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# **Combinatorial Auctions for Transportation Service Procurement: The Carrier Perspective**

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## **Abstract**

The procurement of transportation services is an important task for shippers because of the need to control costs at the same time as providing high service levels. When shippers with goods and/or materials to transport seek transportation services from outside companies they typically put out a request for quotes from a set of carriers. They then assign contracts based on negotiated service charges. This process is similar to a simple sealed-bid auction in which each bidder submits a sealed bid for a single item. In the past, when shippers needed to procure transportation services for a set of distinctive delivery routes (called lanes) they would obtain quotes for each lane individually and repeat the simple auction process for each lane. Alternatively, they might negotiate for bundles of lanes with a single carrier at a time. However, in the last few years software has been developed to allow shippers to make all lanes available for bidding simultaneously and to allow carriers to simultaneously bid upon combinations of individual lanes. This method of awarding contracts, conventionally called a combinatorial auction, has been reported to result in significant cost savings for shippers. Our research examines the benefits of combinatorial auctions primarily from the carrier's perspective. Preliminary findings, based on a simple simulation model suggest that benefits for carriers can also be significant.

## Introduction

The procurement of transportation services is an important task for shippers because of the need to control costs and provide high service levels. When shippers with goods and/or materials to transport seek transportation services from outside companies they typically put out a request for quotes from a set of carriers. They then assign contracts based on negotiated service charges. This process is similar to a simple sealed-bid auction in which each bidder submits a sealed bid for a single item.

In the past, when shippers needed to procure transportation services for a set of distinctive delivery routes (called lanes) with different origins and destinations or delivery schedules, they would obtain quotes for each lane individually and repeat the simple auction process for each lane, or they might negotiate for bundles of lanes with one carrier at a time. However, in the last few years certain software has been developed to allow shippers to make all lanes available for bidding simultaneously and to allow carriers to simultaneously bid upon combinations of individual lanes. For example, a carrier could state its willingness to serve both a lane from Los Angeles to Las Vegas and a lane from Las Vegas back to Los Angeles at a combined price rather than viewing these as individual lanes, each with a potential empty backhaul. This method of awarding contracts, conventionally called a combinatorial auction, has been reported to result in significant cost savings for shippers (1).

It is natural for carriers to have different valuations of different combinations of lanes because lanes can be complementary or substitutable and because carriers can take advantage of these characteristics to reduce their empty movements and to organize their operations in a more efficient way. In addition to transportation service procurement, combinatorial auctions have been applied to the allocation of other assets in which such complementarities and substitution effects exist (2).

Combinatorial auctions have been studied by many economists, and their benefits to auctioneers have been well demonstrated (1). The inherent optimization problem, which is how to assign the winning bids so that maximum profits are obtained, is also a topic of considerable interest among operation researchers and computer scientists. However, in the transportation industry, it is not clear what impact combinatorial auctions will have on carrier operations or profitability when compared to the traditional request-for-quote-and-negotiation process. This research examines this issue by developing a simulation framework for this procurement process. We also begin to examine the question of how carriers should best structure their bids in these kinds of bidding processes.

In this paper we first review research and practice related to combinatorial auctions and identify the underlying optimization problems of interest. We then provide an analysis of problems that carriers encounter in such auctions. This is followed by a discussion of our simulation framework. Simulation data are analyzed and conclusions are given in the subsequent section. Finally, ongoing research on this topic is discussed.

## Literature Review

Transportation procurement is a critical component for shippers' logistics operations. In addition to their private fleets, shippers use outside transportation companies under long or short-term contracts. In practice, most shippers follow a general procedure to procure transportation services. That process includes carrier screening, carrier assignment, load tendering and performance review (3). Using this process, shippers attempt to reduce their costs and also to maintain a stable carrier base so that service levels are guaranteed. In addition, shippers procure services for occasional and spontaneous goods movement using spot markets, which during the last few years have moved from telephone to web based services (4).

In all of these different transportation procurement modes almost all assignments are done in a lane-by-lane manner in which shippers select service providers for each individual traffic lane based on the price submitted by each carrier, or, a set of lanes are combined as a bundle and are considered inseparable. This procurement process is similar to a simple sealed-bid auction, in which an auctioneer (shipper) announces the bidding item (contract to serve this lane), a group of bidders (carriers) review this item and then each one submits their price (quote) in a sealed envelope. The auctioneer then reviews the bids and determines the winner. Each item (a contract for each lane or pre-specified bundle of lanes) is sold by repeating this procedure iteratively. This system may be able to achieve economies of scale for carriers. However, it ignores the economics of scope that are inherent in transportation operations. A significant portion of trucking industry costs is due to the repositioning of empty vehicles from the destination of one load to the origin of a subsequent load. Traffic lane operations exhibit interdependencies, that is, the cost of serving one lane is greatly affected by the opportunity of serving other lane(s). Caplice (3) examined this economies-of-scope property and pointed out that traditional procurement does not properly account for this property. He suggested the use of combinatorial auctions for transportation procurement in which a carrier can bid based on the synergistic values of a set of lanes. In addition, Caplice's research discussed methods for shippers to develop pre-specified bundles of lanes that can then be auctioned as a single unit.

