Quantifying Opportunity Costs in Sequential Transportation Auctions for Truckload Acquisition

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ABSTRACT

The principal focus of this research is to quantify opportunity costs in sequential transportation auctions. This paper focuses on the study a transportation marketplace with time-sensitive truckload pickup-and-delivery requests. In this paper, two carriers compete for service requests; each arriving service request triggers an auction where carriers compete with each other to win the right of servicing the load. An expression to evaluate opportunity costs is derived. This paper shows that the impact of evaluating opportunity costs is dependent on the competitive market setting. A simulation framework is used to evaluate different strategies. Some results and the overall simulation framework are also discussed.

KEYWORDS: Freight Transportation, Carrier Management Strategies, Carrier Profitability, Information Technology, Bidding Strategies, Electronic Commerce, Auctions.

1. INTRODUCTION

The principal focus of this research is to quantify opportunity costs in sequential transportation auctions. The focus is on a marketplace with time-sensitive truckload pickup-and-delivery requests; for the sake of brevity we will refer to this marketplace as the "Truck-Load Procurement Market" or TLPM. In this paper, two carriers compete for service requests; each arriving service request triggers an auction where carriers compete with each other to win the right of servicing the load.

The motivation for this work arises from the growth of business-to-business electronic commerce and by the increasing use of private exchanges, where a company or group of companies invites selected suppliers to interact in a real time marketplace, compete, and provide the required services. High levels of competition characterize this private online marketplaces [1].

In the transport/logistics sector, a large number of online marketplaces have emerged to cater to the needs of shippers and carries. A current review of freight transportation marketplaces business models and market clearing mechanism is presented by Nandiraju and Regan [2]. This research focuses on the sequential auction model which is essentially dynamic. Carriers participating in a TLPM face complex interrelated decision problems. One of them is the dynamic estimation of service costs. As shown in this research, opportunity costs are necessary to accurately estimate future consequences of current decisions (bids or prices submitted). The carrier that accounts for opportunity costs can significantly improve profitability.

The paper is organized as follows: the next section presents a literature review. Section two describes the marketplace framework, operation, and notation. An expression to evaluate opportunity costs is derived and analyzed in section three. Section four presents two methods to estimate costs, one static and one dynamic. The main difference between the methods is whether they include opportunity costs. Section five describes the evaluation settings. Results are analyzed in section six, followed by concluding comments in the final section.

2. LITERATURE REVIEW

The notion of opportunity costs and the magnitude of opportunity cost for specific increments of production or different products have been widely studied in production economics theory. As far back as 1965, Mills indicates that uncertainty about future demand causes uncertainty concerning opportunity cost for specific increments of production or products [3]. Mills further suggests that the expected or ex ante values of direct costs and opportunity costs are more difficult to assess than is commonly supposed by economists due to interdependence between temporal decisions. Steiner suggests a method of analysis to include opportunity costs in the analysis logistics investments decisions [4]. This author indicates that opportunity cost is defined as the sacrifice incurred in choosing one alternative rather than another.

The concept of opportunity costs has been used in a variety of transportation areas. Zhang utilizes opportunity costs to analyze optimal concession of airport operations and facilities [5]. Willies et al. reviews the application of social opportunity costs to evaluate highway projects [6]. Ratcliff [7] uses the concept of container weight opportunity costs to design a container loading algorithms. Polsby proposes the utilization of opportunity costs in airport peak time pricing of arrival and take off slots [8].

The concept of opportunity costs has also been used in auction theory. Smith and Walker utilize different levels of opportunity costs in experimental auction bidding to show that bidders behave consistently with the with the conventional reward/decision model of bidding behavior [9]. Perry and Sakovicks study a sequential auctioning of two contracts [10]. They find that with a fixed number of suppliers the buyer pays a higher expected price than with a sole-source auction because the premium paid to the winner of the secondary contract must also be paid to the winner of the primary contract as an opportunity cost.

To the best of the authors' knowledge there is no work in estimation of opportunity costs in the context of dynamic vehicle routing problems. The closest line of research is the one that deals with sequential auctions for transportation where shipments (contracts) that dynamically arrive to a marketplace. Figliozzi, Mahmassani, and Jaillet present a framework to study transportation marketplaces and explore the complexities of sequential auction bidding [11]; evaluate the competitiveness of different vehicle routing strategies [12] in an auction marketplace; and study the effect of bidding learning mechanisms (reinforcement learning and fictitious play) and auction settings (1st or 2nd price auctions) on the performance of the transportation marketplace [13]. Figliozzi's doctoral thesis [14] suggests a game theoretic equilibrium formulation of the decision problems faced by the carriers (bidders) and recognizing the intractability of that formulation proposes a boundedly rational approach to study carriers' behavior and bidding.

