A Dynamic Cost Allocation Model for Truck Sharing

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Introduction and Motivation

Today’s Logistics Sector

- The backbone of many industries, e.g. manufacturing, food, e-commerce
- Economically, environmentally, and socially inefficient
- Safety threats, freight and passenger traffic interaction
- Uncertainties throughout various stages of operation

Horizontal Cooperation in Logistics

- Sharing transportation networks and pooling customers
- Studied in the literature (Cruijssen et al. 2007, Lewczuk et al. 2011)
- Limited application in the industry (forest industry, Frisk et al. 2010)
Project Objectives

How to enable horizontal cooperation in logistics?

• Fairness
• Efficiency
• Uncertainty

ISSUES

Design a real-time cost sharing transportation system

• Pooling transportation demand and capacity supply
• Operate under uncertainties -> dynamic real-time routing
• Online cost allocation in a dynamic environment

Formulate the real-time cost sharing transportation system

Design an online cost-sharing mechanism

Integrate with dynamic vehicle routing framework

Theoretical analysis + numerical simulation
Literature Review and Contribution

**Two Problems**

become interdependent in the dynamic environment

- Complete realization of customers only known at the end of the planning horizon
- Optimal cost can only be approximated
- Routing schedule depends on customer realization and acceptance
- Shared cost depends on routing schedule and total cost

*Proportional Online Cost Sharing (Furuhata et al. 2015)*
Dynamic Vehicle Routing

Look-ahead dynamic vehicle routing framework

Periodic Re-optimization + Dynamic Real-time Routing

- Partial planning of routing schedule
- Optimize schedule
- Optimize departure and arrival times
Online Cost-sharing Mechanism Design

**DESIRED PROPERTIES**

Online fairness, immediate response, individual rationality, budget balance, Ex-post incentive compatibility

**Common Cost Allocation Methods Fail in the Dynamic Environment**

- Naïve Proportional cost sharing: individual rationality
- Incremental cost sharing: ex-post incentive compatibility
Hybrid Online Cost Sharing Mechanism (HPOCS)

Important Concepts and Terms

- **Total cost formulation** – the grand schedule and induced partial schedule
- **SCPA** - Shared cost per alpha value
- **CCPA** - Coalition cost per alpha value
- **Initial Quote** – The 1st calculated shared cost for a customer
- **Final Shared cost** – The final shared cost that a customer actually pays

Cost Characteristics for Advance Customers (AC) and Dynamic Customers (DC)

- All **AC will form a single coalition** sharing the same scpa
- The initial quote per alpha value for a AC is fixed given the set of AC
- The initial quote per alpha value for a DC is based on the marginal cost
HPOCS Procedures

\[ t = 0 \]
- calculate grand schedule
- quote AC

\[ t = T_{max} \]
Calculate final shared cost for all customers

DC Request
- try to insert DC
- calculate partial schedule
- quote DC
HPOCS Example

Customer Information

<table>
<thead>
<tr>
<th>Customer</th>
<th>Demand</th>
<th>Alpha</th>
<th>Deadline</th>
<th>Time Window</th>
<th>Service</th>
<th>Time</th>
<th>Request Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1</td>
<td>4</td>
<td>—</td>
<td>[0, 10]</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>1</td>
<td>5</td>
<td>—</td>
<td>[5, 10]</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>1</td>
<td>7</td>
<td>—</td>
<td>[25, 30]</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>1</td>
<td>6</td>
<td>10</td>
<td>[10, 25]</td>
<td>1</td>
<td>9</td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>1</td>
<td>3</td>
<td>25</td>
<td>[25, 35]</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>F</td>
<td>1</td>
<td>2</td>
<td>30</td>
<td>[30, 40]</td>
<td>1</td>
<td>20</td>
<td></td>
</tr>
</tbody>
</table>