As demonstrated by Ledyard et al, the benefits of combinatorial auctions to shippers can be significant (1). Their paper records the procurement of trucking services by Sears Logistics Services which involved 854 lanes with a service cost of approximately \$190 million per year. Instead of using a traditional trucking services acquisition process, Sears Logistics Services, through its consulting firm of Jos. Swanson & Co. and Net Exchange, conducted a multi-round combinatorial reverse auction in which participating carriers were pre-selected so as to guarantee service levels. In each round a tentative winning price was announced and the auction continued until the stopping rule was satisfied. Using this process, Sears Logistics Services reported a 13% savings which reduced its transportation procurement cost by \$25 million per year.

In addition to transportation services, combinatorial auctions have also been used in other fields. The idea of combinatorial auctions began to receive significant attention in the 1994 Federal Communications Commission (FCC) auction of spectrum rights. In

that application bidders were interested in bidding on groups of spectrum licenses. However, the FCC did not adopt the suggestion of using a combinatorial auction because they considered it too cumbersome to run, instead, the agency used a separate auction for each license. Bykowsky, Cull and Ledyard (5) pointed out that this method for assigning licenses was inefficient. The FCC later decided to run its first combinatorial auction in June 2002 (6). Other applications include: a proposal by Banks, Ledyard and Porter (7) for a combinatorial auction for selecting space shuttle development projects, a report by Rassenti, Smith and Bulfin (8) for the resource allocation of airport takeoff and landing time slots and a paper by Kelly and Steinberg (9) which details a combinatorial auction designed for the telecommunications industry. In Feb. 2001, Volvo performed a combinatorial auction for the procurement of wooden packaging material. Volvo auctioned the contracts for 600 commodities aggregated into 14 segments. During that auction, the total cost decreased from 180 million to 172.9 million Swedish Kronors, a savings of 7.1 million, furthermore, the number of suppliers was reduced from 15 to 6 (10).

Theoretically combinatorial auctions can be applied to any asset allocation in which complementarities and substitution effects exist and in which bidder prefer bundles of items to single ones. However, these auctions contain some inherently difficult problems that must be addressed.

Auction mechanism design has been a topic of interest to economists for many years. The question of how to design auctions in order to induce participants to bid their true valuations and to allocate assets in an economically efficient way is very important. Bykowsky et al (5) discussed the FCC auction design problem and argued that simple auctions, including sequential single-item auctions and simultaneous independent auctions, are not suitable for resource allocation in which synergistic values exist. These methods either reduce auctioneers' revenue or expose bidders to financial risk by encouraging aggressive bidding. The researchers suggest that the use of combinatorial auctions is more economically efficient. However, there is no general equilibrium solution in combinatorial auctions. This type of auction creates a new problem called a "threshold problem", which occurs when bidders bid less than their true valuation in order to pay less, but at the risk losing the auction. DeMartini et al (11) presented a new design for combinatorial auctions and discussed this problem.

An important question in the design of combinatorial auctions is how bids should be efficiently expressed. On the one hand, the specified bidding language must allow bidders to express their synergistic value on all or most possible combinations of items. In addition, the bidding language should be relatively simple so that the number of bids will not be intractable. Nisan (12) introduced three basic types of bids: *atomic bids* in which a bundle of items are treated as a single bid; *OR bids* which are set of atomic bids in which the bidder will serve any number of disjoint atomic bids for the sum of their respective prices; and, *XOR bids* in which the bidder will serve at most one item in a set of atomic bids at the specified price (12). He demonstrated that a combination of these basic types of bids such as OR-of-XORs or XOR-of-ORs can represent all possible valuations of bidding items. In addition, he proposed a new type of bid known as an OR\* bid. The idea is to turn XOR bids into OR bids by adding a dummy item in each bid. For

example, {A XOR B} can be represented by {(A,g) OR (B,g)} in which g is the dummy item and can only be assigned once so that A and B will not be awarded to the same bidder.