3. PROBLEM DESCRIPTION

The TLPM enables the sale of cargo capacity based mainly on price, yet still satisfies customer level of service requirements. The specific focus of the study is the reverse auction format, where shippers post loads and carriers compete over them (bidding). The auctions operate in real time and transaction volumes and prices reflect the status of demand and supply.

The market is comprised of shippers that independently call for shipment procurement auctions, and carriers, that participate in the procurement auctions (we assume that the probability of two auctions being called at the same time is zero). Auctions are performed one at a time as shipments arrive to the auction market. Shippers generate a stream of shipments, with corresponding attributes, according to predetermined probability distribution functions. Shipment attributes include origin and destination, time windows, and reservation price. Reservation price is the maximum amount that the shipper is willing to pay for the transportation service. It is assumed that an auction announcement, bidding, and resolution take place in real time, thereby precluding the option of bidding on two auctions simultaneously.

In the TLPM there are two carriers competing. A carrier is denoted by $i \in \Im$ where $\Im = \{1, 2\}$ is the set of all carriers. Let the shipment/auction arrival/announcement epochs be $\{t_1, t_2, ..., t_N\}$ such that $t_i < t_{i+1}$. Let $S = \{s_1, s_2, ..., s_N\}$, represent the set of arriving shipments. Let t_j represent the time when shipment s_j arrives and is auctioned. Arrival times and shipments characteristics are not known in advance. The arrival instants $\{t_1, t_2, ..., t_N\}$ follow a Poisson arrival process. Furthermore, arrival times and shipments are assumed to come from a probability space $(\Omega, \mathcal{F}, \mathcal{P})$, with outcomes $\{\omega_1, \omega_2, ..., \omega_N\}$. Any arriving shipment s_j represents a realization at time t_j from the aforementioned probability space, therefore $\omega_j = \{t_j, s_j\}$.

When a shipment s_j arrives, a carrier tenders a price $b_j \in R$. After each shipment offering, the carrier receives feedback y_j regarding the outcome of the offering. The information known at the time of the offering for shipment s_j is $h_j = (h_0, y_1, y_2, ..., y_{j-1})$, where h_0 denotes the information known by the carriers at time t_0 (with $t_0 < t_1$) before bidding for shipment s_1. Similarly, the information known at time t with $t_{j-1} \le t < t_j$ is $h_t = (h_0, y_1, y_2, ..., y_{j-1})$. The amount and quality of feedback information received will depend on the particulars of the market rules. The level of carrier competition is represented by a stationary "price" distribution ξ (which could be correlated to the characteristics of the shipments). The distribution ξ represents the best price offered by the competition and/or the reservation price of the shippers, whichever is least. A central assumption is that the distribution of shipment prices *are not* influenced by the actions (bids or fleet management related) taken by the carrier. If the carrier attains the right to serve shipment s_j then this carrier is paid an amount ξ_j ; a value that is determined using a second price auction mechanism.

The fleet status when shipment s_j arrives is denoted as z_j. There is an state or assignment function such that the status of the carrier when shipment s_j arrives is $\mathrm{z}_\mathrm{j} = a(\mathrm{t}, \mathrm{h}_\mathrm{j}, \mathrm{z}_{\mathrm{j}-1})$ or in general $z_t = a(t, h_t, z_j)$ for any $t_j < t \le t_{j+1}$. The distance or cost incurred to serve the shipments in the system from time t_j up to time t using assignment function a with initial status z_j is denoted by $\mathrm{d}(a, z_j, t)$. Let I_j be the indicator variable for shipment s_j, such that $I_j = 1$ if the carrier secures the offering for shipment s_j and $I_j = 0$ otherwise. The static marginal cost of serving a just arrived shipment s_j is estimated using $c(s_j)$ which is the difference between the costs that the carrier incurs to serve all shipment in his/her system plus s_j and the costs that the carrier incurs to serve all shipment in his/her without s_j.

Quantifying Opportunity Costs

The carrier pricing the last shipment s_N at time t_N is in a situation strategically similar to a one-item second price auction because: a) the carrier's reward depends on the realization of the price distribution for shipment s_N which is ξ_N, b) the reward ξ_N is independent of any action taken by the carrier, and c) the carrier attains the right to serve shipment s_N if $b_N < \xi_N$.

