Competitive Performance Assessment of Dynamic Vehicle Routing Technologies Using Sequential Auctions

Miguel Figliozzi *
Hani Mahmassani *
Patrick Jaillet +

* University of Maryland College Park
+ Massachusetts Institute of Technology
Motivation …

Developments in Information and Communication Technologies are:

– Transforming Supply Chain Operations
– Introducing **new ways of matching supply and demand**
  - Private Exchanges
  - Transportation Auctions
– Allowing carriers to implement more sophisticated Dynamic Vehicle Routing Technologies (DVR)
  - Real Time Operation
  - Improved scheduling decision systems
Dynamic Vehicle Routing Technologies have to increasingly deal with a new class of problems…

**FROM**
- Pre-negotiated Contracts
- Limited, standard services
- Static, Deterministic Conditions
- Optimization for long term equilibrium
- Absence of competition in every day operations

**TO**
- Dynamic Pricing
- Customized services, all the time, everywhere
- Dynamic, Stochastic Environments
- Optimization under Real Time Information
- Highly competitive environments
Traditional Approaches to Evaluate the Performance of Vehicle Routing Technologies

Static
- complexity analysis
- worst case/average case

Dynamic
- Competitive Analysis
  - Competitive ratio against a powerful off-line adversary
  - Adversary determines the sequence of future tasks
  - Oblivious
  - Adaptive

Asymptotic performance
Traditional Approaches to Evaluate the Performance of Vehicle Routing Technologies

Issues in a Dynamic Competitive Environment:

- Does an optimal policy exist?
- Even if there is an optimal policy
  - Comparison is NOT in a level playing field (hind sight advantage)
  - Trivial results using competitive analysis
  - NO dynamic interaction among Carriers under relevant demand scenarios
  - Real Time Implementation
Proposed Approach to Evaluate the Performance of Dynamic Vehicle Routing Technologies (DVR)

1. Make 2 carriers compete under different demand scenarios in a Procurement Market for Transportation Services

2. Use Sequential 2\textsuperscript{nd} price auctions
   - Allocate service requests among carriers
   - Determine the corresponding price

3. Use simulation to obtain the relevant pay-off information
Research Methodology

- Study the impact of:
  - fleet management technological asymmetries

- On carriers’:
  - Costs
  - Revenue
  - Profits
  - Market share

- Under different market settings
  - Shipment Arrival Rates
  - Time Window Lengths
Auction Type: Second Price Auction (one shot)

DEFINITION (reverse auction)
- Carrier with lowest bid wins item
- Winner get paid second lowest bid
- Rest of bidders do not pay or receive anything

PROPERTIES (Vickrey 1961)
- Equilibrium strategies are truth-revealing and dominant strategies
- They do not require gathering or analysis of information about the competitors’ situation
- Leads to complete economic efficiency, the bidder with the lowest cost wins

Equivalent Results with Ascending English Auction and Proxy Bidding
Problems with 2\textsuperscript{nd} Price Sequential Auctions

- Complexity of equilibrium and strategy analysis increases substantially
- No known equilibrium for bidders with multi-unit demands and heterogeneous items
- Marginal Cost is a random variable and depends on the future sequence of arrivals
**Behavioral Assumptions**

**ASSUMPTION**: a carrier bids the “best” estimation of his marginal produced by his technology.

- Obtained:
  - Carriers rationality: preference over outcomes with higher expected profit
  - Dropping common knowledge assumption
    - Minimum Information Revealed
    - Complexity of simulating competitors’ future payoffs and actions
Experimental Factors

- Different Carrier Technologies
  - Naïve
  - Optimal Static (OS)
  - 1 Step Look-Ahead (1LA)

- Different Arrival Rates (AR)
  - $\lambda = 0.5$ arrivals/truck (Low)
  - $\lambda = 1.0$ arrivals/truck (Med.)
  - $\lambda = 1.5$ arrivals/truck (High)

- Different Time Window Lengths (TWL)
  - $1 \times$ loaded distance + $1 \times$ uniform (0,1) (Short)
  - $2 \times$ loaded distance + $2 \times$ uniform (0,1) (Med.)
  - $3 \times$ loaded distance + $3 \times$ uniform (0,1) (Long)