The most difficult problem encountered by the auctioneer in a combinatorial auction is the determination of the optimal set of winning bids. This is known as the Winner Determination Problem. While this problem is known to be NP-complete, it has been well formulated. For example, Rothkopf, Pekec and Harstad (13) presented a formulation equivalent to a set packing problem. Those researchers claim that the manageability of combinatorial auctions depends upon the structure of permitted combinations rather than the number of bids. They also identified several special bidding structures for which the winner determination problem is computationally manageable. de Vries and Vohra (2) gave two formulations and reviewed the past approaches for tackling this problem, both by exact and approximation methods. Most of the past work deals with the single-unit case. Both Leyton-Brown, Shoham and Tennenholtz (14) and Gonen and Lehmann (15) provide a depth-first-search based algorithm embedded with branch-and-bound method to solve the multi-unit winner determination problem optimally, but used different bounding methods and ordering heuristics.

Past research on combinatorial auctions examined the perspective of auctioneers or shipper and has focused primarily on the design of auctions and on methods to solve the winner determination problem. However, to our knowledge, there has been no attempt to examine the benefits of auctions from the perspective of bidders or carriers. Of particular interest are the following questions: How should carriers determine their true valuation for any bundle of lanes? What is the optimal bidding strategy for a carrier competing with others in a combinatorial auction? These questions are not easy to answer even for simple cases. In fact, carriers encounter much more complex optimization problems and decisions than do shippers when faced with a combinatorial auction. In this paper, we examine the first question using a simulation model and present a framework for continued research on this topic.

## Problem Description and Analysis

We first provide some definitions of terms.

- *Shippers* are parties who have loads that need to be transported from origins to destinations and hence the *auctioneers* in the auction language.
- *Carriers* are service providers and *bidders*.
- A *link* is a physical delivery route connecting two locations directly.
- A *lane* is an origin destination pair on which shippers have *loads* to move; a *lane* may include one or more intermediate *links*.
- The items to bid are contracts to serve those *lanes* with new *loads*, i.e. freight movement between an origin-destination pair.
- A *cycle* is a set of links originating and terminating at the same physical location.

- A *bid* consists a set of lanes and a bidding price. For example: Carrier A will provide service on the San Francisco to Los Angeles lane and the Los Angeles to Las Vegas lane at a price of \$X.

For a single-unit transportation service procurement problem, we compare a traditional request-for-quote-and-negotiation process and a combinatorial auction. In this problem, a shipper or its agent (i.e. a third party logistics company) has a set of new lanes that need trucking services. Without loss of generality we assume that each lane has at most one unit demand, and that the shipper will pre-select two qualified carriers and assign contracts between them. This shipper may call these carriers individually, ask them for a quote for each individual lane, and then select that carrier with minimum quote as the service provider, continuing this process until all new lanes are assigned. This process can be modeled as a sequential sealed-bid auction. Alternatively, this shipper can provide information about all of these new lanes simultaneously and invite the carriers to submit quotes for combinations of lanes. This method can be modeled as a combinatorial auction.

Carriers, on the other hand, have pre-existing commitments to service a set of current lanes, and they also have expectations of getting new contracts from other sources. For example, at the time of the auction, a carrier may already have a contract with another shipper on a lane from Los Angeles to Las Vegas and it might currently lack a committed backhaul. However, it might know from historical data that it has a 50% chance of getting a load to serve on the return trip. Carriers will determine their valuations of these new lanes based on their proprietary information and develop their bids accordingly.

Now given a set of new lanes and each carrier's proprietary information, we examine the outcome of these two different procurement methods and to evaluate their impact on shipper procurement costs and carrier operations costs.

Some important issues can impact the outcome of a combinatorial auction.

- *Optimal Bidding Strategy*

The optimal bidding strategy involves carriers' identification of their true valuation of each bundle of new lanes and the strategies used to determine their actual bids. The first decision involves only the carriers' own resources and does not consider competitors' decisions. The second decision is closely related to the auction mechanism, bidders' risk-taking behavior (risk seeking, risk averse or risk neutral), and carriers' knowledge of competitors' private information. In this initial phase of our research, we only consider the first problem and assume that the auction mechanism guarantees that bidders bid their true valuations.

