

Solving Single-Round, Fully Enumerated Combinatorial Truckload Procurement Auctions to Optimality

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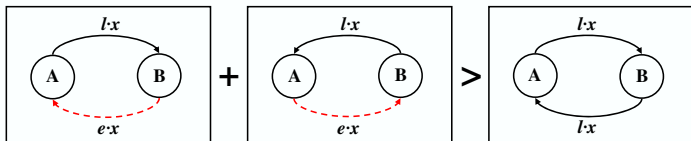
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Introduction/Motivation

- U.S. trucking (truckload, less-than-truckload, private carriage) transportation expenditures in 2005 exceeded \$600 billion. Of this amount, \$300 billion was accounted for by the truckload segment (American Trucking Association 2007).
- Large corporations procure \$billions worth of services annually via internet auctions (Elmaghraby and Keskinocak 2002, Ledyard et al. 2002, and Caplice and Sheffi 2003).
- In practice, the limited use of *combinatorial truckload procurement auctions* (CTPA) has produced realized savings of 6% over traditional methods (Caplice and Sheffi 2003).
- In practice, only 28% of carriers submit multi-load bids in CTPA. Majority of these carriers only submit 2-7 multi-load bids (Plummer 2002).
- **Full benefits of CTPA has not yet been realized in practice.**

Power of Expressive Bidding



- Two loads to be transported. One load from $A \rightarrow B$ and one load from $B \rightarrow A$
- Distance between A and B is x
- Empty and loaded cost per mile are e and l respectively
- Cost to transport both loads separately is $2lx + 2ex$
- Cost to transport both loads in a single tour is $2lx$

Computational Difficulties

- Bid evaluation and communication.
 - Exponential number of load bundles ($2^N - 1$).
 - 30 loads $\rightarrow$ 1,073,741,823 combinations
 - Pricing a bundle involves solving a network optimization problem.
 - Communicating an exponential number of bundles is not possible.
- Solving an exponentially-sized winner determination problem (WDP).

Practical Approaches

- Iterative auctions
- Fast, Approximation and Heuristics Algorithms (Fujishima et al. 1999, Zurel 2001, Sandholm et al. 2002&2005, Günlük et al. 2005)
- Bidding languages (Rothkopf et al. 1998, Nisan 2000, Pekec et al. 2003, de Vries et al. 2003, Günlük et al. 2005)
- Shifting computational burden to bidders (Banks et al. 1989, Bykowsky et al. 1995, Kelly et al. 2000)
- **Current approaches assume exogenously endowed bids**
- **Current approaches do not consider the exhaustive set of bundles**
- **No current approach gives you an optimal solution within a practical time frame**
- Truckload procurement (Caplice and Sheffi 2006, Song and Regan 2003, Raychaudhuri and Veeramani 2006, Porter et al. 2002, Guo et. al 2005)

Traditional Combinatorial Truckload Procurement Auctions

- Bidders construct, price, and submit bids for *bundles* of loads (up to $2^N - 1$)
- Bidders communicate bundle prices to the auctioneer, who solves a winner determination problem (T-WDP)

$$\min \sum_{k \in \mathcal{K}} \sum_{s \in \mathcal{S}^k} p_s^k x_s^k \quad (1)$$

$$\text{subject to: } \sum_{k \in \mathcal{K}} \sum_{s \in \mathcal{S}^k: l \in s} x_s^k = 1 \quad \forall l \in \mathcal{B} \quad (2)$$

$$\sum_{s \in \mathcal{S}^k: l \in s} x_s^k \leq 1 \quad \forall k \in \mathcal{K} \quad (3)$$

$$x_s^k \in \{0, 1\} \quad \forall k \in \mathcal{K}, s \in \mathcal{S}^k \quad (4)$$

Carrier's Cost of Service (1 of 2)

Carriers costs can be broken into two parts – *direct movement cost* and *indirect movement cost*.

