21 Combinatorial Auctions for Truckload Transportation

Chris Caplice and Yossi Sheffi

21.1 Introduction

This chapter explores how combinatorial auctions are being used for the procurement of freight transportation services. It focuses on those attributes of transportation that make combinatorial auctions especially attractive and describes some of the unique elements of transportation auctions. We concentrate on the United States truckload (TL) market, because the characteristics of this mode are the most compelling for using combinatorial auctions and therefore it is where most combinatorial auctions in transportation are taking place.

The actors in the transportation market consist of shippers and carriers. The shippers are the retailers, manufacturers, distributors, and other companies that need to move freight. They are the auctioneers in the procurement of transportation services. In many cases a third party, such as a software vendor, consultant, or third-party logistics provider (3PL) will conduct the auction on the shipper's behalf and thus act as the auctioneer. The carriers are the trucking companies that own the transportation assets and are the bidders in the process. This chapter looks at reverse procurement auctions in which typically one shipper is the auctioneer and many carriers are the bidders looking to win contracts to haul the shipper's freight over a specified future period.

The differences between transportation services auctions and other auctions described in the literature and in this book include the importance of defining the items to be auctioned, the level of uncertainty in the resulting contracts, and the number and variety of business conditions considered in the final winner determination problem (WDP). We describe the nature of shipper-carrier interactions and illustrate how it affects transportation service auctions.

21.1.1 The Freight Transportation Market

The United States commercial freight transportation market exceeded $701 billion in 2003, representing approximately 6.3 percent of the U.S. gross domestic product

(Standard & Poor's 2004). Although the industry includes a myriad of transportation modes, such as railroad, heavy air, parcel, pipeline, and water, the predominant mode in the United States is trucking. Truck transportation represents 86.9 percent of all commercial freight revenues (Standard & Poor's 2004).

Trucking, and indeed most all transportation operations, fall into two major categories: direct and consolidated. In direct operations, the cargo (or people) move(s) on a single conveyance directly from origin to destination, whereas in consolidated operations the cargo has to be unloaded and reloaded to a different conveyance at a terminal. Examples of direct transportation include taxi cabs, charters in all modes, and unit trains. Examples of consolidated transportation include busses, most traditional commercial airlines, rail, less than truckload (LTL) trucking, and package delivery. The dichotomy is very clear in trucking; less than truckload (LTL) operations use break-bulk terminals to consolidate (and break) the shipments, whereas truckload (TL) carriers move in full trailers from origin directly to destination. The operations, economics, and markets differ significantly between these two segments—all of which influence the extent and type of procurement and bidding methods that shippers use.

The TL segment, both private and for-hire, comprises over 78 percent of the total trucking transportation market and is the focus of this chapter.

21.1.2 Literature Review

The first reported use of optimization to solve the winner determination problem (WDP) for a transportation service auction can be traced to the Reynolds Metals Company in the late 1980s. Moore, Warmke, and Gorban (1991) describe how Reynolds centralized its transportation management system and how it bid out and assigned lanes[1] of traffic to carriers. They developed a mixed integer program (MIP) model that minimized transportation costs by assigning carriers to specific shipping locations and traffic taking into consideration individual carrier capacity constraints, equipment commitments, and other transportation specific concerns. Although it allowed for simple bids with volume constraints (see section 21.5), it did not permit package or combinatorial bids.

Porter et al. (2002) describe combinatorial auctions (which they referred to as *combined value auctions*) run in 1992 by Sears Logistics Services, in what was probably the first application of package bidding in the transportation context. They reported savings of 6 percent to 20 percent. Although the model allowed package bids, it did not permit the use of any business specific side constraints as model Moore, Warmke, and Gorban (1991) developed did.

The use of combinatorial auctions for transportation services (incorporating both package bids and business side constraints) increased dramatically throughout the 1990s, as Caplice and Sheffi (2003) and Elmaghraby and Keskinocak (2002) described. The first commercially available software specifically designed for combinatorial auctions for transportation services, OptiBid®, was released in 1997, using formulation and approach from Caplice (1996). Other software companies have followed suit, and by 2003 approximately half a dozen transportation procurement software packages that incorporate package bids were available in the market. These include Manugistics Inc. (RFQ Optimizer®[2]), Manhattan Associates Inc. (OptiBid®[3]), i2 Inc. (Transportation Bid Collaborator®), Baan Inc. (BidPro®), Saitech Inc. (SBids®), and Schneider Logistics Inc. (SUMIT CVA®). Additionally, other nontransportation-specific auction software from CombineNet Inc., Freemarkets Inc., Tigris Inc., and others have been used for transportation services. We estimate that from 1997 to 2003, over one hundred companies have run a total of several hundred combinatorial auctions using these software tools. These companies include Procter & Gamble, Sears, Roebuck and Corporation, Kmart, Wal-Mart, Best Buy, The Home Depot, Bridgestone, Ford Motor Company, Compaq Computer Corporation, Staples, Limited Brands, Ryder System, Rite Aid, and many others.

Although the majority of the research and commercial interest has focused on solving the shipper's problem (WDP), the carrier's (bidder's) problem has received some attention. Song and Regan (2005), for example, develop several optimization-based strategies for carriers to construct package bids. Although ignoring the uncertainty both in the strategic bidding process and in carrier operations, they nevertheless develop a mathematical framework for thinking about the bidders' issues in this very complicated auction setting. Caplice (1996) presents heuristic-based algorithms that carriers can use to create open loop tours, closed loop tours, inbound-outbound reload packages, and short haul packages using potential savings estimates based on historical load volumes.

The insights within this chapter are partially based on the authors' firsthand experience[4] in designing and conducting well over a hundred auctions for transportation services as part of LogiCorp Inc., PTCG Inc., Sabre Inc., Logistics.com Inc., and Chainalytics LLC. Over the last six years, more than fifty of these were combinatorial auctions. These auctions were generally conducted to obtain trucking services for large retailers and manufacturers, but they also included smaller shippers and covered rail, intermodal, and ocean transportation modes. These combinatorial procurement efforts involved more than $8 billion in transportation services and have documented combined savings to the shippers in excess of $500 million.

21.2 The Shippers' (Auctioneer's) Perspective

Since the United States surface transportation industry was deregulated in the 1980s, the transportation procurement process has settled into a fairly standard procedure, with most shippers conducting auctions every one to two years. This section outlines the auction practice and explains the uncertainty associated with the process.

21.2.1 The Auction Process

Transportation procurement generally follows a standard three-step process consisting of pre-auction, auction, and post-auction activities. We highlight those steps that are unique or particular to transportation service auctions.

During the pre-auction stage, the following tasks are completed:

- The shipper forecasts the demand for the upcoming period's transportation needs, which is then translated into a set of expected weekly flows on individual lanes, by period (see section 21.2.3). Shippers have a fair amount of discretion in the exact definition of the lanes and the network in general. Thus, there are tradeoffs involved in the development and communication of the shipper's business (see section 21.4.1).
- The shipper determines which carriers to invite to the auction. Often, shippers will allow certain carriers only to participate in specific regions or portions of an auction. Common practice is to include most incumbents plus a small number of new carriers. Thus, in transportation auctions, most carriers have at least some private information concerning the shipper's business.
- The shipper determines what information the carrier is required to submit back. This usually includes the form of the rate (flat rate per move, rate per mile, rate per hundredweight moved, etc.), service details (days of transit, capacity availability, equipment type, etc.), and the types of bid allowed (bid types such as simple bids, static package bids, flexible package bids, etc.; see section 21.5).

During the auction stage, the following steps are performed:

- The freight network is communicated to the carriers through the use of faxed lists, spreadsheets, online web pages, or direct EDI connections. Email is the most common form of communication tool used for transportation auctions (Caplice, Plummer, and Sheffi 2004).
- The carriers conduct their own analysis on the network and determine the rates to offer. For transportation, the bidder valuation, or carrier problem, is extremely complicated due to cost interdependencies and uncertainty (see section 21.3.3).
- The carriers will then submit their bid rates, and depending on whether the format of the auction involves single (most common) or multiple rounds may receive feedback information and have to resubmit updated rates.

During the post-auction stage, the following tasks are performed:

- The shipper receives the carriers' bids, converts them into a common format and database, and solves the WDP. In transportation auctions, this typically involves creating several dozen "what-if" scenarios by applying different business rules to the WDP (see section 21.6).
- In a multiple round auction, the shipper would send back to the carriers selected information on where they stand. The specific feedback information differs from shipper

to shipper but can include the carriers' rank on each lane, the leading rate on each lane, identification of package bids that are leading, etc.