Due to the economies-of-scope property of transportation services, a carrier's true valuation of a new lane depends not only on the distribution of its current lanes, but also on its ability to obtain additional new lane(s). The bidding price for a set of lanes can be determined using the following observation:

*Observation 1: given a set of current lanes  $U$  and a set of new lanes  $V$ , the bidding price for the set of new lanes can be calculated by solving a set partitioning problem as follows:*

$$\begin{aligned} \min \quad & \sum_{j=1}^n c_j x_j \\ \text{s.t.} \quad & \sum a_{ij} x_j = 1 \quad \forall i \in U \cup V \\ & x_j = 0, 1 \end{aligned}$$

Where  $j = 1, \dots, n$  is the index of valid cycles;  $c_j$  is the cost of cycle  $j$ ;  $x_j$  indicates whether cycle  $j$  is in the optimal allocation; and,  $a_{ij}$  is a binary coefficient which indicates whether lane  $i$  is included in cycle  $j$ . These cycles include either a current lane or a new lane or both new and current lanes and satisfy all operational constraints. The objective function minimizes the total operating cost or total empty cost, and the first constraint set guarantees that every lane (either current or new) will be covered at least once.

The solution to this problem will give the best allocation of new lanes and from this, we can calculate the price for new lanes in each optimal cycle. These prices are based on the revenue from current lanes in this cycle, the operating cost of this cycle and the expectation of obtaining future loads on empty lanes in this cycle. The summation of all prices will be the true valuation of this set of new lanes and can be expressed as: “if and only if carrier A is assigned this set of new lanes, they should charge \$X”. The implication here is that this carrier bids for this set of new lanes as a bundle and presents an all or nothing bid. This is commonly referred to as an atomic bid (see for example Nisan (12)). This atomic bid has an XOR relationship with any other bids.

▪ *Bidding Language*

Bidding language refers to how carriers communicate their true valuation of new lanes. We identify three inter-relationships between lanes as follows:

*Definition 1: Denote  $v(A)$  as a carrier’s true valuation of a set of lanes A if and only if these lanes are assigned, we say two disjoint sets of lanes A and B are:*

- *Complementary: if  $v(A) + v(B) > v(A \dot{\cup} B)$ ;*
- *Substitutable: if  $v(A) + v(B) < v(A \dot{\cup} B)$ ;*
- *Additive: if  $v(A) + v(B) = v(A \dot{\cup} B)$ ;*

It is easy to see examples in practice for any of these scenarios. For example, a lane from Los Angeles to San Francisco is complementary to a lane on the return trip from San Francisco to Los Angeles, at the same time, a lane from San Francisco to Las Vegas to Los Angeles is a substitute to the direct return trip. Also, a lane from Miami to New York is not related to a lane from Los Angeles to San Francisco so the valuations for those lanes are additive.



We make the following observation about the enumeration of all possible combinations of lanes:

*Observation 2: A carrier requires at most  $2^N - 1$  atomic bids with XOR expression to represent all bidding opportunities in a combinatorial auction for a total of  $N$  lanes.*

Proof: a carrier can make an atomic bid by claiming: “I will serve a subset of bidding lanes  $S_i$  and only this subset for a price  $p_i$ ”, and there are  $2^N - 1$  distinct subsets of  $N$  lanes. Since only one subset can be assigned to this carrier, these atomic bids can be expressed as XOR bids.

Though this is the most complete expression of carrier’s valuation of new lanes, the number of atomic bids is an exponential function of  $N$ , the number of new lanes. Pricing each atomic bid requires solving a set partitioning problem as indicated in the last section, which itself is an NP-complete problem. This formidable computing task requires the application of approximation method to form bids.

In our simulation model, we limit the maximum number of lanes in a cycle to 3 and use a current-lane-first strategy to develop the atomic bids. We give higher priority to those new lanes with a matching opportunity with current lanes. The method to build bids is as follows: we first use a search algorithm to scan and delete all full cycles consisting of two or three current lanes without empty links. Then we scan all full 3-lane or 2-lane cycles with a mixture of current and new lanes. For those new lanes we generate an atomic bid and a corresponding bidding price. They are then excluded from further considerations. Next we scan all partial cycles consisting of current and new lanes and empty links and make the bids accordingly. Finally we consider those bids consisting of new lanes and/or empty links. In this procedure, each new lane is considered exactly once, hence all bids can be described as OR bids.

- *Winner Determination Problem*

Since this is a single-unit problem and bids are described with OR expressions, the winner determination problem is a set partitioning problem.

$$\begin{aligned} \min \quad & \sum_{j=1}^n b_j x_j \\ \text{s.t.} \quad & \sum a_{ij} x_j = 1 \quad \forall i \in V \\ & x_j = 0, 1 \end{aligned}$$

The shipper’s objective is to minimize the total procurement cost, that is, the total bidding price, subject to the constraint that each new lane must be assigned to exactly one carrier. We use a commercially available optimization package, CPLEX, version 7.5 to solve this problem.