In a one-item second price auction, the value of the item (to a particular bidder) is a weakly dominant strategy. This value (cost in a reverse auction[1]) is the bid that maximizes the bidder's expected profit [15]. Applying this logic but to a reverse auction, the cost of the

[1] In an auction there is a seller and several buyers; in a reverse auction there is a buyer and several sellers. The value that the buyers assign to the item (auction) is replaced by the cost that the sellers assign to the item (reverse auction)

shipment is a weakly dominant strategy. This cost is the price that maximizes the carrier's expected profit. Therefore, the price for s_N that maximizes the carrier's expected profit is $b_N^* = c(s_N)$.

The carrier pricing the shipment s_{N-1} is NOT in a situation strategically similar to the carrier pricing the shipment s_N because the submitted price b_{N-1} has an impact on the future status of the carrier at time t_N and therefore may affect the profit obtained for shipment s_N. Although the carrier's strategy space is the same at times t_{N-1} and t_N the carrier's private information is different at times t_{N-1} and t_N. At time t_N the carrier knows that the bid b_N will not have an impact on future profits (last arriving shipment); at time t_{N-1} the carrier knows that the bid b_{N-1} may have an impact on the cost of serving shipment s_N, the value of b_N, and future profits.

After submitting b_{N-1} there are just two possible outcomes: 1) the rights for shipment s_{N-1} are acquired; or 2) the rights are lost. Defining $\pi_N(s_N \mid I_{N-1})$ as the expected profit from shipment s_N conditional on the previous outcome as:

$$\pi_N(s_N \mid I_{N-1}=1) \;=\; E_{(\omega_N)}[\,E_{(\xi)}[(\xi - (\mathrm{c}(s_N) \mid I_{N-1}=1))I_N\,]]$$
$$I_N = 1 \quad if \quad \xi > b_N^* \mid I_{N-1}=1 \quad and \quad I_N = 0 \quad if \quad \xi < b_N^* \mid I_{N-1}=1$$
or
$$\pi_N(s_N \mid I_{N-1}=0) \;=\; E_{(\omega_N)}[\,E_{(\xi)}[(\xi - (\mathrm{c}(s_N) \mid I_{N-1}=0))I_N\,]]$$
$$I_N = 1 \quad if \quad \xi > \; b_N^* \mid I_{N-1}=0 \quad and \quad I_N = 0 \quad if \quad \xi < \; b_N^* \mid I_{N-1}=0$$

If the future expected profits are incorporated into the expression that estimates the optimal myopic bid for shipment s_{N-1}, the expected profits are:

$$E_{(\xi)}[\,(\xi - c(s_{N-1}))I_{N-1} + \pi_N(s_N \mid I_{N-1}=1)\,I_{N-1} + \pi_N(s_N \mid I_{N-1}=0)\;\;(1-I_{N-1})\,] \tag{1}$$

The price b_{N-1}^* that maximizes expression (1) is:

$$b_{N-1}^* \in \arg\max\; E_{(\xi)}[\,(\xi - c(s_{N-1}))I_{N-1} + \pi_N(s_N \mid I_{N-1}=1)\,I_{N-1} + \pi_N(s_N \mid I_{N-1}=0)\;\;(1-I_{N-1})\,] \tag{2}$$
$$b \in \mathrm{R},\;\; I_{N-1}=1 \quad if \quad \xi > b \;\; and \;\; I_{N-1}=0 \quad if \quad \xi < b$$

The profit $\pi_N(s_N \mid I_{N-1})$ conditional on the outcome of the previous auction does not depend on the realization of the price function ξ_{N-1}. Integrating expression (1) over the distribution of ξ, the expected value of expression (1) for any price b is:

$$\int_b^{\infty} (\xi - c(s_{N-1}))\; p(\xi)\,d(\xi) + \int_b^{\infty} \pi_N(s_N \mid I_{N-1}=1)\;\; p(\xi)\,d(\xi) + \int_{-\infty}^{b} \pi_N(s_N \mid I_{N-1}=0)\; p(\xi)\,d(\xi)$$

$$=\int_{b}^{\infty} (\xi - c(s_{N-1}) + \pi_N(s_N \mid I_{N-1}=1) - \pi_N(s_N \mid I_{N-1}=0))\, p(\xi)\, d(\xi) \;+\; \pi_N(s_N \mid I_{N-1}=0)$$