- Average Loaded Distance $\approx 0.52$
- Average Empty Distance $\approx 0.25$
Other Market Settings

- Geographic Area: 1 * 1 square space
- Shipment Origin and Destination: \( \approx \) Uniformly distributed on space
- Earliest Pick Up Time = arrival time
- Fleet size: 2 to 6 vehicles serving the market
- The reservation price of the buyer is 1.5 units

Simulation Results: 10 iterations (1000 arrivals)
Carriers’ Technologies

- **Naïve**: Insertion at the end of truck’s list of assigned shipments

- **Tech OS**: “Optimal Static Assignment” at fleet level. Solve optimal assignment for ALL trucks at a time (MIP formulation)
  - MIP formulation objective:
    - Minimize empty distance
Carriers’ Technologies

Naïve

Tech OS

1, 2, 3  
Arrival Order

Empty Movement

Loaded Movement
Carriers’ Technologies Marginal Costs

1, 2, 3 Arrival Order
- - - - - Empty Movement
  → Loaded Movement

Naïve Marginal Cost (Shipment 3)
- - - - -

OS Marginal Cost (Shipment 3)
- - - - (+) - -
(-) - -
= - - - -
Carriers’ Technologies

- **Tech 1LA**: “Optimal Static Assignment” + 1 Step Look-Ahead
  - Elimination of Weakly Dominated Strategies
  - Backward Iteration

\[
\text{Bid} = mc \text{ (static)} + \mathbb{E}(P_1 | \text{lose}) - \mathbb{E}(P_1 | \text{win})
\]

Where:
\[
\mathbb{E}(P_1) = \text{expected profit for the next arriving shipment}
\]

Intuition:
- Better deployment, then future profits $\uparrow$, current $mc \downarrow$
- Worse deployment, then future profits $\downarrow$, current $mc \uparrow$
Carriers’ Technologies

**Tech 1LA**: “Optimal Static Assignment” + 1 Step Look-Ahead

- Solve optimal assignment for all trucks at a time (MIP formulation)
- Simulate future expected profits *With* and *Without* the shipment currently being bid on
  - Carrier learns revenue distribution online (assumed stationary stochastic process)
- Adding opportunity cost to “static” estimation
  - Capacity to serve future shipments
  - Fleet deployment changes
Comparing Naïve and OS Technologies

![Graph showing PROFIT DIFFERENCE and PROFIT DIFFERENCE %]

- PROFIT DIFFERENCE
- PROFIT DIFFERENCE %
Comparing Naïve and OS Technologies

**SHIPMENTS SERVED DIFFERENCE**

- TW Short: Med., Long
- AR Low: Med., High

**SHIPMENTS SERVED DIFFERENCE %**

- TW Short: Med., Long
- AR Low: Med., High
Analysis of Results

- More sophisticated technologies are more competitive
- OS significantly improves over Naïve:
  - Med. arrival rates (competitive environment)
  - Longer time Windows (more shipments)
Comparing OS and 1LA Technologies
Comparing OS and 1LA Technologies
Comparing OS and 1LA Technologies

**SHIPMENT SERVED DIFFERENCE**

**BID VALUE DIFFERENCE %**
Comparing OS and 1LA Technologies

PROFIT DIFFERENCE %

BID VALUE DIFFERENCE %
Analysis of Results

1LA significantly improves over OS:

- Shorter time windows
  - Harder to accommodate new shipments
  - Higher prices $\rightarrow$ Less Shipments $\rightarrow$ Higher Profits
    (static appraisal underestimates cost of a shipment)

- Med. and Long time windows
  (uncongested AR)
  - Easier to accommodate new shipments
  - Lower prices $\rightarrow$ More Shipments $\rightarrow$ Higher Profits
    (static appraisal overestimates cost of a shipment)

- Low arrival rate
  - Higher percentage wise profit increase
Conclusions

Methodology to compare algorithms seems to capture the *competitiveness* of the different DVR technologies in relation to:

- market parameters
- characteristics of DVR algorithms

1SLA technology captures the “opportunity costs” of serving a shipment as function of:

- Arrival rate
- Time window lengths