- Once the shipper solves the WDP, the results are uploaded to the downstream planning, execution, auditing, and payment systems. The transition to a completely new carrier base can take upwards of several months to complete.[5] (The description of this process is out of scope of this chapter, however, and is omitted.)

21.2.2 Characteristics of Transportation Auctions

Table 21.1 provides summary information on the relative size and scope of the several dozens of TL transportation procurement involving combinatorial auctions designed and managed by the authors between 1997 and 2001. We believe it to be representative of combinatorial auctions conducted for transportation services during this time.

The duration of the auctions is measured from the start of the auction process, after all data has been gathered, until the award decisions are made. It does not include the pre-auction data collection efforts or the post-auction process of updating the shipper's systems.

Table 21.1
Characteristics of transportation auctions, 1996–2001

	Minimum	Median	Average	Maximum
Number of lanes	136	800	1,800	~5,000
Number of annual shipments	~6,000	88,000	~200,000	~1,500,000
Annual value of transportation services	\$3M	\$75M	\$175M	\$700M
Number of incumbent carriers	5	100	162	700
Number of carriers participating in the auction	15	75	120	470
Number of carriers assigned business from the auction	5	40	64	300
Reduction in the size of the carrier base	17%	48%	52%	88%
Base reduction in transportation costs (without considering service factors)	3%	14%	13%	24%
Final reduction in transportation costs (considering service factors and other business constraints)	0%	6%	6%	17%
Duration of procurement process (months)	<1	3	3	6+

We should point out four observations from the data in table 21.1. First, note that in all auctions, the shippers significantly reduced the number of carriers being used. In fact, "core carrier" programs have flourished in the 1990s, motivated by the desire to give more business to fewer carriers, thereby becoming a more important customer to these carriers. Many of these auctions have been used to establish core carrier programs.

Second, optimization-based procurement for transportation services tended to be used primarily by large shippers. The average auction size for this period was about $175 million in annual TL transportation expenditures, which is quite large.[6] The cost and effort required to run one of these auctions was not insignificant.

Third, the shippers are, on average, reducing their cost of transportation services by 13 percent—before taking service considerations into account. This is in line with the results that Porter et al. (2002) reported for its Sears auctions. Note, however, that transportation combinatorial auctions permit both simple and package bids, so it is never clear how much of the total savings in any such auction is due to package bids versus other more standard aspects of the process. Current research is aimed at separating and quantifying each of these factors.

Fourth, shippers, on average, forgo 50 percent of the potential savings in order to obtain a better engineered solution. This is done by adding constraints representing service requirements and other business issues into the WDP. These business constraints and performance factors are, in effect, costing the shippers 7 percent of their total annual transportation costs on the average. This points out the importance that shippers place on nonprice factors when solving the WDP.

Table 21.1 does not imply that the number of carriers bidding is related to the number of lanes or size of the network being auctioned. In fact, figure 21.1 shows that there is little correlation between the number of bidders and the number of lanes being auctioned for the same data set.

We have observed over the last several years that more shippers are conducting auctions of smaller magnitude more frequently. It seems that many shippers are replacing network-wide carrier reassignments with regional auctions—but we do not have sufficient longitudinal statistics fully to support or explain this observation.

21.2.3 Uncertainty in Shipper-Carrier Relationships

Many procurement auctions do not result in a transfer of goods, but rather the winner is awarded the right to sell its products or services in the future. For example, if a tire supplier wins the right to furnish an automobile manufacturer with tires for an upcoming model, it will sell the car manufacturer only five tires per car manufactured and no more; there is no absolute a priori tire volume commitment made on the manufacturer's part. It all depends on how many cars are made. Similarly, in the process of procuring transportation services, the winning carrier on a particular lane wins the right to haul traffic—but will only be called when and if there is a load to haul.

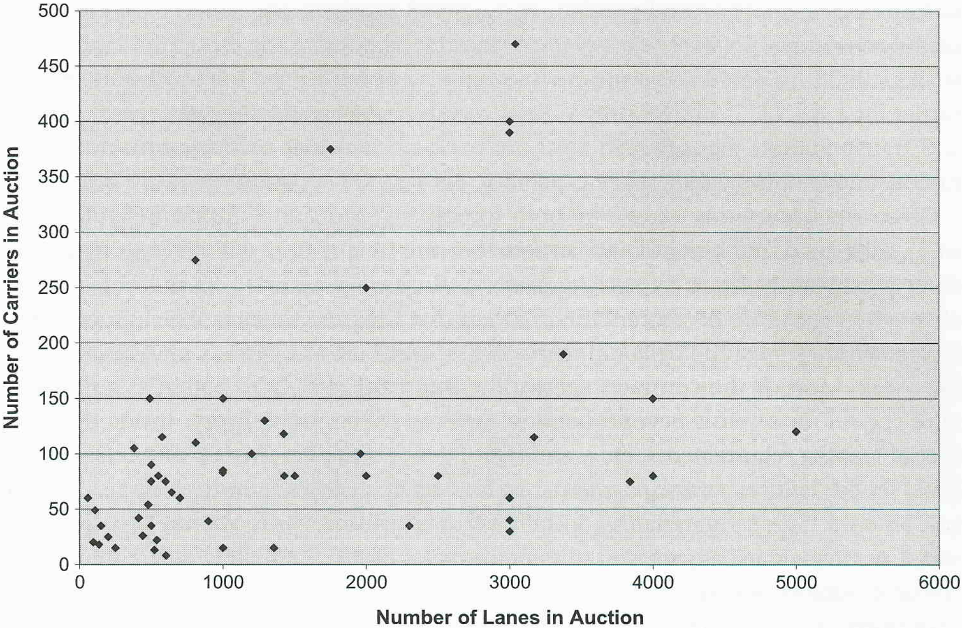

Figure 21.1
Size of transportation auctions, 1997–2001.

The uncertainty with transportation services, however, is even more pronounced due to forecasting uncertainties and prevalent shipper behavior.

Shippers have difficulties forecasting the lane flows that define the items in the auction due to the freight flows being highly disaggregated. It is not enough, for example, for a shipper to know that it will need, say, 3,000 trucks to carry 3,000 loads next year; for auction design purposes the shipper needs to know how many trucks it will need on each lane for each week (or in some cases, at the daily level). The coefficient of variation is very high at this disaggregated (loads per week per lane) level. In addition, most transportation departments, although responsible for buying the transportation services, are not always privy to their own company's marketing, promotion, and manufacturing plans, further adding to the uncertainty.

It is also accepted practice for shippers to capitalize on short-term opportunities. For example, suppose a carrier is hauling an inbound load to the shipper's facility, and that shipper has an outbound load that needs to be picked up later that day from the same facility. The shipper can create a *continuous move* by offering the new load to the inbound carrier, thus reducing or eliminating the carrier's dwell time and *deadhead* miles. A deadhead move is a movement where the carrier does not have a paying load. They are typically used for repositioning a truck from a destination to its next origin for a pickup. A carrier will typically reduce its line haul rate by 5 percent to 8 percent for a continuous move. So, even if another carrier was assigned to the outbound lane in the strategic bidding process, the shipper may choose to tender the load to an alternative carrier for a specific load. Not only is this accepted behavior for shippers, most analysts and transportation management software packages consider such opportunistic continuous move optimization a key capability.

Given the uncertainty caused by both forecasting errors and shipper behavior, it is well understood and accepted by carriers that the freight they will actually haul may differ significantly from the freight patterns they were awarded in the bid. In that sense, the contract is no more than *an option* that the carriers grant the shippers. That is, the shippers have the *right but not the obligation* to use the carriers as determined in the WDP. Most of the contracts specify the line haul rates, any potential accessorial rates (prices for services beyond hauling, such as collect on delivery, inside delivery, special loading requirements, etc.), and contingency remedies (in case of haulage problems, service failures, or nonpayment, not for lack of business from the shipper), which will be used if loads materialize. Specific volume commitments are rarely included—and if so they are usually expressed as percentages of the traffic flow rather than as an absolute number of shipments.

Shippers, however, cannot abuse this option too badly because freight transportation contracts are negotiated frequently and shippers that get a reputation for not living up to their commitments are not likely to see aggressive bidding the next time around (see section 21.4.3).

Because carriers cannot be expected to hold trucks and drivers in reserve, waiting for a shipper's call, shippers do not expect carriers to respond to every call for a truck ("tendering" a load) once a load materializes. Instead, carriers are generally expected to accept a high percentage (typically 70–80 percent) of the tendering requests. In fact, the acceptance rate is one of the performance metrics that shippers use to evaluate carriers. In addition, most transportation contracts specify the percentage of the time that carriers are allowed to bring in a subcontract operator (which they sometimes use instead of their own equipment).

