Procurement of transportation services in spot markets under a double-auction scheme with elastic demand

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Abstract

In the recent years, new electronic procurement technologies have been successfully implemented in freight transportation marketplaces. This new type of trading between freight transportation agents requires new analytical tools to better understand the consequences of different strategies and forms of transportation capacity allocation. I studied two cases. First, a transportation market where an O–D pair is operated round-trip by multiple carriers, providing service to multiple shippers. Second, a multiple O–D pairs’ market, operated by multiple carriers, providing service to multiple shippers. In both cases the shippers’ demand function is elastic to the transportation service prices. The shippers contract each shipment to a single carrier following an open auction, in which the shipper selects the carrier based on the best bidding price. Carriers contracted to serve the shipments will often make empty movements to reposition their equipment. Hence, they will attempt to “generate” demand for these empty trips, in order to obtain revenue for their spare capacity. Carriers may generate demand for this capacity by offering service substantially below the market price (as low as the marginal cost of shipping). Shippers on the other hand, decide when to buy transportation services (and how much), i.e., the frequency of shipment and lot size, based on a strategy to minimize the total inventory and transportation costs. A significant reduction in the transportation tariff triggers an adjustment in the replenishment pattern of shippers, as a response to the beneficial market conditions. The new generated demand transforms shippers into bidders for the available spare capacity at discounted prices. This double-auction scheme allocates shipments to the otherwise unused capacity thus reducing the network’s empty movements, which also reduces the average transportation cost in the network. In this paper, I show that under an EOQ policy an average discount spot price of two thirds of the market price will trigger a demand generation for transportation services in the shippers’ pool. The paper presents a numerical application of the derived model, in which the double-auction scheme reduces the network average transportation tariff by at least 14%.

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1. Introduction

During the last decade there has been an increasing interest in incorporating information technology to commercial transactions in different industries. Perhaps the most prominent example – and one of the pioneers, is eBay.com where thousands of transactions take place every day between roughly 19 million sellers and auctioneers spread all over the globe. In the recent years, these technologies have also been implemented successfully in freight transportation marketplaces. Examples of this model of web-based transactions can be found in www.besttransport.com, www.leanlogistics.com, www.nte.com or its sister company http://www.audacious1.com. This new type of trading between freight transportation agents requires new analytical tools to better understand the consequences of different agent’s behavior and forms of transportation capacity allocation. Unfortunately, no game theoretical model known so far is able to make a realistic representation of the truck-load procurement market (Figliozzi, 2004) Chapter 2. An increasing number of studies of auctions for transportation procurement are now available in the transportation literature (Song and Regan, 2001; Chen, 2003; Figliozzi et al., 2004; Song and Regan, 2005) demonstrating the enormous potential that web-based auctions have in the efficiency of transportation markets.

Freight transportation services can be procured both on the spot market or through longer term contracts, i.e., either the service of a carrier is bought for a shipment at a price instantaneously given by the market at the time of the transaction, or alternatively through a procurement agreement set for a specified time period with fixed prices and conditions. Most freight transportation services are procured in the longer term manner. However, there are many shortcomings of procuring freight transportation services through long term agreements, such as low flexibility for sudden fuel price changes, entrance of new carriers or technology, etc., thus reducing the efficiency of the freight transportation industry. On one hand, under perfect competition conditions, the spot markets may eliminate (or at least alleviate) these shortcomings, and on the other hand the spot market prices fluctuate more (see, for example, Adland and Cullinane, 2006). The conditions on which each one of these modes of procurement outperform the other one has been thoroughly studied and debated in the industrial organization and microeconomics literature (see, for example, Doane and Spulber, 1994; Seifert et al., 2004).

In the trucking industry, if the transportation capacity hired under long term contracts is insufficient, the shipper is forced to contract additional capacity on the spot market, where the prevailing price is typically higher and uncertain. Nevertheless, the existence of vehicles’ relocation (empty movements) opens up a window of opportunities to increase the transportation market efficiency through the procurement of services in spot markets.

Empty movements are an integral part of the trucking business due to the inherent stochasticity in the spatial and temporal pattern of freight demand. In large cities, the share of empty movements may account for almost a third of the total truck trips (Holguin-Veras et al., 2004) which is a signal for a potential cost reduction.

The advent of electronic marketplaces, and real-time information availability in the freight transportation industry, provide a unique opportunity to transform those empty movements into a positive revenue for the carriers and a gain in efficiency for the shippers. Indeed, the capacity slack could be sold if the carrier would know (at the right time) the availability of unfulfilled demand in the area where his empty vehicles are located. Internet auctions may provide such an opportunity for shippers and carriers by offering a platform where both actors could interact (in real time) sharing their needs for spot freight transportation and freight capacity. For example, if a carrier needs to move a vehicle from point A to point B at a given time, and he would know that there is a shipment to be moved between those locations, he could offer that capacity to the shipper at a price lower than the market price. If this interaction takes place on an electronic marketplace, other carriers could also make offers to move the shipment thus generating competition. The winning carrier would be the one who offers the lowest price. This price has an upper bound in the standard market price and a lower bound in the marginal cost of making a loaded trip instead of an empty trip (because that trip from A to B will be done anyways).