Since the last term, $\pi_N(s_N \mid I_{N-1}=0)$, is a constant the bid value that maximizes the expected profits maximizes:

$$\int_{b}^{\infty} (\xi - c(s_{N-1}) + \pi_N(s_N \mid I_{N-1}=1) - \pi_N(s_N \mid I_{N-1}=0))\, p(\xi)\, d(\xi)$$

A bid less than $c(s_{N-1}) - \pi_N(s_N \mid I_{N-1}=1) + \pi_N(s_N \mid I_{N-1}=0)$ is not optimal since for some realizations of ξ_{N-1} the revenue obtained for winning the auction does not cover the expected costs. A bid greater than $c(s_{N-1}) - \pi_N(s_N \mid I_{N-1}=1) + \pi_N(s_N \mid I_{N-1}=0)$ is not optimal since it reduces the likelihood of winning shipment s_{N-1} for some profitable realizations of ξ_{N-1}. Therefore, a weakly dominated strategy is to bid:

$$c(s_{N-1}) - \pi_N(s_N \mid I_{N-1}=1) + \pi_N(s_N \mid I_{N-1}=0) \qquad (3)$$

Opportunity costs

The intuition behind (3) is fairly straightforward. The first term represents the "static marginal cost" of serving shipment s_{N-1} as if it was the last shipment to arrive. The other two terms are linked to the future and are best interpreted together as the opportunity cost of winning a shipment. If the difference $\pi_N(s_N \mid I_{N-1}=0) - \pi_N(s_N \mid I_{N-1}=1)$ is:

a) $\pi_N(s_N \mid I_{N-1}=0) - \pi_N(s_N \mid I_{N-1}=1) > 0$

Having to serve s_{N-1} decreases the future profits since the carrier is better off without serving s_{N-1}. The carrier must hedge against the expected decrease in future profits increasing the static marginal cost by the positive difference. This increase may not be only due to the increase in the probability of deadheading but also due to the carrier's operation at or near capacity levels. In the latter case (due to capacity restrictions serving the present shipment may preclude serving shipment s_N in the future), the term $\pi_N(s_N \mid z^1_{N-1})$ in expression (3) is zero.

b) $\pi_N(s_N \mid I_{N-1}=0) - \pi_N(s_N \mid I_{N-1}=1) = 0$

Having to serve s_{N-1} does not change future profits. The carrier must not hedge any value.

c) $\pi_N(s_N \mid I_{N-1}=0) - \pi_N(s_N \mid I_{N-1}=1) < 0$

Having to serve s_{N-1} increases future profits since the carrier is better off serving s_{N-1}. The carrier must bid more aggressively for shipment s_{N-1} decreasing the static marginal cost by the negative difference. This last case may seem counterintuitive at first glance. However, if a vehicle is located in a "sink" area (a lot of trips are attracted and few are generated) and s_{N-1}

originates in a "sink" and goes to a "source" (a lot of trips are generated and few are attracted), it is absolutely plausible that future expected profits with s_{N-1} are greater than without s_{N-1}.

4. COST ESTIMATION METHODS

The exact or analytical estimation of equation (3) may be quite involved since it entails taking conditional expectations over arrival time and shipment characteristics distributions conditional on previous auction outcomes. Two numerical methods to approximate (3) are presented in this section and later evaluated using simulation. These two approaches are: Static Fleet Optimal method (SFO) and One- Step-Look-Ahead method (1SLA)

Static Fleet Optimal (SFO)

This carrier optimizes the static vehicle routing problem at the *fleet* level. The marginal cost is the increment in empty distance that results from *adding* s_j to the *total pool of trucks and loads* yet to be serviced. Communication and coordination capabilities are needed to feed the central dispatcher with real time data and to communicate altered schedules to vehicle drivers.

If the problem were static, this technology would provide the optimal cost. Like the previous approach, it does not take into account the stochastic nature of the problem. This technology roughly stands for "the best" a myopic (as ignoring the future but with real time information) fleet dispatcher can achieve. A detailed mathematical statement of the mixed integer program formulation used by SFO is given in Yang et al. [16].