This means that the contract is somewhat nonbinding on both sides. The contract may oblige shippers to tender the load to a specific carrier, but only when there is a load, something not known at the time of the auction. And the carriers are obliged to provide a truck at the agreed terms, "most of the time." Naturally, carriers understand that a shipper, during an auction, might award them a set of lanes in a package bid that mimics a continuous move, for example, traffic lanes from A to B, B to C, and C to A, but that in execution, they may be called to haul a load from A to B when there will be no load waiting at B to go to C (or anywhere else). Thus, carriers apply a certain probability of a follow-on load to each bundle of lanes during the auction process (see section 21.3.4). The net effect of this uncertainty is a damping of the potential value and usefulness of package bids in transportation service auctions.

Interestingly, although the high levels of uncertainty are well known within the industry, we know of no use of recourse models or other stochastic programming techniques in practice for transportation auctions. This is a topic of ongoing research by the authors, as discussed in section 21.7.3.

21.3 The Carrier's (Bidder's) Perspective

Although the daily operations of TL carriers are deceptively simple, they result in some rather complicated interdependencies and uncertainties that impact how a carrier can place a value on a shipper's freight. Additionally, carriers operate in a highly competitive market. This section discusses the carrier market, daily TL carrier operations, cost interdependencies, and the carrier valuation process.

21.3.1 Truckload Carrier Market

The TL transportation industry is close to a perfectly competitive market. The barriers to entry (and exit) are very low—mainly the cost of a tractor and trailer, which many lenders are happy to finance using the equipment as collateral.[7] Their service is essentially a commodity—a box on wheels—with the exception of some smaller specialty equipment submarkets. The more than 50,000 U.S. TL firms (ATA 2002) are distributed over the entire nation, making geographic monopolies rare. Switching costs for shippers are generally low.

The TL industry is very fragmented, with 75 percent of the firms owning fewer than six power units (ATA 2002). Most large shippers, however, will deal primarily with relatively large operators that not only can supply additional capacity when demand picks up, but also can comply with an increasing number of information and communication technology requirements, such as electronic data interchange (EDI) for sending advanced shipping notices and invoices, ability to accept automatic electronic fund transfers, automatic provision of GPS-based status reports and digital delivery proofs, and so on. There are only several hundred players like this in the U.S. TL market, many of which use sophisticated information technology tools to optimize their operations and can respond to relatively intricate bidding schemes. The vast majority of the remaining firms subcontract to these larger trucking firms, work through brokerage houses, or serve as regional or local spot capacity for individual shippers. It is these few hundred leading firms who are the active participants in combinatorial auctions.

21.3.2 Truckload Carrier Operations

TL carrier operations generally follow the steps outlined below:

- A customer (shipper) calls for a shipment pickup. Typically shippers do not give carriers advance notice of impending loads.

- The carrier assigns a specific truck and driver to that load, who picks the load up from the origin. Usually, the truck will drive to the origin empty.
- The truck departs and drives directly to the final destination. A typical truck can drive 400–500 miles in a day, and the average length of haul for a shipment is approximately 750 miles.
- At the destination, the truck is unloaded. In some cases, the trailer is dropped in a shipper's facility (a trailer yard) to wait future unloading and the driver picks up an empty trailer (or a full one in the case of a continuous move tied to a trailer pool) to haul away.
- The truck then either holds in a local terminal for the next load, drives empty (deadheading) to a region from which more loads typically emanate (a repositioning movement), or drives directly to the next pick up point. The process then repeats.

The challenge of operating TL carriers is in coordinating the movements of hundreds or thousands of trucks simultaneously. As implied by the last bullet point, freight flows are not symmetric: some regions of the country produce many more shipments than there are shipments destined there (or consumed), and vice versa. And even geographically balanced operations may not be time balanced, in that they require drivers to wait until an appropriate load is available.

Adding to these structural imbalances is the uncertainty of the operation—shippers typically do not tender the loads well ahead of time. TL operations, therefore, entail significant uncertainty regarding follow-on loads. When a truck is sent to a given destination, in most cases neither the driver nor the carrier knows where it will go next.

21.3.3 Cost Interdependency

The basic unit of service that shippers are interested in is a unidirectional flow from a given origin to a given destination, or lane flow. Trucking operations, however, depend on getting the equipment and the operators back to certain fixed points at regular intervals. The reasons are that trucks need to be maintained at certain base terminals and drivers need to get home. The last point is particularly relevant—some TL carriers experience a 100 percent operator turnover annually. Costello (2003) estimates the cost of recruiting and training a new driver at $9,000. With thousands of drivers and razor-thin margins, carriers compete with each other for drivers by providing reasonable working conditions. The most important attribute of job satisfaction for long-haul drivers is getting home frequently and predictably.[8] This is difficult to provide in the uncertain environment of TL transportation, as discussed in section 21.2.3.

The most obvious example of cost interdependency is a round trip, including head-haul and back-haul lanes. If a carrier has the contract to haul both from A to B and from B to A, it can base operations and recruit drivers at one end of the tour and operate its trucks back and forth. Not only will the drivers get home but, if the timing is right, there will be little dwell time and little or no deadheading.

In general, the cost of serving a lane is strongly affected by the probability of finding a follow-on load out of that destination. Securing a balanced network reduces the uncertainty in connection costs and can lower the carrier's overall costs. Thus a carrier may offer a lower price for hauling a given number of loads from A to B if it also hauls loads from B to A.

In most cases, however, it is not obvious which package of lanes and flows make sense for a particular carrier. Some sets may look disjoint to the shipper but when combined with the carrier's other traffic make perfect sense. For example, it is intuitive that a single carrier hauling ten loads per week from Boston to Detroit may have a lower cost if it can also haul ten loads from Detroit to Boston. A carrier, however, may be able to offer a lower price for hauling from Boston to Detroit conditional on, say, hauling ten loads per week from Philadelphia to New York. Such a carrier may have "power lanes"[9] between Detroit and Philadelphia as well as between New York and Boston, and the extra business complements and balances its network. Requiring that carrier to also haul the ten loads per week from Detroit to Boston, in this example, may actually increase the carrier's cost per load because this creates more of an imbalance out of Detroit.

In summary, the economics of direct transportation carriers imply the following:

- A carrier's cost structure for hauling on one lane of traffic is highly influenced by the remainder of its business across its network.
- Carriers can reduce their total costs by intelligently selecting which lanes to serve and at what volume level.
- The effect that a set of potential lanes of traffic has on a carrier's bid valuation consists of both a common information component (due to the prevailing flows in the marketplace) and a private information component (due to the carrier's other business).

In the auction process, these factors imply that the shipper should

- enable and encourage the carriers' preference elicitation in terms of specific lanes, bundles of lanes, and traffic volume
- not bother spending too much time preparing "shipper specific" potential bundles ahead of time
- be able to analyze and evaluate the large number and types of complex bids that will be submitted.

21.3.4 Individual Lane Pricing—Dealing with Uncertainty

As mentioned in section 21.2.3, carriers consider, explicitly or implicitly, the uncertainty of follow-on connectivity when determining the value or price for each shipment. This can be done explicitly by calculating the total system contribution of each shipment hauled for a given type of equipment, in a given time frame (say, a day) $\Pi^q_{i,j}$, as follows:

$$\Pi^q_{i,j} = R^q_{i,j} - D_{i,j} + P^q_j - P^q_i \tag{21.1}$$

where:

- $\Pi^q_{i,j}$ is the total system contribution that the carrier receives for hauling the q^{th} shipment from region i to region j in the time frame under consideration.
- $R^q_{i,j}$ is the rate that the carrier under consideration quotes for hauling the q^{th} shipment from region i to region j in the time frame under consideration.
- $D_{i,j}$ is the direct cost of hauling a load from i to j (including fuel, driver wages, tire wear, etc.). Note that this is the same for all loads from i to j.
- P^q_j is the expected contribution of the extra truck carrying the q^{th} shipment at region j.
- P^q_i is the expected lost contribution from one less truck (the q^{th} shipment) at region i.

The regional potentials, P^q_j and P^q_i, imbed all the information about future loading opportunities out of regions i and j. Naturally, carriers should agree to haul a load only if $\Pi^q_{i,j} > 0$, that is, if the system contribution of a load is positive. Similarly a carrier should haul the loads with the highest $\Pi^q_{i,j}$ if more than one is available.

