



I T L S

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Evaluation of Different
Approaches for the
Truckload Vehicle Routing
Problem in a Competitive
Environment

By

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TITLE: **Evaluation of different approaches for the Truckload Vehicle Routing Problem in a Competitive Environment**

ABSTRACT: The principal focus of this research is to evaluate the effectiveness of different approaches for the vehicle routing problem in a competitive environment (VRPCE). This paper focuses on the study of the VRPCE in a 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. This paper will show how the efficiency of routing and costing approaches in different market settings will depend on these carriers' approaches. A simulation framework is used to evaluate different strategies. Some results and the overall simulation framework are also discussed

KEY WORDS: *Performance, pickup and delivery service, evaluation and assessment, dynamic vehicle routing, sequential auctions, fleet assignment technologies*

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1. 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 2 carriers competing. A carrier is denoted by $i \in \mathfrak{I}$ where $\mathfrak{I} = \{1, 2\}$ is the set of all carriers. Let the shipment/auction arrival/announcement epochs be $\{t_1, t_2, \dots, t_N\}$ such that $t_i < t_{i+1}$. Let $S = \{s_1, s_2, \dots, s_N\}$, represent the set of arriving shipments. Let t_j represent the time when shipment s_j arrives and is auctioned. Arrival times and shipments are not known in advance. The arrival instants $\{t_1, t_2, \dots, t_N\}$ follow a Poisson arrival process. Furthermore, arrival times and shipments are assumed to come from a probability space (Ω, \mathcal{F}, P) , with outcomes $\{\omega_1, \omega_2, \dots, \omega_N\}$. 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 contract s_j arrives, a carrier tenders a price $b_j \in R$. After each contract offering, the carrier receives feedback y_j regarding the outcome of the offering. The information known at the time of the offering for contract s_j is $h_j = (h_0, y_1, y_2, \dots, y_{j-1})$, where h_0 denotes the information known by the carriers at time t_0 (with $t_0 < t_1$) before bidding for contract s_1 . Similarly, the information known at time t with $t_{j-1} \leq t < t_j$ is $h_t = (h_0, y_1, y_2, \dots, y_{j-1})$. 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 contracts). 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 contract prices are not influenced by the actions (bids or fleet management related) taken by the carrier. If the carrier attains the right to serve contract 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 contract s_j arrives is denoted as z_j . There is an estate or assignment function such that the status of the carrier when shipment s_j arrives is $z_j = a(t, h_j, z_{j-1})$ or in general $z_t = a(t, h_t, z_j)$ for any $t_j < t \leq t_{j+}$. 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 $d(a, z_j, t)$. Let I_j be the indicator variable for shipment s_j , such that $I_j = 1$ if the carrier secures the offering for contract s_j and $I_j = 0$ otherwise. The marginal cost of serving a just arrived contract s_j up to time t is estimated using:

$$c(s_j, t) = d(a, z_j | I_j = 1, t) - \{d(a, z_{j-}, t) - d(a, z_{j-}, t_j)\}$$

2. Bidding/Pricing Problem

There are five main characteristics of a VRPCE: a) the vehicle routing problem is dynamic -- service requests/contracts arrive over time; b) there is a degree of uncertainty about customer requests arrival times and characteristics; c) a carrier that tries to act rationally must estimate the marginal cost of servicing the new service request; d) each service provided has a monetary reward – this reward or revenue may be uncertain at the time of estimating the cost; and e) the carrier's profit depends on the revenue obtained – from servicing requests – and on how effective the fleet was managed – service/travel costs to provide the service. The optimal bidding value in the TLPM is the true marginal cost for the arriving shipment s_j (Figliozzi et al., 2004), herein denoted as c_j^* :

$$c_j^* = \bar{c}(s_j) - \pi_{j+1}(s_{j+1} | I_j = 1) + \pi_{j+1}(s_{j+1} | I_j = 0) \quad (1)$$

The term $\bar{c}(s_{N-1})$ is the expected marginal cost. If the probability of abandoning¹ the fleet deployment plan implemented at time t_{N-1} by time t is denoted by $p_{\Omega, \xi}(t | t_{N-1})$ then the expected marginal cost is then calculated as:

$$\bar{c}(s_j) = \int_{t_j}^{t_j} c(s_j, t) p_{\Omega, \xi}(t | t_j) dt + c(s_j, t_j) (1 - \int_{t_j}^{t_j} p_{\Omega, \xi}(t | t_{N-1}) dt)$$