The main contribution of this paper is the finding that the availability of real-time information for shippers and carriers may increase the efficiency of the freight transportation industry through the auction of capacity slack in spot markets.
I studied two cases: a transportation market where an O–D pair is operated round-trip by multiple carriers, providing service to multiple shippers, and a multiple O–D pairs market operated by multiple carriers, providing service to multiple shippers. In both cases the shippers’ demand function is elastic to the transportation service prices. Each carrier has a single depot located at either the origin or destination of any shipment. The shippers assign each shipment to a single carrier following an open auction, in which the shipper selects the carrier based only on the minimum bidding price (it is implicitly assumed that all the level-of-service variables have been previously accounted for, and hence the participating bidders provide indistinguishable service).

As explained below, both shippers and carriers are assumed to play both roles as bidders and auctioneers. This double condition of bidder–auctioneer gives the name to this type of trade as double-auctions.

2. Shippers as auctioneers

Each time a shipment is tendered, the carriers base their bidding price both on the direct cost of serving that particular shipment and the expected cost of the empty movement associated with that shipment. The latter cost is a function of the direct cost of repositioning the vehicle in a desired location and the probability of winning a future contract for that movement.

I also assume that the probability that a carrier wins a bid is a function of the frequency of shipments open for auction on that pair (the higher the frequency of requested service, the higher the probability of winning a shipment) and carrier-specific characteristics (e.g., risk-averseness, knowledge of the tendered lane, visibility in the market, among others). The frequency of requested service, on the other hand, is a function of the market’s transportation price for that O–D pair. Typically, the lower the transportation price, the higher the frequency of requested service. The latter is a direct consequence of the shippers’ logistics decisions. In fact, the replenishment cycles are highly dependent on the transportation costs (along with inventory holding and financial costs). Therefore, there is a trade-off between the price that a carrier offers and the probability of getting future shipments.

Furthermore, I assume that shippers operate with an EOQ policy (i.e., they compute the optimal frequency of shipments such that it minimizes their total inventory and transportation costs under deterministic/known consumers demand and constant lead time) which makes their frequency of shipment elastic to the transportation service price (dependent on the square root of the price). The justification of the EOQ assumption on the shippers’ behavior is twofold. First, to obtain mathematical tractability due to the presence of non-linearities in the model, and second, because even if the EOQ assumptions do not hold, profits are close to optimal due to the robustness of the EOQ results (hence it is a robust assumption on the shippers part).

The market frequency of requested service corresponds to the aggregation of the frequencies for all the participating shippers. The market prices for transportation services – both in the original and repositioning trips, are the result of the auction for all the participating carriers.

3. Carriers as auctioneers

Assume that a carrier has already participated in a series of auctions, as a bidder, and he may have won some lanes to be served along with other lanes previously contracted. At this point there is no demand for his services in the market (as all the available shipments have already been assigned either to him or other carriers). His task is now to deliver those shipments at minimum cost. Almost inevitably, some arcs in the vehicles cycles will be empty or some vehicles will depart with capacity slack and hence no revenue is expected for those operations (those trips have to be done anyways). However, the carrier could attempt to “generate” demand for his capacity slack by offering service substantially below the market price. In fact, he could offer service at the marginal cost of shipping (those extra costs that would be incurred in only if a shipment is served). The shipper on the other hand, decides when to buy transportation services (and how much) depending on her EOQ policy, i.e., the frequency of shipment and the lot size are those that minimize her total inventory and transportation costs. Therefore, a significant reduction in the value of the transportation services price may trigger an adjustment in the replenishment pattern of a shipper, as a response to the beneficial market conditions. Indeed, if the transportation price reduction offsets the extra inventory cost that an early order
would generate, there is an incentive for the shipper to order a shipment ahead of schedule and hence to com-
pete against other shippers for the offered lane at discount price.

4. The double-auction environment

4.1. Shippers’ behavior as auctioneers

Assume that a transportation market is operated by multiple carriers serving multiple shippers. Each ship-
per has elastic demand for the transportation services. The shippers assign each one of their shipments to a
single carrier following an open auction, in which the shipper accepts the best offer based only on the bidding
price (it is implicitly assumed that all the level-of-service variables have been accounted for before the auction,
and hence the participating bidders are those with acceptable level-of-service).