When moving from an area, i, that has many hauling opportunities to an area that does not, j (a head-haul move), P^q_i is high whereas P^q_j is low, and may even be negative (because the destination region may require the carrier to move empty out of there or wait a long time for a follow-on load). Given that $D_{i,j}$ is only a function of the distance, the carrier has to charge a high price, $R^q_{i,j}$, in order ensure that the move is worthwhile, that is, that $\Pi^q_{i,j} > 0$. In back-haul lanes, P^q_i is low, and P^q_j is high. Consequently, the carrier can charge a low price, $R^q_{i,j}$ to haul a shipment from i to j. In fact, if P^q_i is low enough and P^q_j is high enough, the carrier can move the truck empty, with $R^q_{i,j} = 0$. This is the rationale for a repositioning move.

The calculation of the regional potential involves recursive computations (see, for example, Powell et al. 1988). When making real-time decisions about dispatching and spot market pricing, some of the future shipments to be moved are known, and in many cases the carrier is committed to haul them. Thus, they have to be accounted for in the calculations. Furthermore, the short-term regional potentials vary by day of week, week of month, month of quarter, season, and specific holidays and events.

When participating in a strategic auction, carriers typically calculate the regional potentials for each location in the network simply as the average direct contribution of outbound loads over the last year. Thus:

$$P_i = \sum_{\forall m \text{ last year}} \sum_{\forall j} (R^m_{i,j} - D_{i,j}), \tag{21.2}$$

where $R^m_{i,j}$ is the revenue of shipment m. Note that in this case the regional potentials are not indexed by the shipment due to the uncertainty involved.

The value of a lane (or the minimum price at which the carrier will haul the freight, with zero expected system contribution) is then:

$$R'_{i,j} = D_{i,j} - P_j + P_i. \tag{21.3}$$

Regional potentials capture the costs related to the uncertainty of incurring *deadhead* miles or dwell time at a shipper's facility. Carriers often use a formula such as 21.3 to establish pricing guidelines for bids on each lane before factoring in desired margins, competitive pressures, and other considerations.

To be more accurate, a carrier should recalculate the regional values every time it determines the price of a bid because, if won, the business represented by the auction will impact the regional potentials. Furthermore, they should factor in the probability that the loads will actually occur. We do not dwell on this issue further; it is the subject of an ongoing research effort.

Package bids conceptually enable carriers to engineer and modify the regional values by controlling the number of loads in or out of a region. Note that closed loop tour packages would, at this level of analysis, have no impact on the regional values (subject, of course, to the uncertainty mentioned above). Package bids comprising a group of lanes out of a given region increase its regional potential and thus make lanes coming into it more attractive, whereas lanes emanating from it may become less attractive.

21.4 Nature of Contracts and Auctions

The relationships between shippers and carriers, and the contracts that govern them, have certain characteristics that distinguish them somewhat from auctions for electromagnetic spectrums or durable goods. This section looks at some of these differences, and explains why sealed bids are the predominant form of auctions in this market.

21.4.1 Lane Definition

In most auctions, it is pretty clear what the items are. This, however, is not the case in transportation procurement auctions where each shipper may define the items differently.

Actual movements between origins and destinations go from a shipping point to a receiving point. In order to minimize the effort required to create, upload, and manage the large number of potential rates that could be collected, shippers aggregate the individual ship-to and ship-from locations into regions.[10] The aggregation depends on the volumes between regions and can typically range from a single shipping point (a plant or a warehouse), a five-digit postal code area, a three-digit postal code area, to an entire state. The lane can be defined as any combination of these (state-to-state, point-to state, three-digit postal code to five-digit postal code, etc.), depending on the volume. Using larger origin and destination regions can result in higher planned lane flows and a more stable forecast of such flows as compared to smaller regions. It also means fewer lanes in the network, which makes it easier to analyze. Unfortunately, it also increases the uncertainty in terms of deadhead miles *within* a region. Due to the uncertainty in the loads actually materializing, carriers tend to include only lanes with higher volume in their package bids.

Interestingly, using larger origin and destination regions also means that incumbents have a bigger advantage because the distribution of actual shipping points and consignees within regions is fairly stable over time. Although the detailed intra-region distribution of actual shipping locations is typically not included in the auction information, it is known by the incumbents.

21.4.2 Shipper Objectives

The main objective of every procurement auction is to determine the lowest total cost provider(s). Transportation auctions are no different. This main objective, however, is rarely the only one. Most shippers consider both lane-based and system-based objectives along with the total cost when solving the winner determination problem. Hohner, Bichler, Davenport, and Kalagnanam (chapter 23 of this volume) discuss similar issues with procurement auctions in other industries.

Lane-Based Shipper Objectives Lane-based objectives are business requirements that can be considered within the WDP on a lane-independent basis. That is, there are no cross-lane dependencies involved. For example, level of service delivered on each traffic lane can be considered within the WDP by applying a qualifying factor to each carrier-lane bid. This is typically done by allocating penalties and rewards to the bids based on various service attributes. For example, a shipper might consider a 90 percent "on time" performance to be a base level of service on a given lane. Bids from carriers with higher performance on that lane may be rewarded, say, $10 for each percentage point higher than 90 percent and $20 for each point higher than 95 percent, while being penalized by $10 for each percentage point below 90 percent and not being eligible to participate in the auction if the service is below 80 percent. This means that the carriers' bids will be adjusted before it is fed into the WDP to reflect their service level. A common use of lane-based objectives is favoring incumbent carriers by a small percentage to lower the churn of carriers. Many shippers consider the "utility exploration" process of agreeing on these factors across the organization to be one of the most important benefits of a structured auction process.

One of the primary benefits of lane-based objectives is that they can be applied without any modification to the underlying formulation used to solve the WDP; only the cost coefficients need to be adjusted.

System-Based Shipper Objectives System-based objectives are more complex in that they involve conditions that cross multiple lanes, bids, or carriers, and therefore require modification of the model formulation used to solve the winner determination problem. System-based objectives allow shippers to enforce external business rules within the strategic bidding process.

These can include things such as:

- Business guarantees whereby certain carriers, or sets of carriers, are guaranteed to be awarded a predetermined minimum or maximum number of loads or dollar value of business. Common examples include core carrier programs, incumbent carriers, or minority vendor initiatives.
- Size of carrier base the shipper might want to restrict the number of winning carriers (across the system or serving a given region) to simplify its daily operations and increase its visibility and importance to the winning carriers.
- Transit time where the shipper wants a certain percentage of the winning carriers to have specific transit times or specific level of service.
- Mix of carriers many shippers prefer to have a mix of different types of carriers, such as union and nonunion or regional and national in order to mitigate operational risks.

The introduction of these business considerations further complicates the strategic auction process. Each of these business rules has a cost and an impact on the final carrier awards. We discuss this in the context of common and private information in section 21.4.3.

Other Objectives In addition to achieving low cost, high service levels, and complying with other corporate policies, transportation auctions try to meet other objectives, such as efficiency of the auction results, robustness of the awards, and the speed of the process itself.

Efficiency Although efficiency is important in most auctions, another argument is at work in the procurement of transportation services. In an auction for transportation services, the quality of that future service depends on how well the business won in any auction fits with the winner's other business. If the new business does not really fit the winner's capability or its network, the service will likely be poor regardless of contract terms or past performance. Thus, the auctioneer has a vested interest in ensuring that the winners are truly those carriers that most value each of the lanes auctioned.

Robustness A criterion not typically used in standard auction theory is that of robustness. The auction results are robust if a change to the underlying freight flow network—such as a supplier or a customer going out of business, a major port closure, or total volume dramatically increasing or decreasing—does not result in a large cost increase. This criterion is particularly important in TL transportation auctions because many of the possible providers are small and financially unstable and the accuracy of the forecasts at the lane level is typically very low. In addition, the commodity nature of the industry and its meager profits mean that even larger carriers are not always financially secure. In fact, during 2001, over a thousand carriers per quarter filed for bankruptcy protection in the United States (see ATA 2002). Thus shippers would like to be in a situation where back-up carriers can pick up the slack with little cost increase if a primary carrier goes out of business.

Robustness is not easily handled within the WDP framework that virtually all shippers and software vendors use. Some shippers will conduct sensitivity analysis by making multiple optimization runs with modifications to the underlying network flows and the base of winning carriers, but this is not common practice. Creating and incorporating a workable metric of robustness for transportation service auctions is a ripe area for future research.

Simplicity and Speed Many shippers have to conduct large and complicated transportation auctions fairly frequently. Such auctions can involve thousands of lanes (items) and dozens of carriers (bidders) and require significant work on the part of the auctioneer to prepare the items for bid, manage the auction process, and award the business.