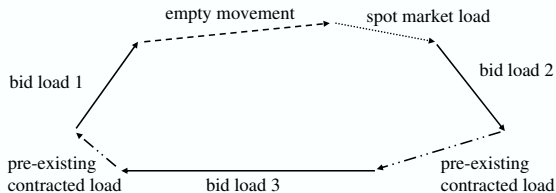
- Direct movement cost – cost associated with actually moving each bid load from the load origin to the load destination. This cost is well understood and largely a function of distance.
- Indirect movement cost – cost associated with repositioning a truck from the destination of the current load to the origin of the next load.

Must consider:

- minimizing empty mileage
- returning drivers home

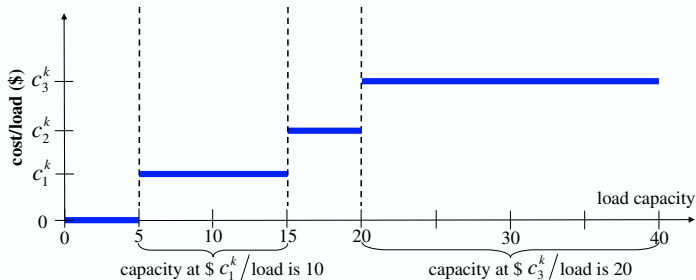
Carrier's Cost of Service (2 of 2)

- To minimize costs, and thus improve profitability, carriers must build efficient **continuous moves**. This can be accomplished not only by combining bid loads, but also by taking advantage of a carrier's pre-existing loads and spot market loads (*backhaul capacity*).



Estimating Backhaul Capacity

- Represent a carrier's backhaul capacity by a set of n -tiered step functions, one for each directed city pair.



Bid-Generating Function

- Given a bundle of loads s , how does each carrier k determine the bid price to cover these loads?

$$f^k(\mathbf{x}^s) := \sum_{a \in \mathcal{A}^{\mathcal{B}}} d_a^k x_a^k + \min \left(\sum_{a \in \mathcal{A}^{\mathcal{E}}} e_a^k y_a^k + \sum_{i \in \mathcal{A}_k^{\mathcal{C}}} c_a^k z_a^k \right) \quad (5)$$

$$\begin{aligned} \text{subject to: } & \sum_{a \in \mathcal{A}^{\mathcal{B}}: \mathcal{O}(a)=i} x_a^k + \sum_{a \in \mathcal{A}^{\mathcal{E}}: \mathcal{O}(a)=i} y_a^k + \sum_{a \in \mathcal{A}_k^{\mathcal{C}}: \mathcal{O}(a)=i} z_a^k \\ & = \sum_{a' \in \mathcal{A}^{\mathcal{B}}: \mathcal{D}(a')=i} x_{a'}^k + \sum_{a' \in \mathcal{A}^{\mathcal{E}}: \mathcal{D}(a')=i} y_{a'}^k + \sum_{a' \in \mathcal{A}_k^{\mathcal{C}}: \mathcal{D}(a')=i} z_{a'}^k \quad \forall i \in \mathcal{N} \end{aligned} \quad (6)$$

$$z_a^k \leq u_a^k \quad \forall a \in \mathcal{A}_k^{\mathcal{C}} \quad (7)$$

$$y_a^k \in \mathbb{Z}^+ \quad \forall a \in \mathcal{A}^{\mathcal{E}} \quad (8)$$

$$z_a^k \in \mathbb{Z}^+ \quad \forall a \in \mathcal{A}_k^{\mathcal{C}} \quad (9)$$

- In a traditional CPTA, carriers must price each bundle of interest individually by solving f^k .

Implicit Bidding Approach

- **PREMISE** - In truckload procurement, bids have underlying cost structures.
- **IDEA** - Instead of pricing and communicating $2^N - 1$ distinct bids, each bidder submits a bid generating function, f^k .
- Embedding f^k directly into WDP we obtain the following:

$$\min \sum_{k \in \mathcal{K}} f^k(\mathbf{x}^k) \quad (10)$$

$$\text{subject to: } \sum_{k \in \mathcal{K}} x_l^k = 1 \quad \forall l \in \mathcal{B} \quad (11)$$

$$x_l^k \in \{0, 1\} \quad \forall l \in \mathcal{B}, k \in \mathcal{K} \quad (12)$$

- f^k can be concisely represented by three polynomial-sized sets $\{d_a^k\}$, $\{c_a^k\}$ and $\{e_a^k\}$.