One- step-look-ahead Opportunity Cost (1SLA)

As in the previous approach, this carrier optimizes the static vehicle routing problem at the fleet level. This provides the *static cost* for adding s_j. In addition, this carrier tries to assess whether and how much winning s_j affects his future profits. The estimated cost in this approach is:

$$c(s_j) - \pi_N(s_N \mid I_{N-1} = 1) + \pi_N(s_N \mid I_{N-1} = 0)$$

Unlike the previous method, the 1SLA carrier takes into account the stochasticity of the problem to estimate the opportunity costs of serving s_j as if there is just one more arrival after s_j (one step look ahead). Limiting the "foresight" to just one step into the future has two advantages: (a) it considerably eases the estimation and (b) it provides a first approximation about the importance of opportunity costs in a given competitive environment.

In this paper $\pi_N(s_N \mid I_{N-1})$ is estimated using simulation. To estimate these two terms it is assumed that the carrier knows the true distribution of load arrivals over time and their spatial distribution Ω (it is not discussed in this research how the carrier has acquired this information). This type of carrier also has an estimation of the endogenously generated prices or payments ξ; in this paper this type of carrier estimates the price function as a normal function, whose mean and standard deviation are obtained from the whole sample of previous prices.

5. EVALUATION SETTING

The TLPM marketplace enables the sale of *truckload* cargo capacity based mainly on price, yet still satisfies customer level of service demands (in this case hard *time windows* or TW). Shipments and vehicles are fully compatible in all cases; there are no special shipments or commodity specific equipment. From the carrier point of view, the ratio between shipment time window lengths and service time duration (or trip length) affects how many shipments can be accommodated in a vehicle's route; in general, the more shipments that can be accommodated, the lesser the deadheading (or average empty distance). Three different TW length/shipment service duration ratios are simulated. These ratios are denoted short, medium, and long; a reference to the average time window length. The different Time Window Lengths (TWL) for a shipment s, where $ld(s)$ denotes the function that returns the distance between a shipment origin and destination, are:

- $\text{TWL}(s) = 1(ld(s) + 0.25) + \text{uniform}[0.0, 1.0]$ (*short*)
- $\text{TWL}(s) = 2(ld(s) + 0.25) + \text{uniform}[0.0, 2.0]$ (*medium*)
- $\text{TWL}(s) = 3(ld(s) + 0.25) + \text{uniform}[0.0, 3.0]$ (*long*)

The shipments to be auctioned are circumscribed in a bounded geographical region. The simulated region is a 1 by 1 square area. Trucks travel from shipments origins to destinations at a constant unit speed (1 unit distance per unit time). Information concerning the origin and destination of the shipments is not known to the carriers in advance. Shipments origins and destinations are uniformly distributed over the region. There is no explicit underlying network structure in the chosen origin-destination demand pattern. Alternatively, it can be seen as a network with infinite number of origins and destinations (essentially each point in the set [0,1]x[0,1]) has an infinite number of corresponding links. Each and every link possesses an equal infinitesimal probability of occurrence.). This geographical demand pattern creates a significant amount of uncertainty for fleet management decisions such as costing a shipment or vehicle routing. Since the degree of deadheading is unknown, any fleet management decision should hedge for this uncertainty. Shipment service times are taken into account in order to simulate dynamic truckload pickup-and-delivery situations (dynamic multi-vehicle routing problems with time-windows). It is assumed that no significant time is spent during all pick-ups and deliveries; however vehicles are assumed to travel at a constant speed in a Euclidean two dimensional space. Vehicles speeds are a unit; the average shipment length is ≅0.52. Carriers' sole sources of revenue are the payments received when a shipment is acquired. Carriers' costs are proportional to the total distance traveled by the fleet. It is assumed that all carriers have the same cost per mile. The market is comprised of shippers that independently call for shipment procurement auctions, and carriers, that participate in them (we assume that the likelihood of two auctions being called at the same time is zero). Auctions are performed one at a time as shipments arrive to the auction market. In this research different demand/supply ratios are studied. Arrival rates range from low to high. At a low arrival rate, all the shipments can be served (if some shipments are not serviced it is due to a very short time window). At a high arrival rate carriers operate at capacity and many shipments have to be rejected. It is assumed that the auction announcements are random and that their arrival process follows a time Poisson process. The expected inter-arrival time is normalized with respect to the market fleet size. The expected inter-arrival times are $1/2$ arrivals per unit time per truck, $2/2$ arrivals per unit time per truck, and $3/2$ arrivals per unit time per truck (low, medium, and high arrival rates respectively).

In all cases it is assumed that a carrier bids only if a feasible solution has been found. If serving s_j unavoidably violates the time window of a previously won shipment, the carrier simply abstains from bidding or submits a high bid that exceeds the reservation price of s_j.