Each time a shipment is tendered, the carriers will base their bidding price both on the marginal cost of
serving that shipment and the expected cost of the empty movement associated with that shipment. The latter
cost is the result of combining the direct cost of repositioning the vehicle in a desired location weighted by the
probability of not finding any shipment for that movement.

4.2. A single origin destination pair

Initially, consider a case where the market consists of a single O–D pair with multiple shippers and carriers.
Following the same logic as (Song and Regan, 2003) for atomic bids, I assume that the cost of serving a ship-
ment by a carrier \( k \) is a function of the direct cost of serving a shipment and the cost of vehicle reposition.
Consequently, for an observer of the auction process, each realization of a bid appears as a stochastic process
that can be described as follows:

\[
b_k = C_k (1 + \rho_k) + C_k \times (1 - P_k^e) + \xi_k, \quad k \in K
\]

where \( b_k \) is the bidding price on the O–D pair for carrier \( k \), \( K \) is the set of carriers, \( C_k \) is the direct cost of
serving the pair, \( \rho_k \) is the desired revenue margin, \( C_k \) is the empty cost associated to repositioning the vehicle,
and \( P_k^e \) is the probability of winning a bid for the repositioning trip, after the shipment has been served. \( \xi_k \) is a
stochastic term that explains unexpected adjustments in the revenue margin. Note that the expected value of
expression (1) is the cost function in (Song and Regan, 2003).

The revenue margin for the carrier \( k \) is not a fixed constant but rather a parameter that he may adjust to the
prevailing conditions. It can be used for strategic purposes. In fact, when a movement has to be done with an
empty vehicle (repositioning) any positive revenue (above the marginal cost) constitutes a gain for the carrier
and hence he may offer service on that particular O–D pair at a price substantially lower than that of a new
movement (which has an alternative use). On the other hand, a service request that arrives during a busy per-
iod is usually charged with a higher price.

Assume now that the probability of winning a bid depends on the size of the market, as well as each car-
rier’s market position, i.e., it is a function of the frequency of shipments in that pair (the higher the frequency
of requested service, the higher the probability of winning a shipment) and a carrier’s specific parameter that
measures the historic ability of that carrier to win bids. Note that the probability of winning bids is not
expressed in terms of the value of the submitted bid but rather in a longer term ability to be the winner, which
is ultimately a function of the success of his past bidding strategies. Note also that this probability is an a pri-
or value that the bidder needs to assess before embarking in his bid; hence, it cannot be expressed in terms of
the participating bids.

This assumption of dependency between the freight flow in an arc and its probability to generate demand
can be implemented through a smooth function such as the logistic operator. Therefore, the probability that
carrier \( k \) wins a bid for a shipment can be expressed as follows:

\[
p_k = \frac{e^{b_k}}{\sum_{j \in K} e^{b_j}} = \frac{1}{\sum_{j \in K} e^{(a_j - a_k)x_f}}, \quad k \in K
\]
where $f$ is the market frequency of shipments (service requests from all the shippers combined) and $a_k$ is a carrier-specific parameter, reflecting its own ability to win bids in this O–D pair. The frequency of shipments, on the other hand, is a function of the market’s transportation price for the shipment in that pair. Typically, the lower the transportation price, the higher the frequency of shipments to reduce inventory costs. Therefore, there is a trade-off between the price that a carrier offers and the probability of getting future shipments.

Shippers are assumed to operate with an EOQ policy, i.e., they choose the optimal frequency of shipments such that it minimizes their total inventory and transportation costs. The EOQ’s shipment cycle (inverse of the frequency) for a shipper $s$, is given by:

$$T_s = \frac{1}{f_s} = \frac{Q_s}{d_s} = \frac{1}{d_s} \times \sqrt{\frac{2 \times t_s \times d_s}{h_s}}, \quad s \in S$$

where $Q_s$ is the optimal lot size, $d_s$ is the final (consumers) demand faced by the shipper $s$ at the destination, $t^*$ is the market (or winner’s) transportation price, $h_s$ is the inventory holding cost for the shipper $s$, and $S$ is the set of shippers.

The market frequency $f$ corresponds to the summation of the frequencies for all the participating shippers:

$$f = \sum_{s \in S} f_s = \sum_{s \in S} \sqrt{\frac{h_s \times d_s}{2r}}$$

Substituting (4) into (2) the following expression is obtained:

$$p_k = \frac{1}{\sum_{j \in K} e^{(y_j - z_k) - \ln(\sum_{s \in S} \sqrt{\frac{h_s \times d_s}{2r}})}}$$