The situation is even more critical for carriers who have to respond to many auctions. Over 80 percent of all carriers who participate in auctions receive, on average, at least one bid a week, with just under 50 percent receiving at least one bid a day, each of which require, on average, over a man-week of effort for analysis (see Caplice, Plummer, and Sheffi 2004).

Keeping on top of multiround bids is too time consuming for these carriers. A shipper that wants to increase carrier participation and response needs to simplify the process as much as possible by, for example, using only one round of bidding. Interestingly, even though the auction theory literature suggests that sealed bid auctions require more effort on the part of the bidders in terms of preparation and market research, in transportation procurement bids when bidders know the market, the administrative burden of multiple rounds more than offsets this consideration.

Consequently, simple formats that can be executed quickly are preferable for both shipper and carriers. Most transportation auctions include only a single round and are based on a sealed bid, first price format. This need for simplicity is also a negative influence on the use of combinatorial auctions because of the effort and energy required by carriers to design package bids. Even with a single round format, the transportation auction process typically takes from three to six months.

The literature has proposed other auction formats with beneficial theoretical properties. These include the Vickery-Clarke-Groves (VCG) design (Ausubel and Milgrom, chapter 1 of this volume) and iterative combinatorial auctions (Parkes, chapter 2). Although we have never actually seen any of these more sophisticated formats used in practice for transportation procurement, it is worthwhile considering why not. As Ausubel and Milgrom (chapter 1) note, three of the main drawbacks of the VCG design are the added complexity it brings to the bidders, the general reluctance of bidders to reveal their own values, and the low revenue generation for the auctioneer. Any one of these three design disadvantages is enough to discourage a shipper from employing a novel auction format outside of industry norms. Iterative CAs hold promise for use in transportation auctions, but the issue still remains on how to handle system-based shipper objectives. In our experience, whenever multiple round CAs have been run for transportation procurement (which is quite rare) the system-based shipper objectives were not considered until the final round. That is, the information feedback to the bidders never included the impact of these side constraints.

21.4.3 Types of Information

As in most other auctions, the value of the items being auctioned off has both private and common components. The common component consists primarily of the direct costs involved in hauling a shipment. The cost for a carrier to haul a certain distance is almost identical for all carriers—they all use the same technology, and driver wages are competitive across the industry. Studies have shown that 80 percent of the variability in TL carrier prices can be explained through the distance hauled (see, for example, Plummer 2003 or SABRE Group 1998).

The common information portion of the regional potentials, as discussed in section 21.3.4, captures freight flow imbalances at the national level; all carriers know that it is more difficult, for example, to find loads leaving the Southeast than to find loads leaving the industrial heartland of the U.S. Midwest. These macro-level geographic factors[11] to capture regional value effects increase the explanatory power of these pricing models by another 5 percent, as these references show.

The primary source of private information for transportation auctions is in the individual carrier's regional potentials. For example, suppose a carrier has a contract with a plant in Freeport, Florida (located in the far western section of the Florida panhandle) that tenders several loads a day outbound to, say, Chicago (a well-known source of potential follow-on loads). This is private information for that carrier that would enable it to bid more aggressively on inbound loads to the Freeport area because it has a reliable source of outbound loads in close proximity. We know of no studies that have attempted to quantify the influence of this private information on carrier's bid prices, even though we have seen its effects in practice.

Another type of information that is common to a set of the bidding carriers (the incumbents) but private from the nonincumbent carriers' perspective is rooted in the shipper's behavior. A carrier's costs, and therefore to some extent the prices charged, are influenced by the business terms and practices of the shipper, such as the speed of turning around loads, payment terms, gate checking and security procedures, handling of missing and damaged items, and so on. Regardless of what information the shipper presents to the carriers within an auction, the carrier will only learn of the *actual* practice after winning the bid and starting to serve the account. Incumbent carriers, then, have an advantage over the nonincumbent carriers in that they can price according to the behavior they have experienced rather than the shipper's purported behavior.[12]

In addition to the common and private information that each bidder has, transportation auctions have a third factor at work. Shippers tend to engineer the final solution by incorporating lane-based and system-based business objectives into the WDP. These objectives constitute a third type of information that influences the final assignment and can, therefore, influence the bidding behavior, if the carriers are aware of the specific objectives. Table 21.1 shows that on average, shippers are willing to pay an additional 6 percent over the lowest cost submitted bid solution (base case) in order to achieve a better engineered assignment. In other words, the impact of this private auctioneer information is greater than that of regional values at the macro level.

Although a carrier has no direct influence over how much a shipper values different business objectives, it can infer these objectives from shipper statements, corporate announcements, and past behavior. For example, if a shipper's new procurement department announces that one of its objectives is to reduce the number of vendors in general, a carrier that bids on many lanes can potentially be less aggressive than a smaller carrier that will only bid on a few lanes. The larger carrier in this example would be betting that the shipper values larger coverage more than their higher relative rates. Similarly, if a shipper has a history of taking incumbency into consideration, then the incumbents can probably hedge their bid prices. The impact and influence of these different types of information messages from the shipper to the carriers is part of an ongoing research effort.

In any case, the carriers utilize both private and common information in determining the value of the freight business and their bids, whereas the shipper uses business rules that are typically not communicated directly to the carriers[13] to modify the WDP outcome.

21.4.4 Long-Term Shipper-Carrier Relationships

Buyers and sellers (auctioneers and bidders) of transportation services develop long-term relationships in the sense that the large carriers and the large shippers depend on each other for business and capacity, respectively. The implications of this are the following:

Repetitive auctions The auctions themselves are typically repeated every one to two years and carriers do get to know their customers' business and the strategies of their main competitors. As mentioned above, shippers also know the market and what to expect from carriers. Consequently, for example, reserve prices are typically used for providing "guidance of expectations" to carriers rather than to "avoid bad surprises," as is the case with some other auctions.

Asymmetric information In every auction some carriers are incumbents on a significant portion of the business. This means that they understand many of the processes of the customer's operation, may have electronic data interchange links already established, or may be located nearby. In addition, they may be aware of contract details that may not be mentioned in the request for proposal, such as extra equipment requirements, the actual payment lead time, and so on. It is also well known in the industry that shippers understand that incumbents know the business and can start performing immediately, whereas new carriers have to learn the nuances of the new business. Thus, many shippers will prefer incumbents either by modifying their actual bid (lane-based objectives) or by using a constraint to place a minimum on the amount of business that incumbents are awarded (system-based objectives).

Auctioneer's reputation Shippers do enjoy, or suffer from, reputation developed ex post. Auctioneers that do not stand by their commitments or are difficult to do business with find that carriers not only bid higher the next time around but also are not reluctant to share their experience across the industry. On the other hand, shippers who pay on time and are fair in dispute resolution may see more aggressive bids.

Collusion is not an important issue By and large, TL carriers do not seem to collude, at least in the United States and Western Europe. The reasons are that the number of bidders is relatively large and the predominant form of bidding involves sealed bids, leaving less opportunity for collusion. Other reasons for the lack of widespread collusion may include: (1) the familiarity associated with the repeated nature of the auctions, (2) the expertise of the shippers who know more or less what to expect, and (3) the ease with which human resources can move between companies and the existence of whistle blowers, both of which make detection easy.

Although these issues are common in practice, very little has been written on them in the game-theoretic literature. An exception to this is Weber 1983.

21.5 Bidding Language

The communication language used during the auction determines how the carriers can respond to the shipper's request for bids. Traditional practice in transportation is for carriers to submit a "per load" (or per load-mile) rate for haulage on each lane, regardless of the volume of business that they might win on that lane or any other lane. We refer to this as a *simple bid*. This form of bid language leads to the carriers hedging their bid prices to cover those instances where they do not win any supporting business.

Combinatorial auctions allow carriers to make explicit their otherwise implicit pricing assumptions. They can provide a lower bid price, given certain that other conditions are met. In transportation, these are sometimes referred to as *conditional bids*. That is, the bid rates submitted are conditional on a predefined set of actions also taking place. Lane-based package bids are but one type of conditional bids.

Below we describe the different types of conditional bids that are currently in use within transportation auctions.

21.5.1 Simple Lane Bid

A bid rate applies to all shipments on that lane regardless of the volume awarded. The number of shipments awarded to the carrier on that lane is determined by the shipper. Each bid may include specific service capabilities (transit time, trailer size, weekend coverage, additional safety factors, etc.) that are only available if that bid at that rate is awarded.