Allocations follow the rules of a second price reverse auction. Furthermore, it is assumed that carriers submit their best estimation of the service cost. The allocations rules are as follows:

- Each carrier submits a single price;
- The winner is the carrier with the lowest bid (which must be below the reservation price set as 1.41 units; otherwise the auction is declared void);
- The item (shipment) is awarded to the winner;
- The winner is paid either the value of the second lowest bid or the reservation price, whichever is the lowest; and
- The other carriers (not winners) do not win, pay, or receive anything

In this research a discrete-event simulation framework is employed. Simulations are used to compare how different opportunity cost approximations perform under different market settings (in our case limited to arrival rates and time windows). All the figures and data presented are obtained with a carriers' fleet size of two and four vehicles. The results obtained reflect the steady state operation (1000 arrivals and 10 iterations) of the simulated system. This is obtained using an adequate warm-up period, in all cases set to one hundred arrivals (a warm up length more than adequate for the fleet sizes and shipment time windows considered).

6. ANALYSIS OF RESULTS

Figures 1 to 3 compare the profit performance of the approach SFO vs. approach 1SLA with different arrival rates: low, medium, and high respectively. All these 3 figures also include 90% significant intervals around the means. A general trend illustrated in each of these figures is that profit levels tend to decrease as time windows grow. As the routing problems become less constrained, there are more possibilities for competition and prices and profits follow a downward trend.

When comparing 1SLA and SFO (the latter use as a base), the more sophisticated method does not outperform the less sophisticated method across the board with medium and long time windows. Profit-wise, the 1SLA carrier obtains higher or equal profits than the SFO, yet no clear pattern emerges from figures 1 to 3. Figure 4 compares the performance of the 1SLA vs. SFO methods in terms of the number of shipments served. The results obtained for the less sophisticated carrier (SFO carrier figure 4) are used as the base line. Any positive difference is indicated in red; any negative difference is indicated in blue. Regarding shipments served, the 1SLA carrier tends to serve fewer shipments when the time windows are short. However, 1SLA carrier tends to serve more shipments for medium and long time windows. Arrival rates affect these differences.

The key to understanding the relative performance of technologies 1SLA and SFO is in the average payment received by each carrier. Figure 5 compares average payment for approach SFO vs. approach 1SLA with high arrival rates and including 90% significant intervals around the means. Clearly, carrier 1SLA manages to obtain higher profits with fewer shipments served (high arrival rate, short time windows, figure 3 and 4) because average payments are significantly higher (figure 5). The difference in pricing shipments is derived from the term: $\pi_N(s_N \mid I_{N-1}=0)-\pi_N(s_N \mid I_{N-1}=1)$. As previously mentioned, this term measures the opportunity cost of winning the current auction. Results indicate that the 1SLA carrier tends to set bid values more aggressively (bids lower) when the time windows are not short and the arrival rate is not too high. The 1SLA carrier tends to bid less aggressively (bids higher) when the time windows are short and the arrival rate is high. There are two distinct forces operating in the market: time windows and arrival rates. An increase in arrival rates increases the bid values (therefore the opportunity cost has increased). A decrease in time window lengths increases the bid values (therefore the opportunity cost has increased). In only one setting SFO outperforms 1SLA, however this result is not statistically significant (figure 2).

7. CONCLUSIONS

The principal focus of this research was to quantify opportunity costs in sequential transportation auctions. An expression to evaluate opportunity costs was derived. This paper shows that the impact of evaluating opportunity costs is dependent on the competitive market setting. A simplified approach (1SLA) to estimate opportunity costs was developed and applied successfully. It was shown that the estimation of opportunity costs in an online marketplace provides a competitive edge. However, the exact calculation of opportunity costs can be quite challenging.

In summary, this research was successful to (1) recognize that different market settings (arrival rates, time windows) affect the value of estimating opportunity costs; (2) to develop an expression to estimate opportunity costs; and (3) to enhance our understanding of the interaction between routing and pricing problems in a competitive marketplace.