Substituting (5) (its equivalent to the repositioning trip) into (1), the bidding price for the carrier $k$ is expressed as follows:

$$b^k = C^k (1 + \rho_k) + \frac{C_k}{\sum_{j \in K} e^{(y_j - z_k) - \ln(\sum_{s \in S} \sqrt{\frac{h_s \times d_s}{2r}})}} + \xi^k, \quad k \in K$$

where the suffix $-$ indicates the repositioning trip. The market price for transportation services in the repositioning trip is derived from the outcome of the auction for all the participating carriers:

$$t^*_k = \min_{k \in K} \{b^k\}$$

Note that expression (7) needs the evaluation of expression (6) for both the forward and repositioning trips ($b^k$ and $b^k_-$). The value of $t^*_k$ also depends on the assumption about the probability distribution of the stochastic term $\xi^k$. Though the latter distribution is not possible to be established a priori, it is clear that any observed bid is the outcome of an extreme event. Indeed, the values of revenue margin (and ultimately the bid itself) are the highest price that each bidder can charge without sacrificing its own chances to win, or alternatively, the lowest price to charge without incurring a loss. In either case, they are extrema. Accordingly, a safe assumption is to consider the $\xi$’s to be Gumbel distributed (Gumbel, 1958). Under this assumption (considering that the minimum of Gumbel distributed variables is also Gumbel distributed) the expected value of the transportation market price is the following:

$$t^*_k = -\frac{1}{\phi} \ln \sum_{k \in K} \exp (-b^k_- \times \phi)$$

where $\phi$ is the scale parameter of the Gumbel distribution of $\xi$.

Expressions (6) and (8) evidence the codependence of the bidding prices for the O–D pair and its repositioning trip (D–O) and the bids of all the competitors. Note that analogue expressions hold for the bidding price on the reverse pair (D–O), which will depend on the result of the auction for O–D. The recursive nature of expressions (6)–(8), and their analogue counterpart for the repositioning trip, preclude the analytical
solution of the bidding price determination problem. The equilibrium prices for the O–D pair can be found iteratively.

5. Multiple origin destination pairs

In this general case, shippers and carriers interact in a transportation network $G(N,A)$, where $N$ is the set of nodes and $A$ is the set of directed arcs. $G(N,A)$ offers multiple possibilities for shipment’s origins and destinations. Demand in each O–D pair is elastic to the transportation price on that particular pair. There is no possibility of spatial changes due to price differences (i.e., the choice of origin and destination of a shipment does not depend directly on the transportation spot prices but rather on longer term decisions) but only the quantity to be transported is affected by that price (volume and frequency). Therefore, the only network effects to be considered are those of economies of scope in the provision of transportation services, i.e., the higher the number of O–D pairs served by a carrier, the lower the vehicles’ repositioning costs and hence the possibility of offering lower bids for auctioned shipments.

All the auctions are assumed to be sequential, i.e., the shippers offer service for specific O–D pairs independently of other shipments being auctioned elsewhere (simultaneously). Note that the cost of selling the capacity slack is independent of the amount of capacity available to be sold. Thus, for example, if a carrier has one empty truck from A to B and another one from C to D that he could sell at discount price, the associated cost of the bundle is the summation of the costs of each lane and no benefit is obtained in selling them as a bundle. Instead, selling them as a bundle decreases the probability of finding a shipper interested in buying them together. This condition excludes the case of combinatorial auctions, which is outside the scope of this paper.

Under these assumptions, the cost of serving a shipment is formed by two parts: the direct cost of shipping through the pair $i \rightarrow j$ (i.e., the shortest path between both nodes) plus the cost of repositioning the empty vehicle in a different location if no shipment is expected to be picked up at the destination $j$. Consequently the corresponding bid for a shipment between the pair $(i,j)$ by the carrier $k$ is the following:

$$b_{ij}^k = C_{ij}^k (1 + \rho_k) + C_{j+}^k \times (1 - P_{j+}^k) + \nu_{ij}, \quad i,j \in N; \quad k \in K$$

(9)

where $C_{j+}^k$ represents the cost of the empty movement from the destination $j$ to an unknown location (i.e., the origin of a new shipment) and $P_{j+}^k$ is the probability of picking up a shipment at the destination $j$ by the carrier $k$.

Given the assumption that the probability of winning a shipment in a certain O–D pair is proportional to the size of the market in that pair, it follows directly that the probability of winning a shipment departing from a given node, is proportional to the total flow that shares that node as its origin. Therefore, this probability can be expressed as follows:

$$P_{j+}^k = \frac{1}{\sum_{\forall l \in K} e^{(x_l-z_k)} f_{j+}}$$

(10)

where $f_{j+}$ is the summation of flows that share the same origin $j$:

$$f_{j+} = \sum_{\forall u \in N} f_{ju}$$

(11)

Substituting (4) for shipper $s$ in (11) and then (11) in (10) the following probability formula is obtained:

$$P_{j+}^k = \frac{1}{\sum_{\forall l \in K} e^{(x_l-x_k) \times \sum_{\forall u \in N, x \in S} \frac{k_{u,x} \cdot f_u}{x_j - x_u}}}$$

