- Clustered spatial pattern, origins (destinations) are generated within a 10*10 grid at the bottom left (top right) corner
- Results are averaged over 100 replications

COMPARE

- **Driver-out-of-coalition (DooC) mechanism**
- **Driver-in-coalition (DiC) mechanism**
- **Passengers Prediction (PP) mechanism**

EXPERIMENT RESULT

MECHANISM WITHOUT DISCOUNT

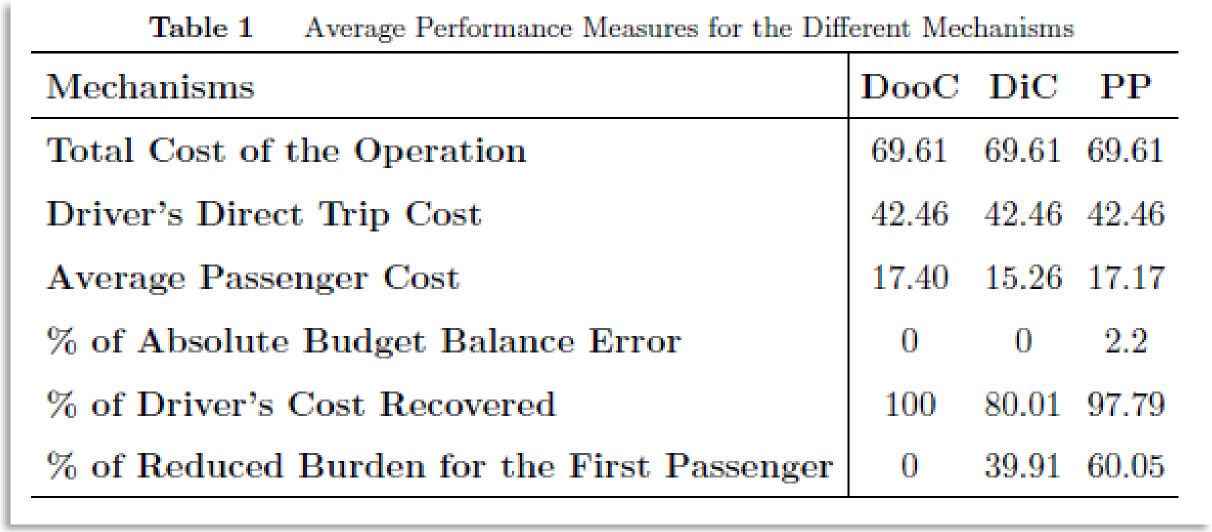


Table 1 Average Performance Measures for the Different Mechanisms

Mechanisms	DooC	DiC	PP
Total Cost of the Operation	69.61	69.61	69.61
Driver's Direct Trip Cost	42.46	42.46	42.46
Average Passenger Cost	17.40	15.26	17.17
% of Absolute Budget Balance Error	0	0	2.2
% of Driver's Cost Recovered	100	80.01	97.79
% of Reduced Burden for the First Passenger	0	39.91	60.05

INSIGHTS

- Supports theoretical analysis
- DiC produces the lowest average passenger cost
- DooC recovers all of the driver's cost
- PP balances the driver and passengers' costs

Choose PP mechanism for sharing F for further experiments in comparing the discount methods