This is the most widely type of bid used. Oftentimes shippers do not even provide carriers with lane volume estimates or forecasts. Carriers can include different service levels in multiple simple bids for the same business in order to "de-commoditize" their offerings.

21.5.2 Simple Lane Bid with Volume Constraint(s)

A bid rate applies to all shipments on a lane but only if the carrier is awarded at or above the *minimum commitment constraint* and at or below the *maximum capacity constraint* for that lane, region, set of lanes, or system—as specified.

Capacity (upper bound) constraints are more commonly submitted by carriers than minimum commitment constraints. They are equivalent to budget constraints in that they allow a carrier to submit a set of bids whose sum total capacity is greater than the carrier's total available capacity.

21.5.3 Static Package Bids (AND)

This is a set of individual lane bid rates that apply to each lane within that set, conditional on the shipper awarding the carrier all lanes within the set at the *exact volume levels* specified by the carrier. Most commercially available software tools handle static package bids.

21.5.4 Static Either/Or Package Bids (XOR)

This is where two or more package bids with rates that apply conditional on the shipper, 1) only awarding the carrier one of the bids and 2) awarding that carrier all lanes within that package bid.

This communicates the message, "give me this set of lanes, or that set of lanes, but not both." The message "Give me this set of lanes or that set of lanes or both" is referred to as an OR bid. It can be achieved through the use of nonoverlapping AND bids.

21.5.5 Flexible Package Bids

A set of individual lane bid rates apply to each lane within that set, conditional on the shipper awarding the carrier all lanes within the set *within volume ranges* specified by the carrier for each lane within the set. Note that with static package bids the shipper does not determine the specific volume level awarded on each lane within that package. The carrier determines the lane volume as part of the submission of the static package bid. With flexible package bids, by contrast, the shipper selects the specific volume level awarded on all lanes within the awarded package bid—as long as it adheres to the carrier's ranges. This means that although a carrier knows the total value of a static package bid at the time of bid submission, it only knows the potential range of values for a flexible package bid at that same time. Only after the WDP is solved will the carrier know the actual number of shipments and total dollar value of a flexible package bid.

The carrier specifies for each lane within the package both the rate per load and the minimum and maximum volume per week, month, or year. Additionally, the carrier can provide package level capacity ranges. If the shipper is awarding only one carrier per lane, then these bids are equivalent to static package bids.

21.5.6 Simple Reload Bids

A carrier specifies that the total number of awarded inbound loads to a facility is equal to (or within some parameter of) the number of awarded outbound loads from the same facility. The WDP model determines the actual volume awarded, so that the conditional bid only specifies the ratio of the awards. This is done to improve the balance at a specific site and increase the potential for *continuous moves* at that site. It differs from flexible package bids in that the condition is added that the balance between two sets of lanes must be met.

21.5.7 Tier Bids

A schedule of bid rates apply to a lane for a predetermined set of volume ranges on that lane. The relevant rate is applied to each shipment depending on the volume of loads processed that week or month. This captures the economies of scale effect on the lane level. Because the actual rate charged is determined during execution, it more accurately maps the carrier's costs.

Regardless of the type of conditional bid used, the end result is a rate per load for each lane that is used in execution. Although the total value of each bid is used for analysis, it is always divisible and easily allocated to each specific lane. In fact, the final upload to the downstream systems is a set of individual lane rates for each winning carrier. The conditions under which the carrier was awarded those rates are rarely included, or even tracked, in actual execution, thus increasing the uncertainty described previously in section 21.2.3.

21.6 Winner Determination Problem

Part III of this book discusses the winner determination problem (WDP) in depth. We will only relate what is being used in practice for transportation services, where this problem is generally referred to as the "carrier assignment" problem.

Shippers will either assign business to carriers by lane (a single carrier is responsible for hauling on each lane) or by load (each carrier is assigned a number of loads to haul on each lane awarded). In practice, most software applications use models that assign by load because this permits other network and business specific aspects to be considered.

21.6.1 Bid Types

The most straightforward carrier assignment model allows only simple bids with no side constraints:

$$\min \quad \sum_{c}\sum_{k}\sum_{i,j} {}_{c}c^{k}_{i,j}\,{}_{c}x^{k}_{i,j} \tag{21.4a}$$

subject to:

$$\sum_{c}\sum_{k} {}_{c}x^{k}_{i,j} = x_{i,j} \quad \forall i, j \tag{21.4b}$$

$${}_{c}x^{k}_{i,j} \geq 0 \quad \forall i, j, c, k \tag{21.4c}$$

where the notations are:

Indices

i Shipping origin region

j Shipping destination region

k Bid package identification

c Carrier identification.

Decision Variables

${}_{c}x^{k}_{i,j}$ number of loads per time unit (week, month), on lane i to j, assigned to carrier c, under package (which in this case is a simple bid) k.

Data

$x_{i,j}$ Volume of loads from shipper s, on lane i to j, that are being bid out
${}_c c_{i,j}^k$ Bid price per load on lane i to j, for carrier c, as part of conditional bid k.

The objective function 21.4a minimizes the total price charged by carriers to haul loads over the shipper's network. The coefficient ${}_c c_{i,j}^k$ is the price per load submitted by carrier c under the terms of a specific bid k.[14] Constraints 21.4b ensure that the planned volume on each lane is covered.

Simple bids, ${}_c c_{i,j}^k$, allow the carrier to submit a rate per load and the shipper to determine the specific quantity of loads awarded to each carrier on each lane. This is the most common bid type used in transportation auctions. The k index permits the carriers to submit multiple bids (with correspondingly different rates) for the same lane but with potentially different service levels, equipment types, or other characteristics. So, although these are not package bids, we refer to them as conditional bids (or packages) nevertheless.

Permitting both simple bids and static package bids into the carrier assignment problem results in the formulation:

$$\min \quad \sum_c \sum_k \left[\left(\sum_{\forall i,j \in k} {}_c c_{i,j}^k \, {}_c \delta_{i,j}^k \right) {}_c y^k + \sum_{i,j} \left({}_c c_{i,j}^k \, {}_c x_{i,j}^k \right) \right] \tag{21.5a}$$

subject to:

$$\sum_c \sum_k \left({}_c x_{i,j}^k + {}_c \delta_{i,j}^k \, {}_c y^k \right) = x_{i,j} \quad \forall i, j \tag{21.5b}$$

$${}_c x_{i,j}^k \geq 0 \quad \forall i, j, c, s, k \tag{21.5c}$$

$${}_c y^k = [0, 1] \quad \forall c, k \tag{21.5d}$$

where the additional variables and data are:

${}_c y^k$ $= 1$ if carrier c is assigned static package bid k, $= 0$ otherwise
${}_c \delta_{i,j}^k$ Volume of loads on lane i to j, that carrier c is bidding on as part of package bid k.

The objective function 21.5a minimizes the cost of assigning carriers to haul loads over the shipper's network. The package bid cost coefficient is the total cost per planning time period for all volume on all of the lanes included in the package bid k submitted by carrier c. Constraints 21.5b ensure that the planned volume on each lane is covered—either by simple or static package bids. Note that the carrier must specify the exact number of loads requested for each lane within each static package bid, ${}_c \delta_{i,j}^k$. Static package bids are the most common form of package bids used in transportation auctions—the carrier specifies the lanes and the exact level of flow per each lane. Most of the commercial software programs use similar formulations.

More recently, flexible package bids are being discussed—both with and without capacity limits. By introducing flexible package bids, the model becomes:

$$\min \quad \sum_{c}\sum_{k}\sum_{i,j}({}_cc^k_{i,j}\,{}_cx^k_{i,j}) \tag{21.6a}$$

subject to:

$$\sum_{c}\sum_{k}{}_cx^k_{i,j} = x_{i,j} \quad \forall i,j \tag{21.6b}$$

$$-{}_cM^k_{i,j}\,{}_cy^k + {}_cx^k_{i,j} \le 0 \quad \forall c,k,i,j \tag{21.6c}$$

$$-{}_cLB^k_{i,j}\,{}_cy^k + {}_cx^k_{i,j} \ge 0 \quad \forall c,k,i,j \tag{21.6d}$$

$$-{}_cUB^k_{i,j}\,{}_cy^k + {}_cx^k_{i,j} \le 0 \quad \forall c,k,i,j \tag{21.6e}$$

$$-{}_cPL^k\,{}_cy^k + \sum_{ij}{}_cx^k_{i,j} \le 0 \quad \forall c,k \tag{21.6f}$$

$${}_cx^k_{i,j} \ge 0 \quad \forall i,j,c,s,k \tag{21.6g}$$

$${}_cy^k = [0,1] \quad \forall c,k \tag{21.6h}$$

where the additional variables and data are:

${}_cM^k_{i,j}$ Large constant

${}_cLB^k_{i,j}$ Lower bound in loads on lane i to j, that carrier c is bidding on as part of flexible package bid k

${}_cUB^k_{i,j}$ Upper bound in loads on lane i to j, that carrier c is bidding on as part of flexible package bid k

${}_cPL^k$ Lower bound in loads across all lanes, that carrier c is bidding on as part of flexible package bid k.