(12)

In the event that no new shipment is originated at the destination $j$ of a served shipment, the corresponding vehicle will be moved empty to a new (yet unknown) location. As the new location is unknown, the empty cost $C_{j+}^k$ cannot be computed with certainty. However, given the probabilities of winning shipments originated at any node $u$, the expected cost of the empty movement can be estimated as follows:
\[ C_{j+} = \sum_{x \in N} C_{jx} \times P_{x+} = \sum_{x \in N} \frac{C_{jx}}{\sum_{y \in K} (y \in x) \times \sum_{l \in K \cap S \setminus j \in N; k \in K} \sqrt{\frac{b_y \times C_0^x}{2 \times t_{ij}}}}, \quad j \in N; \quad k \in K \tag{13} \]

Substituting (13) and (12) in (9) the following bidding price is obtained:

\[ b_{ij} = C_{ij}(1 + \rho_k) + \sum_{x \in N} \frac{C_{jx}}{\sum_{y \in K \cap S \setminus j \in N; k \in K} \sqrt{\frac{b_y \times C_0^x}{2 \times t_{ij}}} \times \left( \sum_{t \in K} C_{t} \times \sum_{l \in K \cap S \setminus j \in N; k \in K} \sqrt{\frac{b_y \times C_0^x}{2 \times t_{ij}}} \right) + r_{ij} \tag{14} \]

Note that the optimal strategy (either expression (6) or (14)) requires that all the players have perfect information. This assumption is usually unrealistic. Therefore, the second best to perfect information is the use of modeling to estimate parameters that define the transportation demand functions and other carrier’s specific parameters. The uncertainty on these parameters is reflected in the stochastic components \( \xi_{ij} \).

### 6. Carriers’ behavior as auctioneers

Assume a risk-neutral carrier that already participated in a series of auctions, as a bidder, and he has won some lanes to be served along with other lanes previously contracted. At this point, there is no demand for his services in the market (as all the available shipments have already been assigned either to him or other carriers). His task is now to deliver those shipments at minimum cost. Almost inevitably, some arcs in the vehicles cycles will be empty or with capacity slack and hence no reward is expected for those operations (to be done anyways). However, the carrier could attempt to “generate” demand for his unused capacity by offering a price substantially below the market price. In fact, he could offer service at the marginal cost of shipping (those extra costs that would be incurred in if and only if a shipment is served). An efficient allocation of that capacity would be to sell it through ascending auctions (Fan, 2004). The shipper on the other hand, decides when to buy transportation services (and how much) depending on her EOQ policy, i.e., the frequency of shipment and the lot size are those that minimize the total inventory and transportation costs according to the expression (3). Therefore, a significant reduction in the value of the transportation services price \( t^* \) may trigger an adjustment in the replenishment pattern of a shipper, as a response to the beneficial market conditions. Note however, that a sudden reduction in a spot transportation price will not be taken as the expected future price to be paid by the shipper. As a spot price, it is not guaranteed to remain fixed for the next cycle (and probably will not be), hence a rational risk-neutral carrier would still consider the original transportation price (the one with which he estimated the lot size) as the most likely cost of the next order and consequently, the optimal strategy would be to continue (in the long run) with the same lot size and frequency computed in the absence of the discounted transportation spot price.

If the transportation price reduction offsets the extra inventory cost that an early order would generate, there is an incentive to order a shipment ahead of schedule. This condition is expressed as follows:

\[ t^*_w - \tilde{t}_w \geq C(\Delta \text{Inv}) \tag{15} \]

where \( t^*_w \) is the transportation market price, \( \tilde{t}_w \) is the discount transportation price and \( C(\Delta \text{Inv}) \) is the cost of the extra inventory induced by the early order (as compared to the optimal EOQ strategy). There are two main alternative ways that a rational risk-neutral shipper may follow:

**Case 1:**
To place an early order that allows shifting the EOQ saw-teeth curve leftward as shown in Fig. 1. This early order would act as an order-up-to policy, in which the target level is the original lot Q.

**Case 2:**
To place an early order in which the lot size is optimized for a one-time discount price. This case is shown in Fig. 2.

For the Case 1, the effect of an early order (say at \( t \) units of time after the beginning of a cycle) is that the inventory is increased compared to the initial conditions. The shift in the ordering pattern produces an
increase in the available inventory to satisfy the same final demand (the only change in the market is a spot discount price for transportation). Hence, after the adjustment, the EOQ policy continues to operate cyclically with the same optimal strategy. The initial average inventory for one cycle is \( Q/2 \) (the average height from 0 to \( T \) in Fig. 1). When the discount price becomes available, the next order is placed before its scheduled time \( (T - t) \) units ahead of time. Therefore, from the time \( t \) up to the time \( (T - t) \) there is an extra inventory for that cycle, and from then on the saw-teeth shape graph is resumed. The average extra inventory level equals \( dt \) and its cost, as a function of the time \( t \), is the following:

\[
C(\Delta \text{Inv}(t)) = d \times t \times (T - t) \times h
\]  

where \( d \) is the final demand rate and \( h \) is the inventory holding cost per unit of time.