EXPERIMENT RESULT

MECHANISM WITH DISCOUNT

Small Dataset

↳ low probability in passengers having inconvenience costs

↓

Go with Large Dataset

↳ the problem becomes too large to solve optimally

↓

Use heuristics for quick solution with good quality

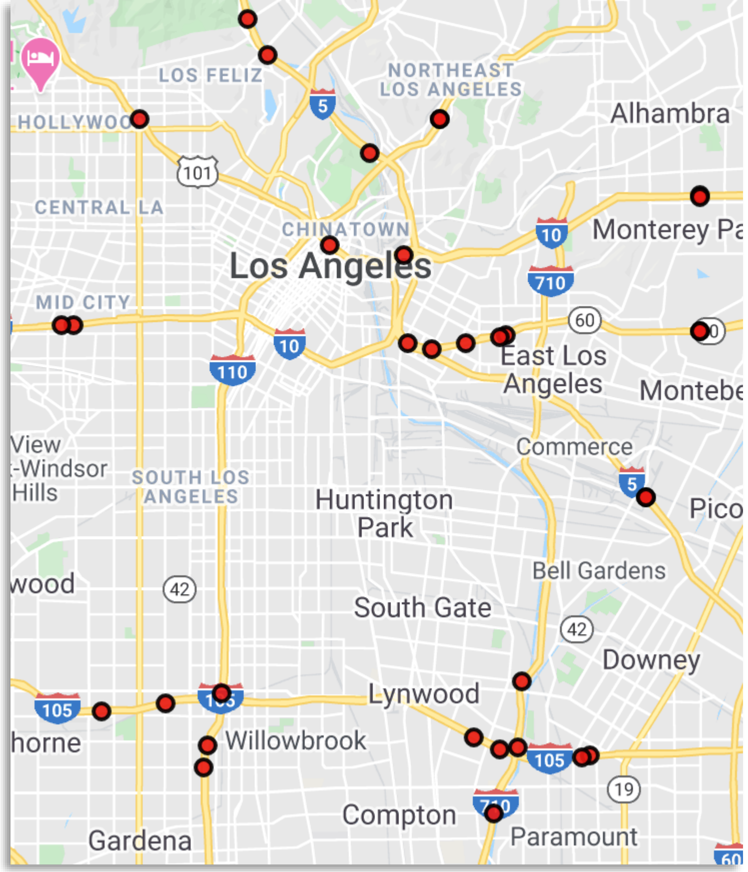
↳ the Ex-Post Incentive Compatibility is lost

↓

The effect of the loss of the property is tested in the paper

EXPERIMENT RESULT

MECHANISM WITH DISCOUNT



DATASET

- Road sensor data by LA Metro (archived by USC researchers)
- LA county region including 33 sensors on 7 freeways
- Generate origin-destination (OD) probability matrix using the sensor data
- OD generated randomly using the OD probability matrix

EXPERIMENT RESULT

MECHANISM WITH DISCOUNT

GENERAL SETTINGS

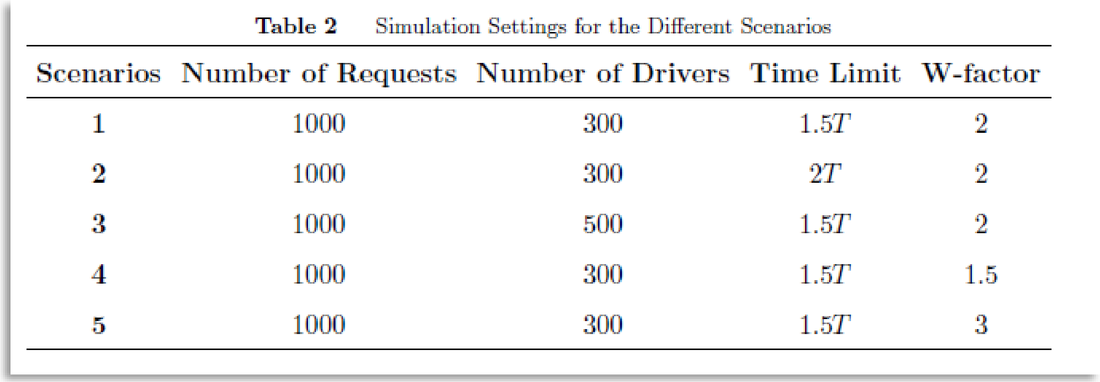


Table 2 Simulation Settings for the Different Scenarios

Scenarios	Number of Requests	Number of Drivers	Time Limit	W-factor
1	1000	300	$1.5T$	2
2	1000	300	$2T$	2
3	1000	500	$1.5T$	2
4	1000	300	$1.5T$	1.5
5	1000	300	$1.5T$	3

- Average vehicle speed: 36 mph
- Each passenger has **different linear function** value of in-vehicle time
- Maximum in-vehicle time is set to be either **1.5 or 2 times** their direct travel time
- Each passenger has a willingness-to-pay-level of **1.5, 2 or 3** times (W-factor) the passengers' direct cost
- The system has **1,000 passenger requests** and **300 or 500 ride-sharing drivers**
- Results are averaged over **100 replications**