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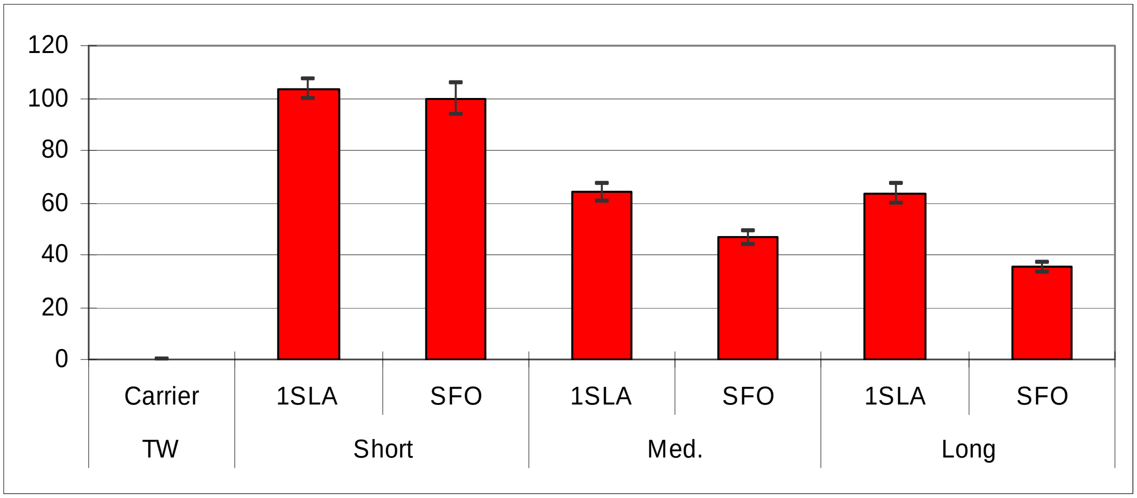

Figure 1 Profits and Significant Intervals (1SLA vs. SFO Technology) – Low Arrival Rates

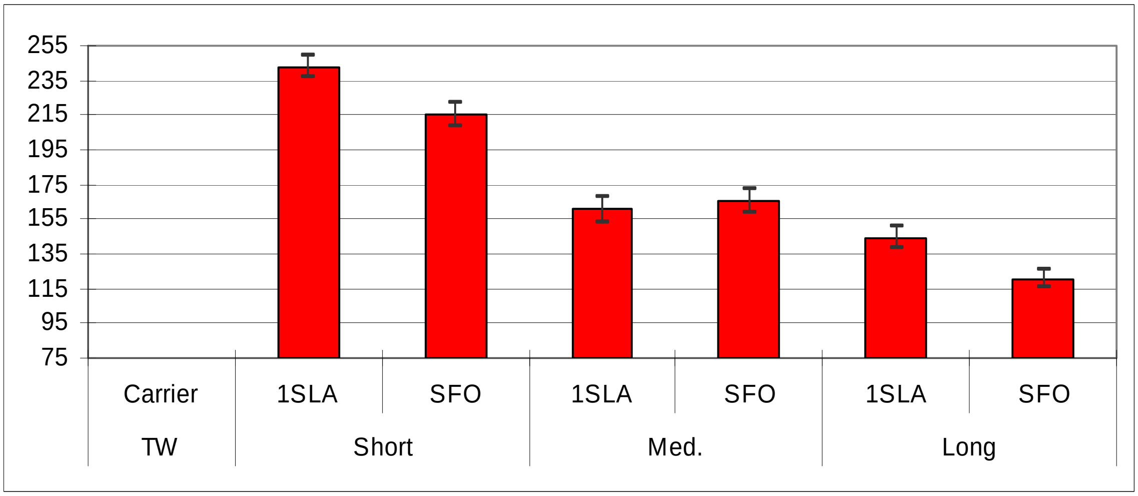

Figure 2 Profits and Significant Intervals (1SLA vs. SFO Technology) – Medium Arrival Rates