Implicit Winner Determination Problem (I-WDP)

$$\min \sum_{k \in \mathcal{K}} \sum_{a \in \mathcal{A}^{\mathcal{B}}} d_a^k x_a^k + \sum_{k \in \mathcal{K}} \sum_{a \in \mathcal{A}^{\mathcal{E}}} e_a^k y_a^k + \sum_{k \in \mathcal{K}} \sum_{i \in \mathcal{A}_k^{\mathcal{C}}} c_a^k z_a^k \quad (13)$$

$$\text{subject to: } \sum_{k \in \mathcal{K}} x_a^k = w_a \quad \forall a \in \mathcal{A}^{\mathcal{B}} \quad (14)$$

$$\begin{aligned} & \sum_{a \in \mathcal{A}^{\mathcal{B}}: \mathcal{O}(a)=i} x_a^k + \sum_{a \in \mathcal{A}^{\mathcal{E}}: \mathcal{O}(a)=i} y_a^k + \sum_{a \in \mathcal{A}_k^{\mathcal{C}}: \mathcal{O}(a)=i} z_a^k \\ = & \sum_{a' \in \mathcal{A}^{\mathcal{B}}: \mathcal{D}(a')=i} x_{a'}^k + \sum_{a' \in \mathcal{A}^{\mathcal{E}}: \mathcal{D}(a')=i} y_{a'}^k + \sum_{a' \in \mathcal{A}_k^{\mathcal{C}}: \mathcal{D}(a')=i} z_{a'}^k \quad \forall i \in \mathcal{N}, k \in \mathcal{K} \end{aligned} \quad (15)$$

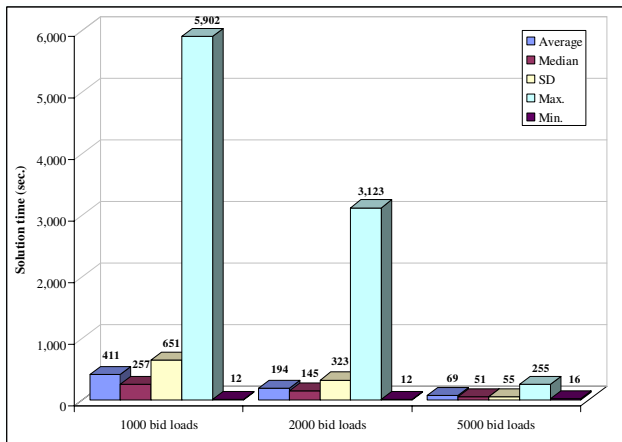
$$z_a^k \leq u_a^k \quad \forall a \in \mathcal{A}_k^{\mathcal{C}}, k \in \mathcal{K} \quad (16)$$

$$x_a^k \in \mathbb{Z}^+ \quad \forall a \in \mathcal{A}^{\mathcal{B}}, k \in \mathcal{K} \quad (17)$$

$$y_a^k \in \mathbb{Z}^+ \quad \forall a \in \mathcal{A}^{\mathcal{E}}, k \in \mathcal{K} \quad (18)$$

$$z_a^k \in \mathbb{Z}^+ \quad \forall a \in \mathcal{A}_k^{\mathcal{C}}, k \in \mathcal{K} \quad (19)$$