$t = 0$, The Grand Schedule


Partial Schedules

# HPOCS Example – Cost Allocation

## Total Cost & Marginal Cost

<table>
<thead>
<tr>
<th>Time</th>
<th>Request</th>
<th>Total Cost</th>
<th>Marginal Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A</td>
<td>6.0</td>
<td>6.0</td>
</tr>
<tr>
<td>0</td>
<td>B</td>
<td>13.5</td>
<td>7.5</td>
</tr>
<tr>
<td>0</td>
<td>C</td>
<td>24.0</td>
<td>10.5</td>
</tr>
<tr>
<td>9</td>
<td>D</td>
<td>24.0</td>
<td>0.0</td>
</tr>
<tr>
<td>25</td>
<td>F</td>
<td>28.0</td>
<td>4.0</td>
</tr>
</tbody>
</table>

## Final Shared Costs

<table>
<thead>
<tr>
<th>Time</th>
<th>Coalitions</th>
<th>Shared Costs per Alpha</th>
<th>HPOCS Shared Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>0</td>
<td>(A)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>0</td>
<td>(A, B)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>0</td>
<td>(A, B, C)</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>9</td>
<td>(A, B, C, D)</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>25</td>
<td>(A, B, C, D) (F)</td>
<td>1.1</td>
<td>1.1</td>
</tr>
<tr>
<td>50</td>
<td>(A, B, C, D) (F)</td>
<td>1.1</td>
<td>1.1</td>
</tr>
</tbody>
</table>
HPOCS Analysis & Results

Properties Maintained
1. Budget Balance
2. Online Fairness
3. Immediate Response
4. Individual Rationality
5. Ex-Post Incentive Compatibility

Simulation Settings
- Customer information – Soloman RC201 instances
- # of all customers – $N = 100$
- Length of planning horizon – $T_{max} = 960$
- % of advance customers – $ACP\text{percent} = 0.25$
- Dynamic customer’s request probability – $Request\text{Prob} = 0.75$
HPOCS Analysis & Results

Trajectories of the shared cost per alpha values
HPOCS Analysis & Results

Initial quotes and final shared cost values
HPOCS Extensions

**HPOCSD**
HPOCS mechanism including the concept of discounts

- Three overcharge heuristics: level, linear and exponential
- This is to provide incentives to advance customers and realized dynamic customers who request early.
  - **Budget Balance property lost**

**HPOCSrO**
HPOCS mechanism with periodical re-optimization on total cost function

- This is to improve the overall performance of HPOCS when the number of realized customers is small and provide some incentives to advance customers and realized dynamic customers who request early.
  - **Ex-Post Incentive Compatibility property lost**
HPOCS Extensions – HPOCSD Results

Discount = 0.1

Discount = 0.2

Discount = 0.3

Discount = 0.4
HPOCS Extensions – HPOCSD Results

[Graphs showing the impact of different discount values on the initial quotes and final charges under HPOCSD with exponential overcharge]
HPOCS Extensions – HPOC SRo Results

Simulation Settings

- Customer information – Soloman RC201 instances
- # of all customers – $N = 100$
- Length of planning horizon – $T_{max} = 960$
- % of advance customers – $ACPercent = 0.1, 0.25$
- Dynamic customer’s request probability – $RequestProb = 0.25, 0.5$
HPOCS Extensions – HPOCsrO Results

Initial quote and final shared cost of the two methods in scenario 3

Scenario 3: # Advance Customers = 10; RequestProb = 0.5

Figure 13a: HPOCS

Figure 13b: HPOCsrO

Initial quote  Final price

Initial quote  Final price
HPOCS Extensions – HPOCSrO Analysis

To better understand the tradeoff between the performance of our designed mechanism and the effect brought by the loss of Ex-Post Incentive Compatibility property, extra simulations have done for testing purpose.