EXPERIMENT RESULT

MECHANISM WITH DISCOUNT

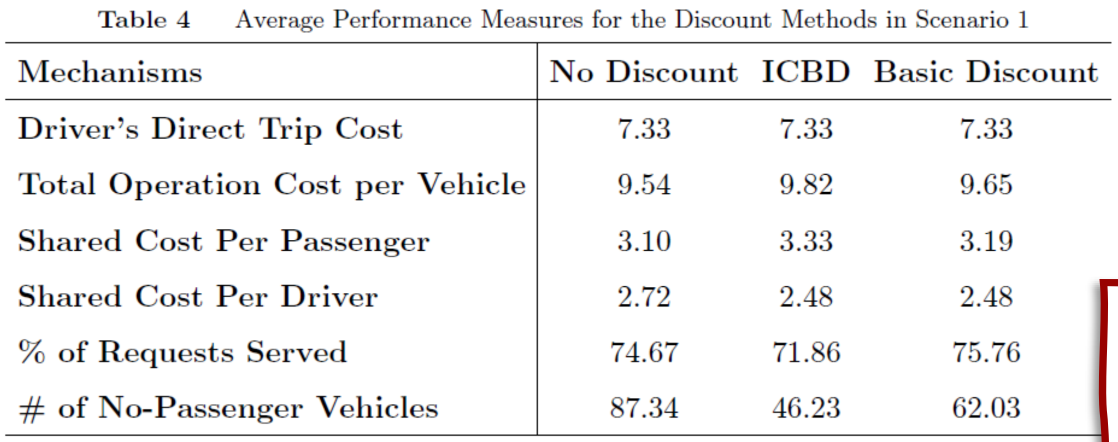


Table 4 Average Performance Measures for the Discount Methods in Scenario 1

Mechanisms	No Discount	ICBD	Basic Discount
Driver's Direct Trip Cost	7.33	7.33	7.33
Total Operation Cost per Vehicle	9.54	9.82	9.65
Shared Cost Per Passenger	3.10	3.33	3.19
Shared Cost Per Driver	2.72	2.48	2.48
% of Requests Served	74.67	71.86	75.76
# of No-Passenger Vehicles	87.34	46.23	62.03

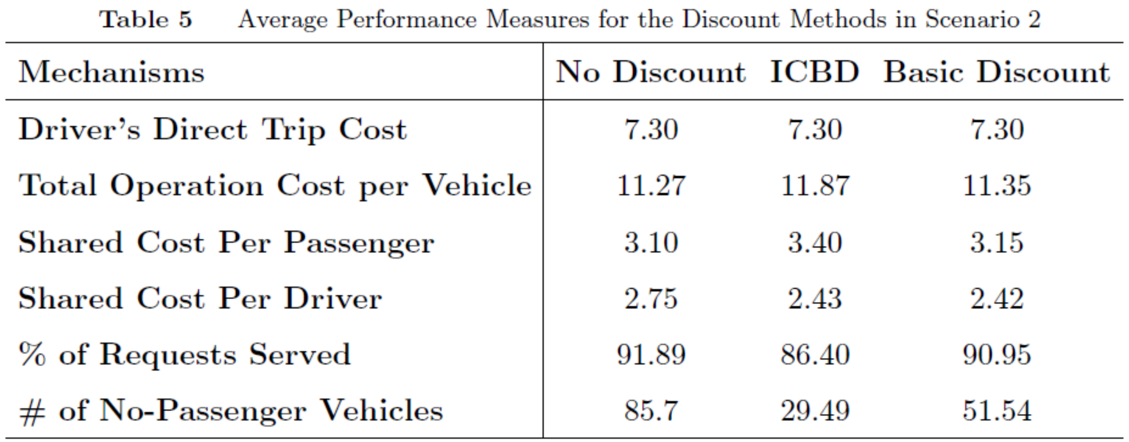
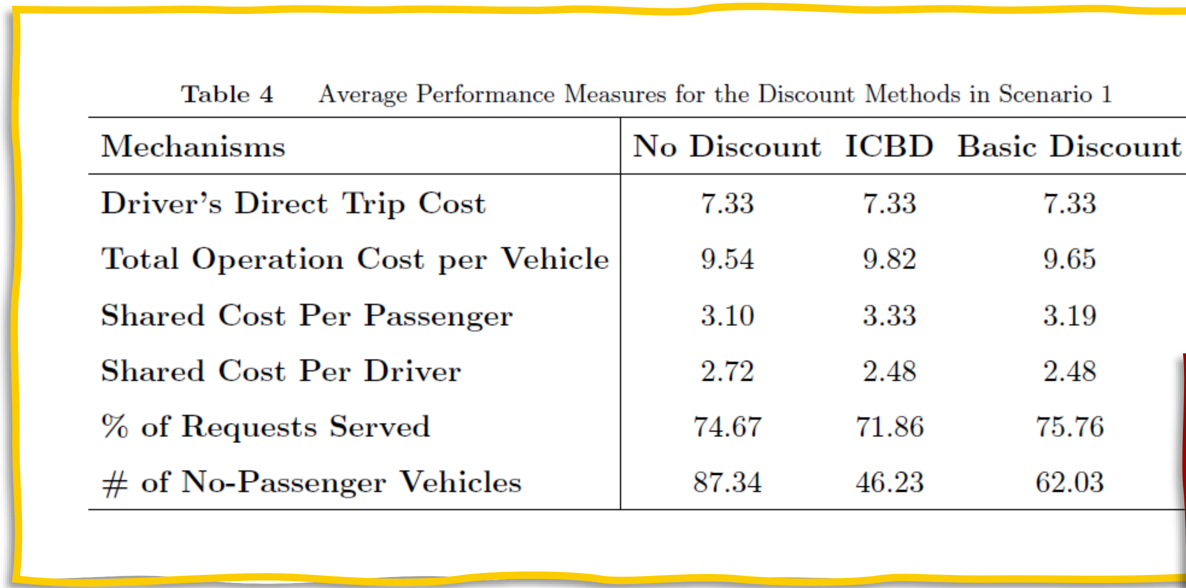


