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
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 compatibility, efficiency.

Use of Social Networking Sites (SNS)
- Get to know the driver/rider
- ZimRide, Carma, Participate

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.
### AN EXAMPLE

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<tr>
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</table>
**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

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<td>30</td>
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- × 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:

\[
\text{cost}^t_{\pi(k)} := \alpha_{\pi(k)} \min_{k \leq j \leq t} \max_{1 \leq i \leq j} \frac{\sum_{l=i}^{j} mc_{\pi(l)}}{\sum_{l=i}^{j} \alpha_{\pi(l)}} \text{ccpa}_{\pi(i,j)}
\]

- 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

\[
\text{Total Cost} = \text{Driver’s Direct Cost } F + \text{Total Detour Cost}
\]

\[
\text{Total Shared Cost} = \text{Shared Cost of } F + \text{Shared Cost of the Total Detour}
\]

- **Any sub-mechanism**
- Propose 3 mechanisms

- **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 = \( F \times \frac{\text{passenger’s demand}}{\text{total demand of the estimated passengers}} \)

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)
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**

\[
\text{Total Shared Cost} = \text{Shared Cost of F} + \text{Shared Cost of the Total Detour} + \text{Discount Component}
\]

**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

<table>
<thead>
<tr>
<th>Mechanisms</th>
<th>DooC</th>
<th>DiC</th>
<th>PP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Cost of the Operation</td>
<td>69.61</td>
<td>69.61</td>
<td>69.61</td>
</tr>
<tr>
<td>Driver’s Direct Trip Cost</td>
<td>42.46</td>
<td>42.46</td>
<td>42.46</td>
</tr>
<tr>
<td>Average Passenger Cost</td>
<td>17.40</td>
<td>15.26</td>
<td>17.17</td>
</tr>
<tr>
<td>% of Absolute Budget Balance Error</td>
<td>0</td>
<td>0</td>
<td>2.2</td>
</tr>
<tr>
<td>% of Driver’s Cost Recovered</td>
<td>100</td>
<td>80.01</td>
<td>97.79</td>
</tr>
<tr>
<td>% of Reduced Burden for the First Passenger</td>
<td>0</td>
<td>39.91</td>
<td>60.05</td>
</tr>
</tbody>
</table>

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

- 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

<table>
<thead>
<tr>
<th>Mechanisms</th>
<th>No Discount</th>
<th>ICBBD</th>
<th>Basic Discount</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driver’s Direct Trip Cost</td>
<td>7.33</td>
<td>7.33</td>
<td>7.33</td>
</tr>
<tr>
<td>Total Operation Cost per Vehicle</td>
<td>9.54</td>
<td>9.82</td>
<td>9.65</td>
</tr>
<tr>
<td>Shared Cost Per Passenger</td>
<td>3.10</td>
<td>3.33</td>
<td>3.19</td>
</tr>
<tr>
<td>Shared Cost Per Driver</td>
<td>2.72</td>
<td>2.48</td>
<td>2.48</td>
</tr>
<tr>
<td>% of Requests Served</td>
<td>74.67</td>
<td>71.86</td>
<td>75.76</td>
</tr>
<tr>
<td># of No-Passenger Vehicles</td>
<td>87.34</td>
<td>46.23</td>
<td>62.03</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Mechanisms</th>
<th>No Discount</th>
<th>ICBBD</th>
<th>Basic Discount</th>
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</thead>
<tbody>
<tr>
<td>Driver’s Direct Trip Cost</td>
<td>7.30</td>
<td>7.30</td>
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<tr>
<td>Total Operation Cost per Vehicle</td>
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<td>11.87</td>
<td>11.35</td>
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<tr>
<td>Shared Cost Per Passenger</td>
<td>3.10</td>
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<tr>
<td>Shared Cost Per Driver</td>
<td>2.75</td>
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<td>% of Requests Served</td>
<td>91.89</td>
<td>86.40</td>
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<td># of No-Passenger Vehicles</td>
<td>85.7</td>
<td>29.49</td>
<td>51.54</td>
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</table>
EXPERIMENT RESULT

MECHANISM WITH DISCOUNT

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

<table>
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<th>Basic Discount</th>
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Table 6  Average Performance Measures for the Discount Methods in Scenario 3

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<td>Shared Cost Per Driver</td>
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<td>% of Requests Served</td>
<td>90.89</td>
<td>90.67</td>
<td>91.63</td>
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<td># of No-Passenger Vehicles</td>
<td>208.29</td>
<td>115.97</td>
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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