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>% Better off</th>
<th>% Worse</th>
<th>% Same</th>
<th>AVG Price Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>0AC_21DC</td>
<td>27.2%</td>
<td>50.6%</td>
<td>22.2%</td>
<td>8.871%</td>
</tr>
<tr>
<td>10AC_21DC</td>
<td>32.4%</td>
<td>56.8%</td>
<td>10.8%</td>
<td>8.623%</td>
</tr>
<tr>
<td>20AC_21DC</td>
<td>36.6%</td>
<td>57.6%</td>
<td>5.8%</td>
<td>5.921%</td>
</tr>
<tr>
<td>Total</td>
<td>32.1%</td>
<td>55.0%</td>
<td>12.9%</td>
<td>7.805%</td>
</tr>
</tbody>
</table>

Average gap results of 500 samples in each scenario

Simulation Settings

- Customer information – Soloman RC201 instances
- # of all customers – \( \mathcal{N} = 100 \)
- Length of planning horizon – \( T_{max} = 960 \)
- # of dynamic customers – DCNumber = 21
- # of advance customers – ACNumber = 0, 10, 20
- The positions which the 1st DC delays to – Delay slots = 2, 6, 11, 16, 21
## HPOCS Extensions – HPOCSErO Analysis

### Percentage of customers better off in each slot across different scenarios

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Slot 2</th>
<th>Slot 6</th>
<th>Slot 11</th>
<th>Slot 16</th>
<th>Slot 21</th>
</tr>
</thead>
<tbody>
<tr>
<td>0AC_21DC</td>
<td>20%</td>
<td>37%</td>
<td>28%</td>
<td>33%</td>
<td>18%</td>
</tr>
<tr>
<td>10AC_21DC</td>
<td>30%</td>
<td>39%</td>
<td>39%</td>
<td>31%</td>
<td>23%</td>
</tr>
<tr>
<td>20AC_21DC</td>
<td>44%</td>
<td>40%</td>
<td>44%</td>
<td>41%</td>
<td>14%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>31.3%</strong></td>
<td><strong>38.7%</strong></td>
<td><strong>37.0%</strong></td>
<td><strong>35.0%</strong></td>
<td><strong>18.3%</strong></td>
</tr>
</tbody>
</table>

### Percentage of customers worse off in each slot across different scenarios

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Slot 2</th>
<th>Slot 6</th>
<th>Slot 11</th>
<th>Slot 16</th>
<th>Slot 21</th>
</tr>
</thead>
<tbody>
<tr>
<td>0AC_21DC</td>
<td>12%</td>
<td>37%</td>
<td>63%</td>
<td>59%</td>
<td>82%</td>
</tr>
<tr>
<td>10AC_21DC</td>
<td>35%</td>
<td>50%</td>
<td>55%</td>
<td>67%</td>
<td>77%</td>
</tr>
<tr>
<td>20AC_21DC</td>
<td>40%</td>
<td>53%</td>
<td>52%</td>
<td>57%</td>
<td>86%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>29.0%</strong></td>
<td><strong>46.7%</strong></td>
<td><strong>56.7%</strong></td>
<td><strong>61.0%</strong></td>
<td><strong>81.7%</strong></td>
</tr>
</tbody>
</table>

### Average price change of delayed customers in each slot across different scenarios

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Slot 2</th>
<th>Slot 6</th>
<th>Slot 11</th>
<th>Slot 16</th>
<th>Slot 21</th>
</tr>
</thead>
<tbody>
<tr>
<td>0AC_21DC</td>
<td>-0.433%</td>
<td>0.837%</td>
<td>1.803%</td>
<td>2.905%</td>
<td>51.782%</td>
</tr>
<tr>
<td>10AC_21DC</td>
<td>0.267%</td>
<td>0.036%</td>
<td>1.183%</td>
<td>2.767%</td>
<td>63.275%</td>
</tr>
<tr>
<td>20AC_21DC</td>
<td>0.276%</td>
<td>0.706%</td>
<td>1.258%</td>
<td>3.147%</td>
<td>47.849%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>-0.007%</strong></td>
<td><strong>0.541%</strong></td>
<td><strong>1.449%</strong></td>
<td><strong>2.928%</strong></td>
<td><strong>54.391%</strong></td>
</tr>
</tbody>
</table>
Conclusions

The HPOCS mechanism meets all desirable properties.

The drawbacks of HPOCS are compensated by two extensions which are shown to be effective in tested scenarios.

The tradeoff of the two extensions is the lost of certain properties, but the results in tested scenarios are acceptable.