Table 5 Average Performance Measures for the Discount Methods in Scenario 2

Mechanisms	No Discount	ICBD	Basic Discount
Driver's Direct Trip Cost	7.30	7.30	7.30
Total Operation Cost per Vehicle	11.27	11.87	11.35
Shared Cost Per Passenger	3.10	3.40	3.15
Shared Cost Per Driver	2.75	2.43	2.42
% of Requests Served	91.89	86.40	90.95
# of No-Passenger Vehicles	85.7	29.49	51.54

EXPERIMENT RESULT

MECHANISM WITH DISCOUNT



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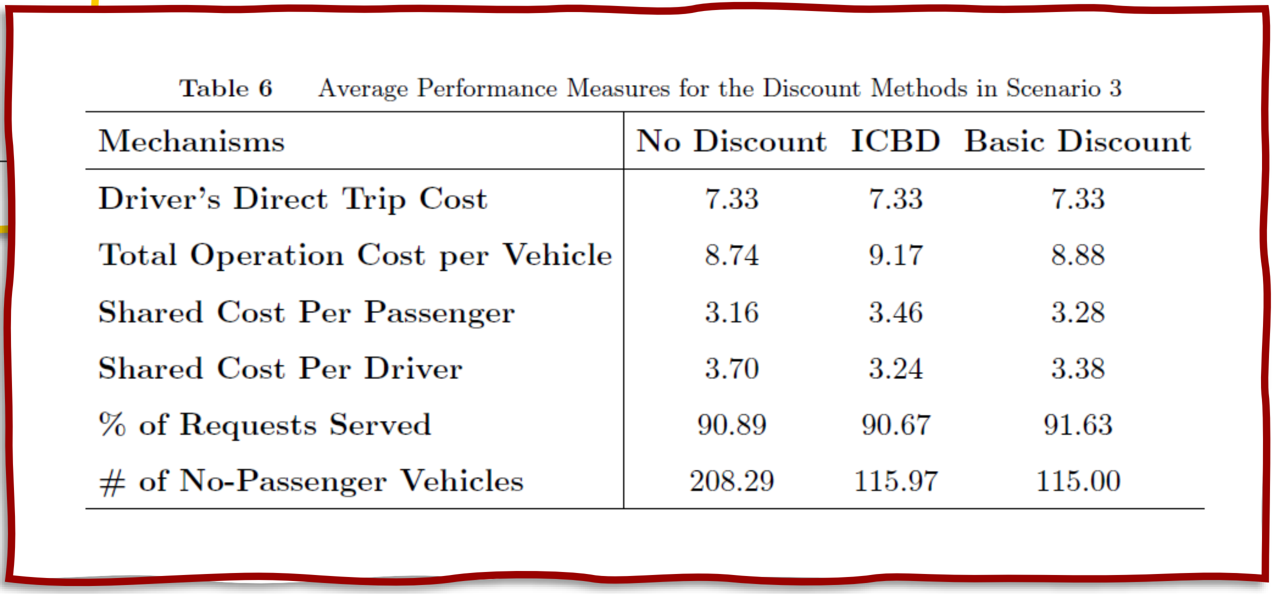