The term $\pi_{j+1}(s_{j+1} | I_j)$ is defined as the expected profits from shipment s_{j+1} onwards and conditional on the previous outcome as:

$$\pi_{j+1}(s_{j+1} | I_j = 1) = E_{(\omega_{j+1})} [E_{(\xi)} [(\xi - \bar{c}(s_{j+1}) | I_j = 1) I_{j+1} + \pi_{j+2}(s_{j+2} | I_{j+1} = 1) I_{j+1} + \pi_{j+2}(s_{j+2} | I_{j+1} = 0) (1 - I_{j+1})]] \quad (2)$$

$$I_{j+1} = 1 \quad \text{if } \xi > b_{j+1}^* | I_j = 1 \quad \text{and} \quad I_{j+1} = 0 \quad \text{if } \xi < b_{j+1}^* | I_j = 1$$

¹ Abandoning the previous fleet schedule due to the acquisition of a new load

or

$$\begin{aligned} \pi_{j+1}(s_{j+1} | I_j = 0) = & E_{(\omega_{j+1})}[E_{(\xi)}[(\xi - \bar{c}(s_{j+1}) | I_j = 0)I_{j+1} + \pi_{j+2}(s_{j+2} | I_{j+1} = 1)I_{j+1} + \\ & + \pi_{j+2}(s_{j+2} | I_{j+1} = 0)(1 - I_{j+1})]] \quad (2') \end{aligned}$$

$$I_{j+1} = 1 \quad \text{if } \xi > b_{j+1}^* | I_j = 0 \quad \text{and} \quad I_{j+1} = 0 \quad \text{if } \xi < b_{j+1}^* | I_j = 0$$

3. VRPCE Technologies

The exact estimation of equation (1) is quite involved. In the rich spectrum of possible approximations to tackle equation (1), three inherently distinct and archetypical approaches are evaluated. These three approaches (technologies) require different levels of sophistication in communication capabilities, static optimization, and the evaluation of opportunity costs. The three approaches are presented in an order that shows an increasing and distinct level of sophistication.

3.1 Base or Naive Technology

This type of carrier simply serves shipments in the order they arrive. If the carrier has only one truck, it estimates the marginal cost of an arriving shipment s_j simply as the additional empty distance incurred when appending s_j to the end of the current route. If the carrier has more than one truck, the marginal cost is the cost of the truck with the lowest appending cost. This technology does not take into account the stochastic or combinatorial aspect of the cost estimation problem and is considered one of the simplest possible. Each vehicle acts as if it were an independent carrier; in fact, the auction and fleet assignment results are not altered if each vehicle submits its own bid. Communication and coordination overheads are reduced to a minimum. Nonetheless, this technology provides a useful benchmark against which to compare the performance of more complex and computationally demanding technologies. Denoting by a^1 the appending type of assignment and by \hat{c}_j^1 (the tilde over the cost is to indicate that it is an approximation to the true cost) the estimated cost using this approach are:

$$\hat{c}_j^1 = c(s_j, t_j) | a^1 = d(a^1, z_j | I_j = 1, t_j) - \{d(a^1, z_{j-}, t_{j-}) - d(a^1, z_{j-}, t_j)\} \quad (3)$$

It is clear that equation (3) is very simply heuristic and only approximates the expected marginal cost component of equation (1).

3.2 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. (2004). Denoting by a^2 the appending type of assignment and by \hat{c}_j^2 the estimated cost using this approach:

$$\hat{c}_j^2 = c(s_j, t_j) | a^2 = d(a^2, z_j | I_j = 1, t_j) - \{ d(a^2, z_{j-}, t_{j-}) - d(a^2, z_{j-}, t_j) \} \quad (4)$$

It is clear that equation (4) only approximates the expected marginal cost component of equation (1) but in this case with the fully realized optimal myopic marginal cost. Additionally, in both equations (3) and (4) significant opportunity costs are completely ignored.

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

The previous two approaches implicitly assume that acquiring shipment s_j does not affect the marginal cost of future loads (i.e. $s_{j+1}, s_{j+2}, \dots, s_N$). However this is not entirely correct for two reasons since acquiring a new load (a) temporarily reduces the carriers’ capacity (capacity defined as the ability to serve additional shipments at a point in time) and (b) changes the current schedule and therefore possibly changes fleet deployment at the time of the next shipment auction. The only exception to this takes place in the final auction (shipment s_N) and there are no repositioning costs (trucks do not return to depot).