I-WDP Computational Results - Unconstrained



instances = 100/scenario # nodes(cities) = 100

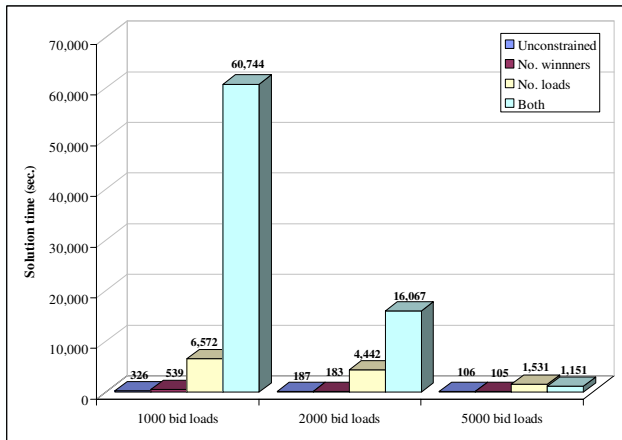
carriers = 50

backhaul capacity/carrier = 5%-15% of # of bid loads

Practical Considerations

- **Number of winners:** The shipper might want to award loads to no fewer than i_{min} carriers and to no more than i_{max} carriers.
- **Number of loads:** The shipper and carrier can specify the minimum and maximum numbers of loads that each carrier can be awarded.
- **Total mileage per carrier:** The shipper and carrier can specify a minimum, μ_{min}^k , and maximum, μ_{max}^k , miles that a carrier can travel.
- **Network configuration:** Bid loads can be distributed within a random network or a hub-and-spoke network. Carriers can be national or regional.

I-WDP Computational Results - Constrained



instances = 10/scenario # nodes(cities) = 100

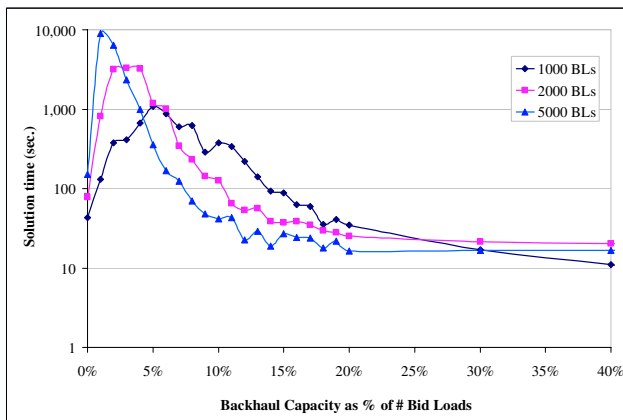
carriers = 50

backhaul capacity/carrier = 5%-15% of # of bid loads

Empirical Analysis

- How does size (i.e., number of bid loads and amount of backhaul capacity) impact run time and solution characteristics?
- How do differences in network structure impact run time and solution characteristics?

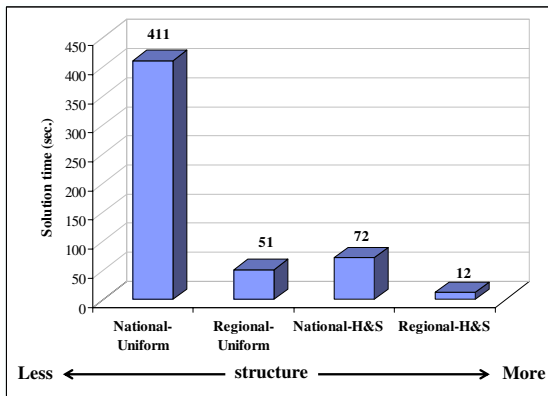
Empirical Analysis - Impact of bid load size and backhaul capacity



INSIGHT - Problems with a small and large amount of backhaul capacity are easy to solve.

Problems with moderate amount of backhaul capacity are more difficult to solve.

Empirical Analysis - Impact of Network Structure



INSIGHT - More structure makes WDP easier to solve! Note that all our computational results are based on the hardest instances to solve where there is minimal structure.

Summary

- Presented tractable models and mechanism to solve a basic CTPA to optimality in a single round, fully considering (implicitly) the exhaustive set of all possible bids;
- Showed that we can use MP to extend the basic problem to include additional important real-world operational considerations and still maintain tractability;
- Took advantage of this new capability to solve fully-enumerated CTPAs as a tool for conducting empirical analysis on the quality and characteristics of CTPA solutions.

Future Work

TRUCKLOAD AUCTIONS

- Perform further empirical analysis of solution quality and characteristics.
- Use this approach to study VCG and other auction designs, and assess their quality.
- Develop a tour-based approach that addresses all operational considerations and scales to practical size.
- Develop a stochastic approach that takes into consideration spot market variability, carriers' uncertainty about their existing/future network, and timing effects.

GENERAL

- Apply the implicit bidding approach to other application domains such as: wireless spectra, energy markets, and operations procurement.

The End