Table 6 Average Performance Measures for the Discount Methods in Scenario 3

Mechanisms	No Discount	ICBD	Basic Discount
Driver's Direct Trip Cost	7.33	7.33	7.33
Total Operation Cost per Vehicle	8.74	9.17	8.88
Shared Cost Per Passenger	3.16	3.46	3.28
Shared Cost Per Driver	3.70	3.24	3.38
% of Requests Served	90.89	90.67	91.63
# of No-Passenger Vehicles	208.29	115.97	115.00

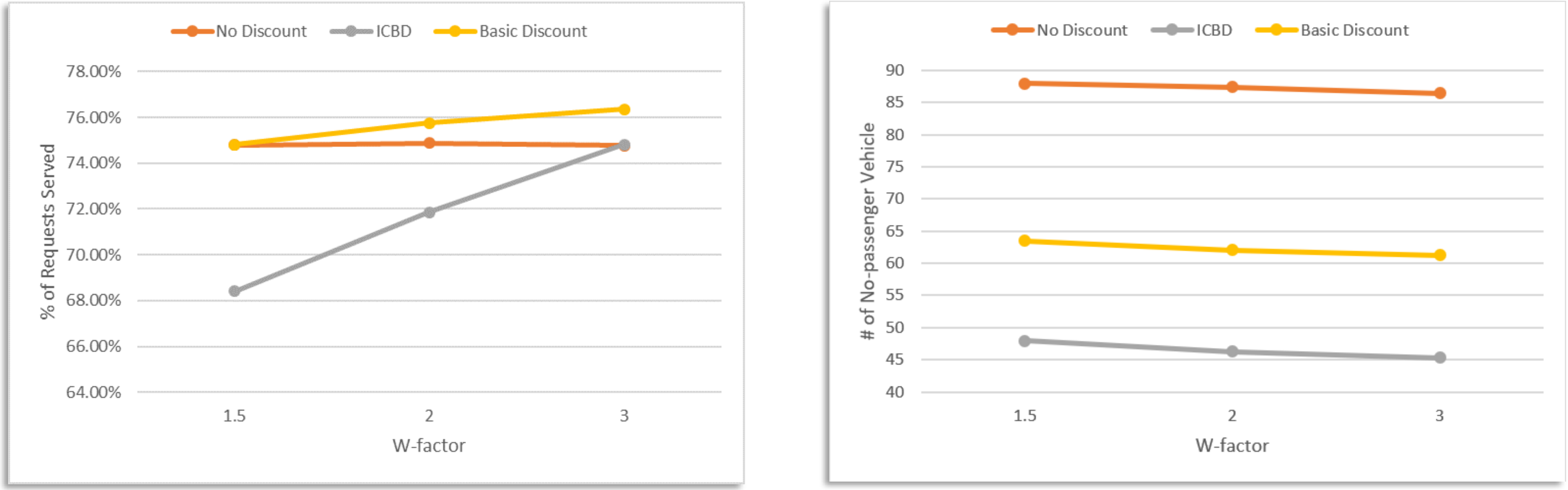
EXPERIMENT RESULT

MECHANISM WITH DISCOUNT

The effect of willingness-to-pay-level on passengers' cost and drivers' cost

EXPERIMENT RESULT

MECHANISM WITH DISCOUNT



The effect of willingness-to-pay-level on % served and # of no-passenger vehicles

CONCLUSION

WHAT HAVE WE DONE

- Developed RSMF for designing cost-sharing mechanisms in ride-sharing
  - Modular
  - Caters to different requirements
- Proposed 3 mechanisms in detail
  - PP mechanism balances driver cost with passenger cost
- Developed 2 discount methods
  - BD outperforms ICBD in shared cost per passenger and number of requests served
  - ICBD leads to a more distributed system

FUTURE DIRECTIONS…

- Develop cost-sharing mechanisms for the dynamic case
- Develop a dynamic ride-sharing routing method
- Combine the cost-sharing mechanisms and the routing method in the dynamic case and test their performances

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