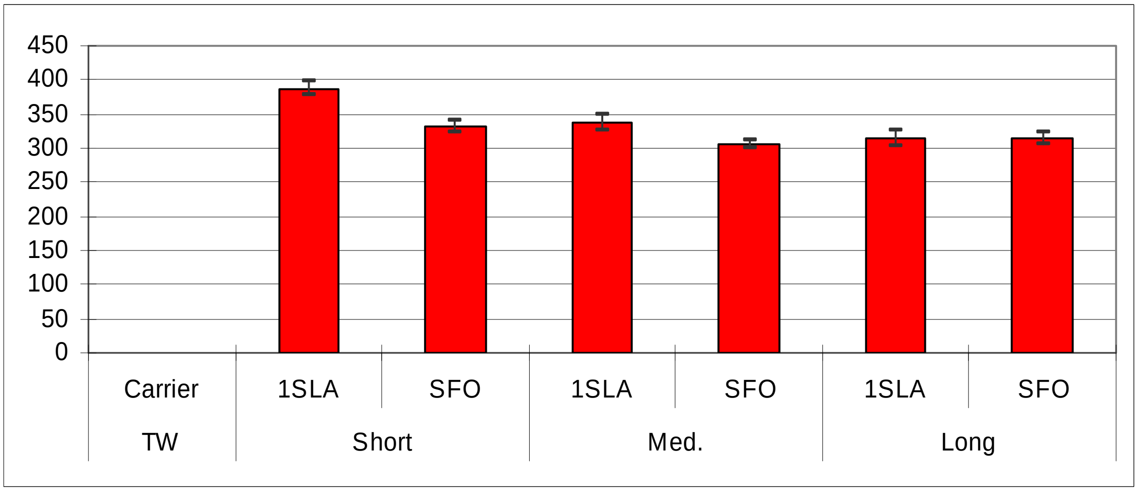

Figure 3 Profits and Significant Intervals (1SLA vs. SFO Technology) – High Arrival Rates

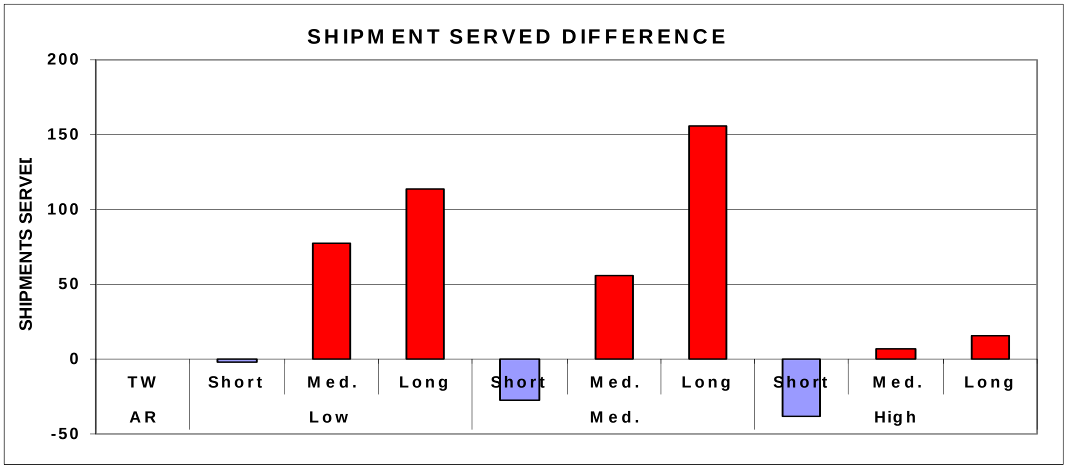

Figure 4 Shipments Served Difference 1SLA vs. SFO Technology

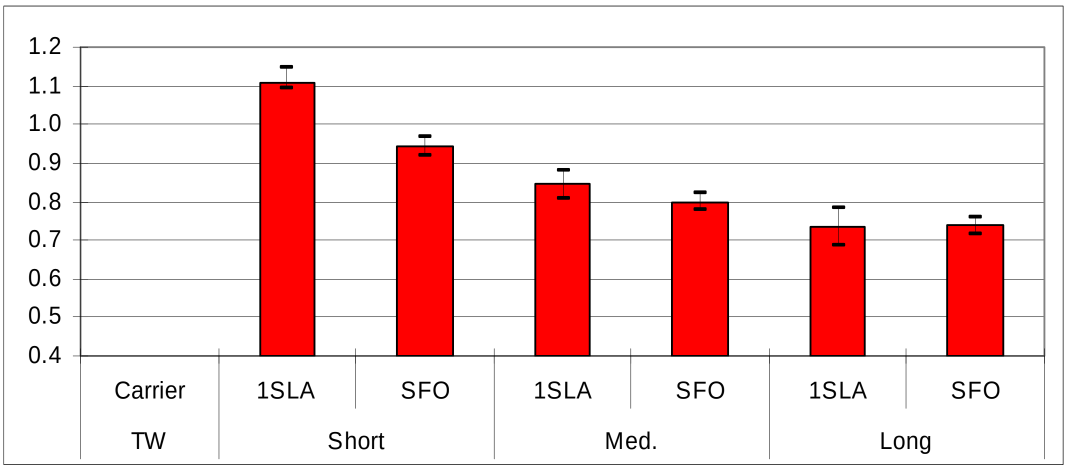

Figure 5 Average Payment Value and Significant Difference (1SLA vs. SFO) – High Arrival Rate