The spot discount price can become available at any given time and without further information about it, it is safe to assume that it is uniformly distributed during the cycle of length \( T \). Therefore, the expected value of expression (16) can be computed as follows:

\[
C(\Delta \text{Inv}) = \int_0^T C(\Delta \text{Inv}(t)) \times \frac{1}{T} dt = \int_0^T d \times t \times (T - t) \times h \times \frac{1}{T} dt = \frac{d \times h \times T^2}{6}
\]

Substituting (17) into (15), we obtain the following condition for the demand generation:

\[
\tilde{t}_w - \tilde{t}_w \geq \frac{d \times h \times T^2}{6}
\]

Since the EOQ policy is resumed after the early order, the value of \( T \) is still the optimal cycle in expression (3). Replacing \( T \) by its optimal EOQ value, the condition for the demand generation is simplified to the following expression:

\[
\tilde{t}_w \leq \frac{2}{3} \tilde{t}_w
\]

Condition (12) implies that a spot transportation price will be effective in generating demand only if it offers at least a 33.3% discount compared to the market value.

For the Case 2, the shipper must determine the lot size to be ordered with the available discount transportation price. In this case, the average extra inventory level equals \( q \) and its cost, as a function of the time \( t \), is the following:

\[
C(\Delta \text{Inv}(t)) = q \times (T - t) \times h
\]
Following the same logic as in expression (17), the expected value of this cost is:

\[
C(\Delta \text{Inv}) = \int_0^T C(\Delta \text{Inv}(t)) \times \frac{1}{T} dt = \int_0^T q \times (T - t) \times h \times \frac{1}{T} dt = \frac{q \times h \times T}{2}
\]

(20)

The maximum value that \( q \) can take is given by the point where the cost of extra inventory equals the transportation cost reduction (boundary of expression 1.15), therefore:

\[
\frac{q \times h \times T}{2} = t_w^* - \bar{t}_w \Rightarrow q = \frac{t_w^* - \bar{t}_w}{T \times h}
\]

(21)

But \( T = \frac{Q}{a} \) and \( Q \) is the EOQ, therefore, the value of \( q \) in expression 21 can be rewritten as follows:

\[
q = 2 \times \frac{(t_w^* - \bar{t}_w) \times d}{\sqrt{\frac{2 \times t^* \times d}{h}}} \times \left( 1 - \frac{\bar{t}_w}{t_w^*} \right) = Q \times \left( 1 - \frac{\bar{t}_w}{t_w^*} \right)
\]

(22)

Therefore, the generated order size is a proportion of the EOQ lot size, which decreases linearly with the proportion of transportation price discount.

Note that there are no benefits in offering capacity slack in bundles. As the slack is randomly generated in different lanes at different times, offering bundles of capacity slack would greatly reduce the probability of finding an interested shipper. For example, if a carrier tries to auction a bundle of unused capacity from A to B and another one from C to D in a given time period, the likelihood of finding (in the short run) an interested shipper is much smaller than that of finding interested bidders for any single movement. In addition, the private valuation of each leg to the carrier is their marginal cost (because the movements will be done anyways), hence the valuation of both legs equals the summation of the single valuations and consequently there is no economy of scope. While combinatorial auctions may significantly improve the efficiency of carriers, due to the exploitation of the economies of scope (see (Ledyard et al., 2002 and Song and Regan, 2003)), the absence of such economies when offering discount spot transportation tariffs removes all the incentives to offer and buy a combination of services. Under these circumstances, the carrier’s private valuation of any auctioned service equals its marginal cost of service regardless of the number of lanes or their spatial location in the network. Therefore, the rational bid for a risk-neutral carrier is to post each potential capacity slack as an atomic bid.

7. Numerical example

A simulation experiment is designed to exemplify the benefits of this shipper–carrier behavior in the procurement of transportation services under this type of double-auctions. The simulation consists of a single O–D network for which a series of shipments (to be transported from O to D and vice-versa) is auctioned. There are three carriers competing for each shipment. Each shipment is auctioned sequentially. The vehicles’ depots are not located in either O or D but outside the served pair. Each time a shipment is auctioned, the three carriers make their bids according to the expressions 6 and 7 and the counterpart for the reverse trip. The standard deviation of the stochastic term \( \xi^k \) in expression 6 is varied from 1 to 10. Each shipment is assigned to the highest bidder. If a carrier wins both trips (from O to D and vice-versa) and he is currently located on node O, he receives the winning price for each leg. Nevertheless, if a carrier wins a shipment originated on a node different from the one he is located at that time, he offers a discount price (following expression 15) for the relocation trip (based on the fact that he has to relocate the vehicle anyways, with or without a payload). The average transportation rate at network level is computed as the average tariff in both directions considering both the standard auction results and the discount rate (which equals the marginal transportation cost).