The objective function 21.6a sums the product of the individual lane bid prices and the awarded lane volume on each lane within each conditional bid. Constraints 21.6b ensure that the volume in each lane is covered by some carrier; 21.6c enforce the condition that any carrier assigned any volume on a lane within a flexible package bid is awarded the entire package bid; 21.6d and 21.6e enforce the conditions that if any volume is assigned to a lane within a flexible package bid it satisfies the carrier's specified minimum and maximum lane volume requirements for that bid; and 21.6f enforce the condition that if any volume is assigned to any lanes within a flexible package bid the total package volume awarded to that carrier under that bid package satisfies the carrier's minimum volume requirement for the entire package.

Note that 21.6 is a more general formulation than 21.5 in that it handles simple, static package and flexible package bids all within the same decision variables. Simple bids are modeled as flexible package bids consisting of just one lane. Static package bids are modeled as flexible package bids but with the upper and lower lane volume restrictions set equal to the same value. Thus, the same decision variable, ${}_{c}x^{k}_{i,j}$, can be used for all three of the primary conditional bid types.

Simple reload bids also can be incorporated into 21.6 by adding constraints 21.6i and 21.6j for each facility, j, that is subject to reload simple bid, k, for carrier c.

$$\beta_j \leq \sum_i {}_{c}x^{k}_{i,j} - \sum_i {}_{c}x^{k}_{j,i} \leq \beta'_j \quad \forall j,k,c \tag{21.6i}$$

$$\alpha_j \leq \sum_i {}_{c}x^{k}_{i,j} \Big/ \sum_i {}_{c}x^{k}_{j,i} \leq \alpha'_j \quad \forall j,k,c. \tag{21.6j}$$

The terms β_j, β'_j, α_j, α'_j are constants capturing the possible relationships between the outbound and inbound volumes. Shippers typically use either of these two sets of parameters, but rarely both. A simple reload bid would typically also contain minimum and maximum volume constraints at the lane and package levels.

21.6.2 Side Constraints

Section 21.4.2 discussed the different shipper objectives that are frequently considered in transportation auctions. This section illustrates the three most commonly used constraints, using formulation 21.6 as the basis.

Business Guarantee Constraints A shipper often wants to ensure that the amount of traffic that a carrier, or set of carriers, wins is within a certain bound. The shipper might not want to rely too heavily on a single carrier, thus setting a maximum coverage. Conversely, the shipper might want to give enough business to a carrier to remain a significant customer, thus setting a minimum. Coverage can be measured in terms of loads won or in total estimated dollar value. The constraints below ensure that all carriers within some set of carriers C' are awarded business within some preset volume (dollar value) bounds.

$${}_{C'}\text{MinValue}^{K'}_{N'} \leq \sum_{c\in C'} \sum_{k\in K'} \sum_{ij\in N'} ({}_{c}c^{k}_{i,j}\,{}_{c}x^{k}_{i,j}) \leq {}_{C'}\text{MaxValue}^{K'}_{N'}, \tag{21.7a}$$

$${}_{C'}\text{MinVolume}^{K'}_{N'} \leq \sum_{c\in C'} \sum_{k\in K'} \sum_{ij\in N'} ({}_{c}x^{k}_{i,j}) \leq {}_{C'}\text{MaxVolume}^{K'}_{N'}. \tag{21.7b}$$

Note that these constraints can apply to a specified set of carriers (C'), bid packages (K'), or geographies (N'). Some common constraints include guaranteeing that the core carrier group is awarded, say, at least 100 loads a week out of a facility; ensuring that at least half of the loads covered in the Northeast are awarded to carriers providing 53-foot trailers, setting a maximum of 20 percent of the total volume in the network to be awarded to intermodal services, and so on. These constraints are easy to explain and shippers tend to think of their business in these terms. Care needs to be taken when MinVolume or MinValue constraints are used to ensure feasibility. There is a tendency for some shippers to over-specify or over-engineer a final award using these types of constraints.[15]

Carrier Base Size Constraints Another typical business constraint is the restriction of the total number of carriers winning—at the system, region, or lane levels. The number of carriers in the system or at a location can be restricted through the use of either hard or soft constraints. The system-based (or hard) approach adds the following constraints to limit the number of carriers assigned at the system and facility levels:

$$-{}_cM^k_{i,j}\,{}_cw_i + {}_cx^k_{i,j} \le 0 \quad \forall c, k, i, j \tag{21.8a}$$

$$\sum_c {}_cw_i \le L_i \quad \forall i \tag{21.8b}$$

$$-{}_cM^k_{i,j}\,{}_cz + {}_cx^k_{i,j} \le 0 \quad \forall c, k, i, j \tag{21.8c}$$

$$\sum_c {}_cz \le S \tag{21.8d}$$

$${}_cw_i = [0, 1] \quad \forall c, i \tag{21.8e}$$

$${}_cz = [0, 1] \quad \forall c \tag{21.8f}$$

where the additional variables and data are:

${}_cw_i$ = 1 if carrier c is assigned to facility i, = 0 otherwise
${}_cz$ = 1 if carrier c is assigned to the network, = 0 otherwise
L_i Location limit of carriers desired to serve facility i
S System limit of carriers desired to serve network as a whole.

The traditional approach of using a single large "M" variable, although creating more compact formulations, can result in extremely fractional LP solutions, making it very weak in solving the IP. Barnhart et al. (1993) show in most cases, disaggregating the model leads to tighter bounds when solving the IP as will minimizing the constant, M. Setting ${}_cM^k_{i,j}$ to the maximum of $({}_cx^k_{i,j})$ for each carrier, bid identifier, and lane combination accomplishes this.

Although the hard constraints make sense at the facility or system levels, when applied to individual lanes it often results in one carrier winning the lion's share of the volume and the others winning the bare minimum to satisfy the constraint. This is less desirable in practice because many shippers want a more balanced distribution. A way to create more balance is simply to add in a maximum volume constraint for each carrier for the location or lane in question equal to the percentage of the business that the largest carrier is desired to haul using the business guarantee constraints shown earlier.

Soft constraints can also be used to discourage additional carriers being awarded business by modifying the objective function as follows:

$$\min \quad \sum_{c}\sum_{k}\sum_{i,j}({}_{c}c^{k}_{i,j}\,{}_{c}x^{k}_{i,j}) + \sum_{c}\sum_{i} F^{c}_{i}\,{}_{c}w_{i} + \sum_{c} F^{c}\,{}_{c}z \tag{21.9}$$

where all variables are the same as previous models with the addition of:

F^c Cost of including carrier c into the system and
F_i^c Cost of including carrier c serve location i.

These fixed costs can be both carrier and location specific as shown above, or the same for all carriers and all locations. Essentially, these fixed costs act as penalties for adding additional carriers to the winning set.

The two most common uses of these constraints are to limit the total number of carriers awarded any business and to limit the number of carriers serving a facility on both the inbound and outbound sides so as to minimize the size of the required trailer pool. The latter consideration also encourages the use of continuous moves at that facility—because specific carriers will tend to win both inbound and outbound business.

If Then Constraints Shippers will often wish to guarantee that if a carrier is awarded any business, then it has to be of a certain minimum level. Constraints 21.10 below ensure that if a carrier is awarded any business across the network, then it must be at least ${}_{c}SV$ loads.

$$-{}_{c}SV\,{}_{c}z + \sum_{k}\sum_{i,j}({}_{c}x^{k}_{i,j}) \geq 0 \quad \forall c \tag{21.10a}$$

$$-{}_{c}M^{k}_{i,j}\,{}_{c}z + {}_{c}x^{k}_{i,j} \leq 0 \quad \forall c,k,i,j. \tag{21.10b}$$

21.7 Conclusion

Three observations from practice warrant discussion in this chapter: the lack of widespread adoption of package bids (or the incentive problem), the unexpected (by us) apparent value of solving the WDP, and the benefits of using CAs over traditional transportation auctions used in practice. We conclude this section and the chapter with some observations on future research directions.