- *Calculating the Optimal Operating Cost*

After the auction ends, it is left to carriers to determine the optimal way to operate the new lanes awarded, combined with their current lanes, at a minimum cost. The

operating costs are used to evaluate the impact of those two different auction methods on carriers. In order to find this cost, a carrier has to solve the following problem:

$$\begin{aligned}
 & \text{Min. total empty cost} \\
 \text{s.t.: } & \text{each load is served once;} & (1) \\
 & \text{each load is contained in one cycle;} & (2) \\
 & \text{flow conservation constraints;} & (3) \\
 & \text{other operational constraints;} & (4)
 \end{aligned}$$

The problem is to find the minimum cost assignment of loads subject to the constraints that each load is served once, each load is contained in exactly one cycle, flow conservation is maintained and operational constraints are met. These operational constraints include but are not limited to maximum cycle length or scheduling constraints.

If we relax the last two constraints, we can formulate this problem as a set partitioning problem where the decision variables are every possible cycle in the carrier's network. Hence, we use a depth first search algorithm to search for all cycles that satisfy the last two constraints. We call these valid cycles, and we solve the set partitioning problem over these cycles to achieve an optimal solution. This is similar to a column generation scheme except that all valid cycles (columns) are enumerated.

### Simulation Framework

Since an examination of the impact of combinatorial auctions involves many inherent difficult sub problems, it is virtually impossible to describe this problem using a closed form quantitative model, either game-theoretic or optimization-based. For this reason, we developed a simulation of the transportation contract procurement process and used a 21-node transportation network to test the process. The simulation framework includes the following steps:

- *Transportation Network and Load Data Generation*

The test transportation network in this simulation includes 21 nodes and 74 direct links without intermediate nodes. At the beginning of each simulation run, a set of current lanes are randomly generated for each carrier and each lane is assigned a probability of tendering future demand. These probabilities are generated randomly – uniformly between zero and one. Here a lane refers to an O-D pair and may involve traveling a few direct links, and we also assume that each carrier will take the shortest path back to the origin if there is no matching load on the return trip. A restriction here is that a trucking unit can travel at most 1200 miles (1930 km) per trip which limits the valid cycle length. Hence we generate loads only on those O-D pairs with a distance of no more than 600 miles (965 km) in one direction. In our test network, a total of 124 O-D pairs satisfy this condition.

A set of new loads is generated randomly between any O-D pairs satisfying the maximum-cycle-length restriction. The above input data is used to test a simple sequential auction and a combinatorial auction run in parallel. In the simple auction, new

loads are shown to carriers in a random sequential order, while in the combinatorial auction, they are made available for bid simultaneously. Both auctions are sealed-bid and single-round, and we assume each carrier will bid for every new lane based on their true valuation.

- *Carriers' Bidding Strategy*

The development of packages of atomic bids depends on the form of the auction.

In a simple sequential auction, carriers simply take a look at whether there is an opportunity to combine new lane(s) with current lane(s) to form a valid cycle. However, in a combinatorial auction, bids are created and described using the methods described earlier.

Another decision for carriers in making bids is to decide the bidding price for an atomic bid. We use the following formula to calculate the bidding price  $p$  for new lane(s) in an atomic bid:

$$p = c_i \times (1 + \mathbf{b}) + c_j \times \mathbf{a}_j$$

Where  $c_i$  is the total cost of serving the new lane(s) in that atomic bid;  $c_j$  is the empty cost associated with serving those lanes;  $\mathbf{b}$  is the carrier's average profit margin, which typically ranges from 4% to 6%; and,  $\mathbf{a}_j$  is the carrier's risk of not tendering any future demand on those empty lanes  $j$ . Since normally a carrier's cost is proportional to distance, we use distance directly to represent costs. Note that costs for current lanes are not needed in this formula.

- *Bid Assignment*

After the two carriers submit their bids, the shipper solves a winner determination problem as described in the previous section.

- *Evaluation Step*

For shippers, since we assume all carriers are pre-screened and that the level of service is guaranteed, the only thing that matters at this stage is the procurement cost. Hence we use this criterion to evaluate the relative advantage of a combinatorial auction compared to a simple sequential one.

Carriers wish to maximize their expected profits, which are determined by revenues and costs. Because revenues are determined by the carrier's bidding behavior and pricing scheme, and also by the competitors' bidding strategy, it is hard to simulate the real situation. Moreover, our objective is to evaluate the impact of different procurement methods on carrier operations, for these reasons and also because total carrier costs for current and new lanes are fixed, we use carrier empty costs under optimal operations as the evaluation criterion.