Table 1 shows the parameters used for this example, Table 2 shows the carriers’ parameters, and Tables 3 and 4 show the results of the simulated example.

Table 3 shows that the effect of an increase in the variability of the stochastic component of \( \xi^k \) in expression 6 has a significant impact on the market share for the three competitors. In fact, when the standard deviation \( \sigma \) is small, the market share is mainly explained by the carrier-specific parameter \( z_k \) from expression 2, that reflects the carrier’s ability to win bids in the pair (historical efficiency), but when the variability increases,
Table 1
Network parameters for the single O–D example

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auctioned shipments</td>
<td>1000</td>
</tr>
<tr>
<td>Carriers</td>
<td>3</td>
</tr>
<tr>
<td>O–D Transportation cost</td>
<td>$100</td>
</tr>
<tr>
<td>D–O Transportation cost</td>
<td>$100</td>
</tr>
<tr>
<td>Marginal transportation cost</td>
<td>33% Transportation cost</td>
</tr>
</tbody>
</table>

Table 2
Carriers parameters for the single O–D example

<table>
<thead>
<tr>
<th>Carrier</th>
<th>( \rho_k ) from expression (1)(%):</th>
<th>( z_k ) from expression(2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>15</td>
<td>0.10</td>
</tr>
<tr>
<td>2</td>
<td>15</td>
<td>0.15</td>
</tr>
<tr>
<td>3</td>
<td>15</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 3
Variation of market shares with the standard deviation of the stochastic component of the bids

\[ \sigma \]

<table>
<thead>
<tr>
<th>( \sigma )</th>
<th>Market share O–D</th>
<th>Market share D–O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Carrier 1</td>
<td>Carrier 2</td>
</tr>
<tr>
<td>1.00</td>
<td>14.60% (0.353)</td>
<td>30.90% (0.462)</td>
</tr>
<tr>
<td>1.25</td>
<td>17.30% (0.378)</td>
<td>32.00% (0.467)</td>
</tr>
<tr>
<td>1.50</td>
<td>19.30% (0.395)</td>
<td>32.40% (0.468)</td>
</tr>
<tr>
<td>1.75</td>
<td>20.40% (0.403)</td>
<td>31.60% (0.465)</td>
</tr>
<tr>
<td>2.00</td>
<td>21.90% (0.414)</td>
<td>30.60% (0.461)</td>
</tr>
<tr>
<td>3.00</td>
<td>24.80% (0.432)</td>
<td>35.30% (0.478)</td>
</tr>
<tr>
<td>4.00</td>
<td>28.00% (0.449)</td>
<td>33.40% (0.472)</td>
</tr>
<tr>
<td>5.00</td>
<td>30.50% (0.461)</td>
<td>31.70% (0.466)</td>
</tr>
<tr>
<td>6.00</td>
<td>30.00% (0.458)</td>
<td>32.60% (0.469)</td>
</tr>
<tr>
<td>7.00</td>
<td>31.10% (0.463)</td>
<td>30.40% (0.460)</td>
</tr>
<tr>
<td>8.00</td>
<td>32.00% (0.467)</td>
<td>32.80% (0.470)</td>
</tr>
<tr>
<td>9.00</td>
<td>30.20% (0.459)</td>
<td>35.10% (0.478)</td>
</tr>
<tr>
<td>10.00</td>
<td>31.00% (0.463)</td>
<td>32.60% (0.469)</td>
</tr>
</tbody>
</table>

(): Standard deviation

Table 4
Average transportation price savings

\[ \sigma \]