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. Given the complexity of estimating $\pi_{j+1}(s_j | I_j = 1)$ and $\pi_{j+1}(s_j | I_j = 0)$ the carrier approximates them (articulate) as if shipment s_{k+1} is the last shipment to ever arrive at the marketplace. The estimated future profits then become $\hat{\pi}_{j+1}^1(s_j | I_j = 1)$ and $\hat{\pi}_{j+1}^1(s_j | I_j = 0)$ respectively where the super index indicates how many steps into the future where used. The estimated cost in this approach is:

$$\hat{c}_j^3 = \hat{c}_j^2 - \hat{\pi}_{j+1}^1(s_j | I_j = 1) + \hat{\pi}_{j+1}^1(s_j | I_j = 0) \quad (5)$$

Unlike previous types, this 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 $\hat{\pi}_{j+1}^1(s_j | I_j = 1)$ and $\hat{\pi}_{j+1}^1(s_j | I_j = 0)$ are 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 $\hat{\xi}$; 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.

4. Evaluation of Online VRPCE

The fair evaluation of the performance of dynamic routing and scheduling problems has long been recognized as a difficult quandary (Powell et al., 1995). The lack of systematic evaluation methodologies has led researchers to compare algorithms performances using simulation in a variety of environments or to establish performance bounds. These commonly used methods are particularly ill-suited for VRPCE.

Trying to obtain bounds using Competitive Analysis (CA) to the VRPCE would result in a competition among two carriers; one denoted O for “ordinary” (whose performance we would like to evaluate) and one denoted P for “powerful”. The carrier O possesses a given fleet assignment and pricing functions, he has uncertain information about the future (only knows the parameters of the demand function, not the future instances), and only knows with certainty his private information (the status of his/her fleet). The carrier P possesses a given fleet assignment and bidding functions, determines the sequence of future shipment arrivals (the future instances), and knows with certainty his private information as well as O’s private information. The objective of P is to maximize the competitive ratio: $\max[\pi^P(S)/\pi^O(S)]$ which is the ratio between P’s and O’s profits after a sequence of N contract arrivals. On the other hand, O’s objective is to minimize the competitive ratio:

$$\min[\pi^P(S)/\pi^O(S)] = \max[-\pi^P(S)/\pi^O(S)] .$$

These perfectly conflicting objectives determine a zero sum game between carriers O and P. Under the extremely asymmetric assumptions of CA the results obtained would be trivial; i.e. the adversary P is so powerful that the competitive ratio would not be sufficiently distinguished among VRP assignment and pricing technologies, otherwise of distinct quality. If carrier P determines the sequence and characteristics of shipment arrivals, these can be easily chosen to minimize his fleet empty distance. If carrier P knows carrier O’s private information, P also knows O’s prices. With this information, carrier P can bid in a way that completely minimizes carrier O’s profits in a first or second price auction, even if P does not determine the shipment arrivals. In a second price auction, P can bid O’s bid plus a non negative negligible amount in order to limit O’s revenues. In a first price auction, P can maximize his revenues by bidding O’s bid minus a non negative negligible amount (Figliozzi, 2004).

The assumptions of competitive analysis go against standard notions of fair market competition and operation. Firstly, in a procurement marketplace the sequence and characteristics of arrivals are determined by the shippers' needs, carriers cannot determine those needs. Secondly, assuming that just one carrier has full and precise knowledge about competitors' private information (deployment, assignment, costing, and bidding functions), the information asymmetry provides such an advantage in the bidding process that it conceals any qualitative difference among carriers VRP and pricing technologies. Thirdly, competitive analysis assigns the adversary P with an off-line technology (since P has full information) and limits O to have an online technology. Thus, the two carriers are not even "competing" in the same type and problem instance. Even limiting P's advantage to hindsight is not fair or behaviorally sound.

Alternatively, average case analysis could be used to evaluate the performance of each approach. Then the performance of the approaches could be compared: a) against each other or b) against the best possible hindsight solution. Though this could provide useful information about the performance of each approach in a monopoly like situation, it would not capture any market interaction. On these grounds, the sole use of average performance (just one carrier at a time) as a basis of comparison seems unjustified.

This research will compare the performance of the different approaches using a sequence of second price auctions. It is assumed that carriers submit as a price their marginal cost estimation. It seems more realistic to analyze the performance of VRPCE approaches in a market environment characterized by cut-throat competition and perfect information symmetry than in: a) a market characterized by one dominant player and extreme information asymmetry or b) an unrealistic monopoly like situation².

Next section describes the context and parameters chosen to study the three distinct approximations to the VRPCE.

5. Evaluation Setting

The VRPCE is a new kind of problem that requires a set of parameters and settings that are not indispensable in other VRPs, however many settings are common. To better distinguish the particular VRPCE evaluation settings the following scheme is used to classify settings as they relate to: a) static VRPs, b) dynamic VRPs, c) real-time VRPs, d) VRCPE proper, and e) simulation related.

a) Static VRP Settings

a.i Type of routing problem

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.