### Preliminary Analysis

The simulation is implemented in C++ with an imbedded CPLEX optimization component. We examined various cases where the ratio of new lanes to valid O-D pairs (percent of new lanes) ranges from 0.1 to 0.9 and the ratio of current lanes to valid O-D pairs (percent of current lanes) ranges from 0.1 to 0.9. For each of these 81 different cases the simulation was run 2000 times. Each simulation involves solving three integer programming problems (a winner determination problem for the shipper and the optimal cost calculation problems for each of the two carriers). The results are encouraging, and suggest that despite the sub-optimal bidding rules implemented in our simple simulation system, that both shippers' procurement costs and carriers' average empty costs are lower in combinatorial auctions than in simple sequential auctions.

All cases indicate that shippers will gain cost reductions in combinatorial auctions compared to simple sequential ones. This conclusion is comparable to those reported earlier in the literature (*l*). The reduction rate in our simulation study ranges from 4% to 14%, depending on the density and distribution of new lanes and current lanes. As shown in figure 1, the shipper's cost reduction using this combinatorial auction based procurement method appears to monotonically increase as new lane density increases. Intuitively this makes sense. When more lanes have new loads, there are more opportunities for carriers to combine these into cycles, thus to reduce the empty backhaul movement. This not only results in the improvement of carrier operational efficiency, but also makes carriers willing to bid lower prices, which in turn reduces the shipper's procurement costs.

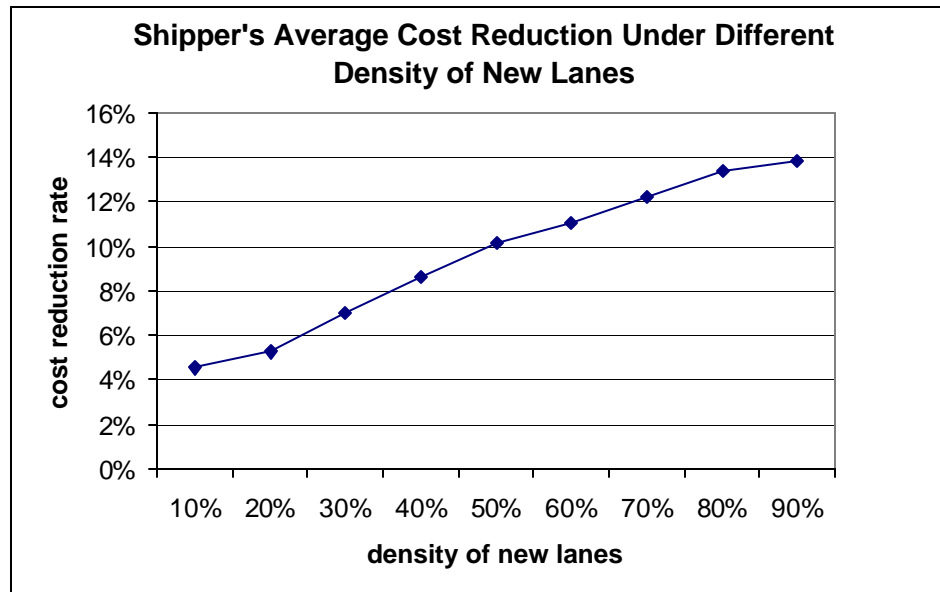


Figure 1. Shipper's Average Cost Reduction Under Different Density of New Lanes

It is interesting to observe the relationship between shippers' average cost reduction rates and carriers' average current lane percentage. Figure 2 shows that relationship displays a convex curve – when carriers have very limited or very high current lane densities shippers will typically have lower procurement costs. This phenomena is mostly due to the current-lane-first bidding strategy that carriers adopted in this simulation. When carriers have fewer current lanes, the opportunity to match new lanes with current lanes is lower, and this will cause more matching opportunities among the new lanes only and will hence reduce the bidding price. However, in a simple sequential auction, this opportunity is not available and if a new lane cannot be matched with current lanes, it will incur an empty backhaul cost which increases its price. When the density of current lanes is high, because we search for matching opportunities among current lanes first in our bidding strategy and exclude those matched current lanes from further consideration, current lanes will mostly be matched among themselves. This implies that new lanes will have more opportunities to form cycles with other new lanes, which is same as in the low-current-lane case.