<table>
<thead>
<tr>
<th>( \sigma )</th>
<th>Average transportation price</th>
<th>Average transportation price savings (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>124.81 (24.37)</td>
<td>15.17</td>
</tr>
<tr>
<td>1.25</td>
<td>120.80 (24.40)</td>
<td>17.80</td>
</tr>
<tr>
<td>1.50</td>
<td>118.90 (24.17)</td>
<td>19.00</td>
</tr>
<tr>
<td>1.75</td>
<td>118.01 (24.06)</td>
<td>19.50</td>
</tr>
<tr>
<td>2.00</td>
<td>116.70 (23.78)</td>
<td>20.30</td>
</tr>
<tr>
<td>3.00</td>
<td>114.97 (23.37)</td>
<td>21.10</td>
</tr>
<tr>
<td>4.00</td>
<td>113.65 (23.06)</td>
<td>21.53</td>
</tr>
<tr>
<td>5.00</td>
<td>112.97 (22.97)</td>
<td>21.63</td>
</tr>
<tr>
<td>6.00</td>
<td>111.99 (22.91)</td>
<td>21.70</td>
</tr>
<tr>
<td>7.00</td>
<td>111.02 (22.51)</td>
<td>22.07</td>
</tr>
<tr>
<td>8.00</td>
<td>109.97 (22.33)</td>
<td>22.27</td>
</tr>
<tr>
<td>9.00</td>
<td>109.77 (22.65)</td>
<td>22.00</td>
</tr>
<tr>
<td>10.00</td>
<td>108.27 (22.40)</td>
<td>22.60</td>
</tr>
</tbody>
</table>

(): Standard deviation
the market shares tend to level out as the probability of being the winner depends more heavily on non-systematic aspects. The ability to win trips in the O-D pair is positively correlated with the ability to win the reverse trip.

Table 4 shows the average savings in the transportation price as a result of the double-auctions scheme. When the stochasticity of the bids is moderate ($\sigma = 1$) the double-auction yields a 15.17% reduction compared to a standard base case. The average savings increase as the variability of the stochastic component increases (though at a decreasing rate). This phenomenon is explained by the fact that a greater variability allows the bids to reach lower values and hence the minima will be lower than the case of small a variability with respect to the systematic portion in expression 6.

8. Conclusions

In this paper, I have studied the procurement of freight transportation services, within an electronic auction system, based on the fact that empty movements may be used jointly with real-time information about shippers’ necessities, to exploit spot market opportunities. The spot market prices can be substantially lower than average market prices because they respond instantaneous transportation capacity slack and the need for immediate service on the shipper’s part. In fact, carriers can lower their service rates down to the marginal cost of service for trips that have to be performed whether or not they carry a load. Thus, a significant decrease in the transportation cost for the shippers can generate demand for transportation service, in the sense that the frequency of shipments can be increased by the shipper to take advantage of the availability of (potentially unused) carriers resources at the place and time she needs them. On the carrier’s part, if he manages to sell the capacity slack he would gain positive revenue for any price greater than the marginal cost of moving his vehicle loaded instead of empty between origin and destination.

To materialize the spatial–temporal match between carriers’ supply and shippers’ demand, a double-auction system was proposed, where both the carriers and shippers act as auctioneers and bidders. This scheme needs real-time information about the transportation capacity slack in time and space as well as the necessity to move shipments between origins and destinations at any given time. An open electronic auction system can provide such an environment where both carriers and shippers can interact to trade their services.

I analyzed two cases: a transportation market where an O-D pair is operated round-trip by multiple carriers, providing service to multiple shippers, and a multiple O-D pairs market operated by multiple carriers, providing service to multiple shippers. In both cases the shippers’ demand function is elastic to the transportation service prices. Each carrier has a single depot located at either the origin or destination of any shipment. The shippers assign each shipment to a single carrier following an open auction, in which the shipper selects the carrier based on the minimum bidding price.

The double-auctions system assumed that the bids depend on a systematic component (direct costs and expected costs) plus a stochastic component that takes into consideration non-systematic aspects such as bidder’s strategies, revenue margin and other unobservable effects.

Two types of shippers’ behavior were analyzed. In the simplest case, a sudden transportation price reduction triggers an early order by the shipper, assuming everything else equal, i.e., the lot size does not change due to the price drop, but only the time at which the order is placed. The other case, assumes that a sudden transportation price reduction triggers both an early order plus an adjustment in the value of the lot size. The new lot size is smaller than the original one, in the same proportion of transportation price reduction.

A numerical example showed that the effect of an increase in the variability of the stochastic component of a bid has a significant impact on the carriers’ market share. In fact, when the standard deviation of the stochastic component is small, the market share is mainly explained by the carrier-specific parameter that reflects the carrier’s ability to win bids in a given O-D pair (historical efficiency), but when the variability increases, the market shares tend to level out as the probability of being the winner depends more heavily on non-systematic aspects. The numerical example also showed that the average savings in the transportation price varies significantly with the stochasticity of the bids. Indeed, when the standard deviation of the bids is moderate ($\sigma = 1$) the double-auction yields a 15.17% reduction compared to a standard base case. The average savings increase at a decreasing rate as the variability of the stochastic component increases.
The results of this experiment do not demonstrate any general consequence of the double-auction system, but give an indication that significant efficiency may be obtained through its use. Being the first study of this phenomenon, it opens new opportunities to analyze the impact of integrating real-time information to electronic marketplaces in search for more efficient freight transportation industry.

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References