21.7.1 The Incentive Problem

As detailed earlier in the chapter, package bids make clear economic sense for TL carriers and more shippers are running combinatorial auctions than ever before. Unfortunately, the number of carriers submitting package bids (static or flexible) has rarely exceeded a small minority in any single auction. Most carriers when presented with the opportunity to submit package bids opt to submit only simple bids. The question, then, is how can shippers provide incentives to carriers to create and submit more package bids?

We feel that there are two major reasons for the low use of package bids (and therefore two avenues of approach for increasing their use). The first is the lack of tools to assist carriers in formulating robust and worthwhile package bids. Unfortunately, many carriers and researchers approach the strategic problem of formulating package bids from an execution (truck by truck) perspective. In the very first uses of combinatorial auctions, it was not uncommon for carriers to submit package bids with upwards of a dozen lanes linked together in a closed loop tour with only one or two loads per week of volume on each lane. The carriers were trying to construct a real-time continuous move in a strategic auction. This practice is becoming less common among carriers, but many software solutions and researchers still take this approach. What carriers need is a methodology to incorporate the numerous levels of risk and uncertainty inherent in the planning problem and formulate those packages that provide the greater probability of retaining a balance of loads across their entire network.

Second, most shippers and carriers rarely even track, much less enforce, compliance of contracted volumes and rates. Frequently, carriers will win lanes in a strategic auction, but never be tendered any business on them. This can be caused by a change in business shipping patterns as well as local preferences in the transportation manager's decision process. The net result is that there is a significant gap between what is awarded and what is actually tendered to a carrier, which means that the effort spent formulating a package bid could go for naught—even if it is awarded—when the actual loads do not materialize.

Our experience suggests that providing carriers with more robust, probabilistic tools for forming package bids and improving the contractual compliance systems of shippers and carriers will lead to the wider acceptance of package bids by carriers.

21.7.2 Unexpected Value of the Winner Determination Problem

Although our initial research and model formulation in the early 1990s allowed for the insertion of constraints into the carrier assignment model, it was felt that they would not be widely used in practice. Similarly, the initial model in Porter et al. (2002) for Sears did not consider any business constraints besides covering the available volume.

The common thought was that there would be minimal use of these side constraints because the model would select the "optimal" assignment. Our experience has taught us otherwise. In fact, having the ability to model various business constraints and "philosophies" directly in the assignment problem is now viewed as the most valuable component of the procurement process. Shippers use the optimization model to price out various "what if" scenarios in order to conduct a value assessment. As discussed in section 21.4.3, the cost of including these business considerations averages 6 percent of the total lowest submitted bids.

It is not uncommon to run several dozen scenarios during an auction process, each of which features hundreds of specific business constraints. Shippers, once enabled with this type of decision support, typically spend a considerable amount of time exploring various assignments to maximize the fit to their business needs rather than just looking for the lowest cost. This "what if" analysis or scenario management capability is frequently used as a tool to drive consensus among different factions within a shipper (or among shippers in a multicompany engagement)[16] where the consequences of different business decisions are weighted against each other. The power of these "what if" analyses is that they are conducted with actual relevant and operational bids, not based on historical costs. Bichler, Davenport, Hohner, and Kalagnanam (chapter 23 of this volume) discuss similar benefits of running multiple scenarios within procurement auctions in other industries.

The increasing use of the WDP to estimate the financial impact of various business rules contributes to the growing use of sealed bid auctions. This is because the constraints used within the WDP are not visible to the bidders—only the final results are. Thus, the information provided to the bidders is not sufficient to make accurate or intelligent price adjustments in between rounds.

21.7.3 Benefits of Combinatorial Auctions over Traditional Auctions

The transportation industry has benefited tremendously from the introduction of CAs in the 1990s. Many of these benefits, however, are indirectly, rather than directly, the result of CAs.

The primary benefit is that CAs forced shippers to improve the quality and quantity of data that they provide to the carriers. The shippers realized that in order for a carrier to formulate a complex bid, they would need to have exceptionally accurate and detailed information. This is not the case in traditional transportation auctions where only origin and destination are typically provided.

Second, CAs forced shippers to recognize the underlying economics of their carriers. This manifested itself in shippers allowing, and encouraging, their carriers to "be creative" in engineering their proposed solutions. Shippers are more cognizant of the interplay between lanes and locations for carriers. Traditional transportation auctions ignore these complexities.

Third, because CAs require the use of optimization, the shippers were enabled to consider nonfinancial information when running a procurement auction. This has lead to the inclusion of level of service and other factors in most of the larger procurement auctions. Traditional transportation auctions ignore any factors aside from bid rate.

Overall, then, the introduction of CAs into the truckload transportation industry has led to more accurate, collaborative, and comprehensive interaction between shippers and carriers.

21.7.4 Areas for Future Research

The use of combinatorial auctions for transportation procurement offers many opportunities for future research. Although it has been used in practice for the better part of a decade, the adoption rate is not as large as the theory would indicate it should be. This leads to a large number of potential areas of investigation, including the following:

Carrier bidding behavior The way in which carriers actually approach and participate in combinatorial auctions has not been studied to any significant degree. This could lead to better and more standardized auction rules.

Carrier bidding methodology As mentioned earlier, carriers do not utilize very sophisticated systems or approaches when setting prices or creating package bids. A methodology that incorporates the stochastic nature of the underlying transportation services as well as the uncertainty of the actual award is sorely lacking.

Cross shipper auctions Many shippers have attempted to form coalitions to better procure transportation services collectively. These have in general not been successful. It would be interesting to develop auction approaches and rules to enhance cross company auctions.

Improved robustness in the WDP A key weakness of the traditional WDP approach is that it tends to over-concentrate the awards in order to minimize the planned cost. Unfortunately, the WDP does not take variability into account. This can result in assignments that are lowest cost for the assumptions made in the plan, but are highly susceptible to any operational changes. A better approach is needed so that shippers can measure, manage, and decide how much additional redundancy to secure in order to minimize total system risk. The use of real options in transportation contracting is a step in this direction.

This is just a short list of research topics that we and other researchers in the field are pursuing.

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Notes

1. A lane is an origin-destination pairing of freight flows; in other words: "X truckloads per week going from A to B." It is typically the item being auctioned off in TL transportation procurement engagements.

2. This product line was developed by Digital Freight, which was acquired by Manugistics in 2001.

3. The OptiBid product line was developed originally by PTCG. It was acquired by Sabre in 1996, Logistics.com in 2000, and Manhattan Associates in 2003.

4. The authors have no financial or commercial interests in the development, leasing, or sale of any of the software created or marketed by any of the companies mentioned in this chapter or others.

5. Although replacing a single carrier on a small subset of lanes has very low switching costs, the effort required for a wholesale change is quite high.

6. A manufacturer with such an annual TL transportation bill will probably have annual revenue of $5–15 billion.

7. In the late 1980s, North American Van Lines, one of the market leaders at the time, was accused of making a higher return from financing and repossessing trucks than from transportation operations.

8. When the flow of traffic is such that drivers spend too much time on the road, carriers will allow operators to drive home empty or even fly them home, just to ensure that they will visit their families.

9. A power lane for a carrier is an origin destination pair that has a very large number of reliable shipments.

10. For example, a medium sized shipper that has, say, 5,000 point-to-point movements may aggregate them into 1,000 three-digit zip code to three-digit zip code lanes or several hundred state-to-state lanes. There are generally orders of magnitude of difference between the number of point to point moves and the number of lanes used in an auction.

11. In both Plummer 2003 and SABRE 1998, the nation was divided into seven zones: Northeast, Southeast, Midwest, Southwest, Central, and Northwest. Separate regional values were estimated for both inbound and outbound effects.

12. In fact, one quality check that many auctioneers run in these bids is to compare the gap between the leading bid and the leading incumbent's bid on each lane. A large gap indicates the potential of some common "incumbent" information that should be investigated and potentially shared with the non-incumbents. This can reduce the incidence of the winner's curse that, due to the nonbinding nature of the relationships, can hurt both the carrier and the shipper.

13. In many cases, level of service preferences are communicated to the carriers but not other business constraints, for obvious reasons.

14. Note that although the carrier might submit a bid specifying a rate per mile or weight per hundredweight, this is typically converted to a cost per load for analysis within the WDP.

15. Interestingly, some traffic managers will try to use these constraints to force the model to assign the incumbents to their exact original lanes—in order to avoid any change while still adhering to the letter, if not the spirit, of a corporate directive to conduct an auction.

16. The software tools mentioned in this chapter enable and therefore encourage multiple shipper auctions, where several shippers combine their volume in order to exploit the carriers' economics across more freight to achieve lower costs and therefore lower prices.

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