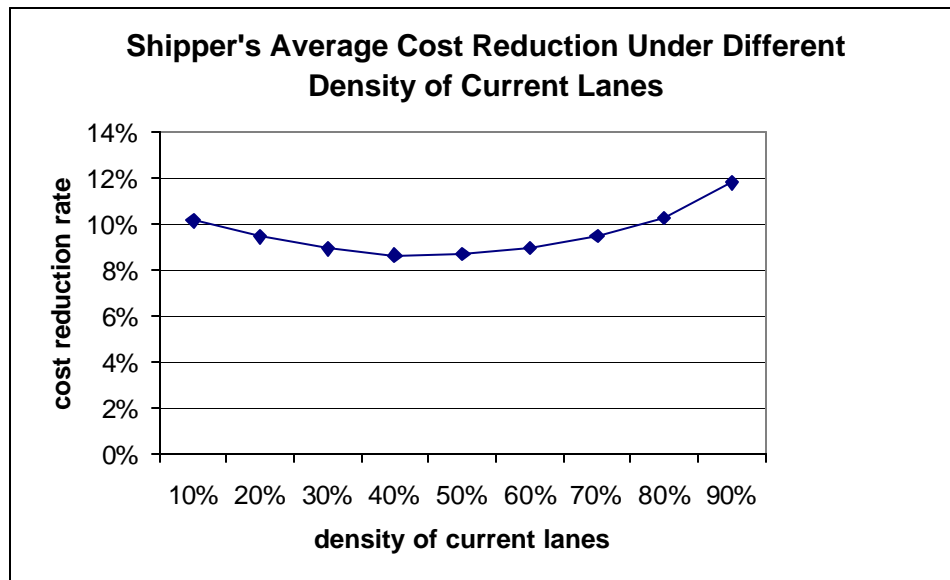


Figure 2. Shipper's Average Cost Reduction Under Different Density of Current Lanes

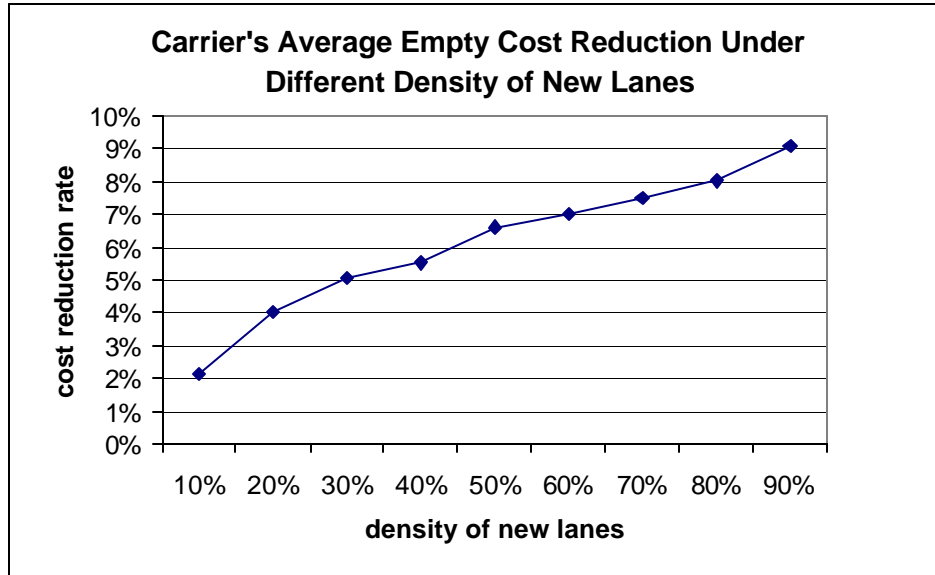


Figure 3. Carrier's Average Empty Cost Reduction Under Different Density of New Lanes

As for carriers, it is not surprising to see that their final empty cost will also decrease under a combinatorial auction compared a simple sequential auction due to economics of scope. The average carrier empty cost reduction in individual cases varies greatly from 2% to almost 14%. The relationship between carriers' empty cost reduction rate and distribution of current and/or new lanes follows similar patterns as those of shippers. As shown in Figure 3, if more new lanes are available for bidding, lower empty travel costs can be achieved. The reduction in travel costs relative to an increase in the percent of new lanes is monotonically decreasing. This result fits very well with shippers' curve. If carriers are able to optimize their transportation operations and reduce empty costs, it is then possible for them to bid lower and let shippers enjoy a procurement cost reduction as well.

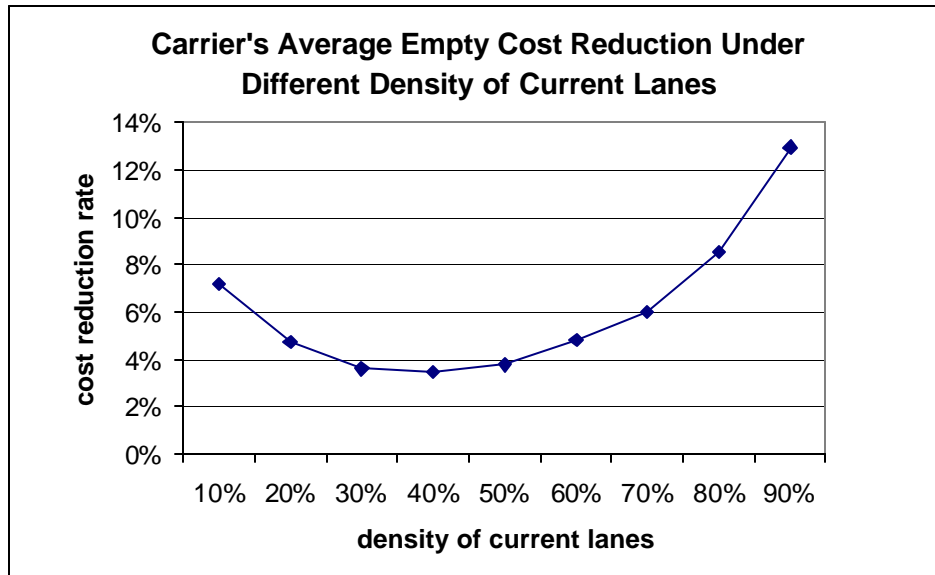


Figure 4. Carrier's Average Empty Cost Reduction Under Different Density of Current Lanes

As shown in Figure 4 this inter-relationship between carriers' operation and shippers' procurement cost is also demonstrated by the fact that carriers' empty cost reduction rate follows a similar convex curve pattern as that of shippers. When carriers have limited current lanes, they tend to combine new lanes into bundles and cut the bidding price and hence reduce their empty cost. On the other hand, if carriers already have a large number of current lanes they have more opportunity to optimize their own operation.

### Conclusion and Ongoing Research

In this paper, we analyzed both shipper and carrier problems in a combinatorial auction based transportation service procurement process, and examined the benefits of combinatorial auctions compared to the traditional call-for-quote-and-negotiation procurement method using an optimization based simulation study. While the results support the observation made in earlier literature on this problem – namely that shippers can achieve significant cost reductions under combinatorial auctions, they also demonstrate that carriers should benefit too. The experiments also show that both shipper and carrier cost reduction is closely related to the distribution density of new lanes, in addition each carriers' current lanes. In our study, the combinatorial auction seems to benefit shippers more than carriers but this is likely due to the sub-optimal bidding strategy used by carriers in our simulation.

Though this study only examined the case where a single unit of demand is available on each lane, it demonstrates the potential benefits of combinatorial auction based procurement methods. If there are multiple units in demand, carriers should be able to take advantage not only economies of scope, but also of economies of scale.

We should point out however that the real procurement situation is much more complicated than that is examined in this study. Shippers can identify matching opportunities among new demands and can pre-define bundles prior to bidding. While this may bring better outcome than a simple sequential sealed-bid auction as used here, it should be also observed that the sub-optimal bidding strategy and truth-revelation mechanism assumed for carriers make our results a lower bound on the true benefits available.

While it is certain that a carrier's gain in a combinatorial auction is greatly dependent on its bidding strategy, there are many very difficult problems involved in this process. Of our particular interest is a carrier's valuation problem: given any cluster of demand, how should a carrier identify its true valuation quickly? This problem should be combined with the bidding language problem since a more efficient bidding language will provide more resources for carriers to explore valuations of underlying clusters of lanes. Enumeration and exact solution to these problems are not realistic due to the formidable size of inherent optimization problems. Hence, approximation methods to quickly reveal carrier's valuation, as well as efficient ways to express carriers' preferences, must be developed. For example, using current or empty lanes as dummy items can transform XOR bids into OR bids and hence reduce the number of bids.

Extensions of this work include the examination of more sophisticated bid generation methods for carriers, including the introduction of logical bids and algorithms to calculate optimal bidding prices under pre-existing commitments. Multi-unit demands and/or multiple round combinatorial auctions, which are often encountered in real practice should also be examined. Another aspect ignored in this initial study but very important in real life is the matching of schedules when building cycles for a vehicle. The time window of a subsequent lane must be compatible with that of the previous lane and the travel time between them in order to match them as a potential cycle.



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