² Trying to combine competition and monopoly in the same environment is an oxymoron and thus an unrealistic approach a prima facie

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:

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

a.ii Spatial settings (geographic area) and network characteristics. Travel/service times/costs. Demand distribution over the space.

The shipments to be auctioned are circumscribed to 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 $[0,1] \times [0,1]$) 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 $\cong 0.52$.

a.iii Significant cost/profit elements

Carriers' sole sources of revenue are the payments received when a contract 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.

b) Dynamic VRP Settings

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).

c) **Real Time VRP Settings**

Response or solution time is a key consideration in real time applications. However, given that the objective of this paper is to analyze how much can be gained using different technologies, it is assumed that carriers have enough computational power to submit a bid before another request comes in. It is assumed that the auction announcement, bidding, and resolution take place in real time, thereby precluding the option of bidding on two auctions simultaneously.

d) **VRPCE Settings**

d.i **Competing algorithms**

Three distinct approaches were described in section 4.

d.ii **Knowledge of carriers regarding arrival and price function.**

The price distribution ξ is not known, it must be estimated from past data/observations. The distribution of contracts (shipments) arrival and characteristics Ω is assumed to be known by all carriers. Only the 1SLA type of carrier uses an approximation of the endogenously generated prices or payments $\hat{\xi}$ with a normal function.

d.iii **Market allocation rules**

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

e) **Simulation Related Settings**

In this research a discrete-event simulation framework is employed. Simulations are used to compare how different approximations to the VRPCE 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 1 (naïve) vs. approach 2 (SFO) with different arrival rates: low, medium, and high respectively. Figures 4 to 6 compare the profit performance of the approach 2 (SFO) vs. approach 3 (ISLA) with different arrival rates: low, medium, and high respectively. All these 6 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.

As expected, a more sophisticated technology outperforms the naïve one. However, relative performance critically depends on the arrival rate and time windows. The analysis of Figures 1 to 3 indicates that the naïve approach fares well with short time windows only (profits are not significantly different). A similar behavior can be observed in Figure 7 with respect to the number of shipments served. In Figure 7 the results obtained for the less sophisticated carrier (approach 1 in Figure 7) are used as the base line. Therefore, any positive difference (indicated in red) in the last first four graphics demonstrates that the more sophisticated carrier (approach 2 – SFO - in this case) has served more shipments than the less sophisticated carrier has; negative differences are indicated in blue.

To understand why the SFO technology outperforms the naïve one with medium and long time windows, it is useful to look at how the carriers estimate the cost of serving a shipment. The “appending” technique has at most a polynomial number of solutions, while the static optimal may have an exponential number of solutions. The two techniques provide the same costs when they search over the same set of feasible solutions. Intuitively, if time window constraints are very tight, the only feasible solutions may be to append the arriving shipment to the end of existing routes. A very low arrival rate would have a similar effect. If all vehicles are idle, the two technologies would provide the same cost. However, the greedy polynomial approach is in serious disadvantage when “inserting” is possible. The insertion of shipments in existing routes is facilitated when time windows are wide enough to accommodate the service of several shipments. As the cardinality of the set of shipments to be served grows linearly, the set of feasible solutions can have an exponential growth.

Unlike previous results, when comparing 1SLA and SFO the more sophisticated technology does not outperform less sophisticated technology 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 4 to 6. Figure 8 compares the performance of the 1SLA vs. SFO technology in terms of the number of shipments served. The results obtained for the less sophisticated carrier (SFO carrier Figure 8) are used as the base line. The color convention remains unchanged. 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 9 compares average payment for approach 2 (SFO) vs. approach 3 (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 6 and 8) because average payments are significantly higher (Figure 9). The difference in pricing shipments is derived from the term: $-\hat{\pi}_{j+1}^1(s_j | I_j = 1) + \hat{\pi}_{j+1}^1(s_j | I_j = 0)$. 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).

Conclusions

This analysis applies different approaches to solve the VRPCE in a truckload environment. 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.

Different methods to evaluate carrier strategies were discussed. Although it was argued for the appropriateness of sequential second price auctions to model a competitive environment and evaluate carrier strategies, other evaluation methods must be seen as complementary. Further research work is necessary to provide a sound methodology to evaluate online algorithms.

In summary, this research was successful to (1) recognize that different market settings (arrival rates, time windows) deeply affect the efficiency of routing and costing approaches; (2) to develop a basic approach for measuring routing technologies' business value in a competitive environment; and (3) to enhance our understanding of the behavior of some archetypical assignment technologies in a competitive marketplace.

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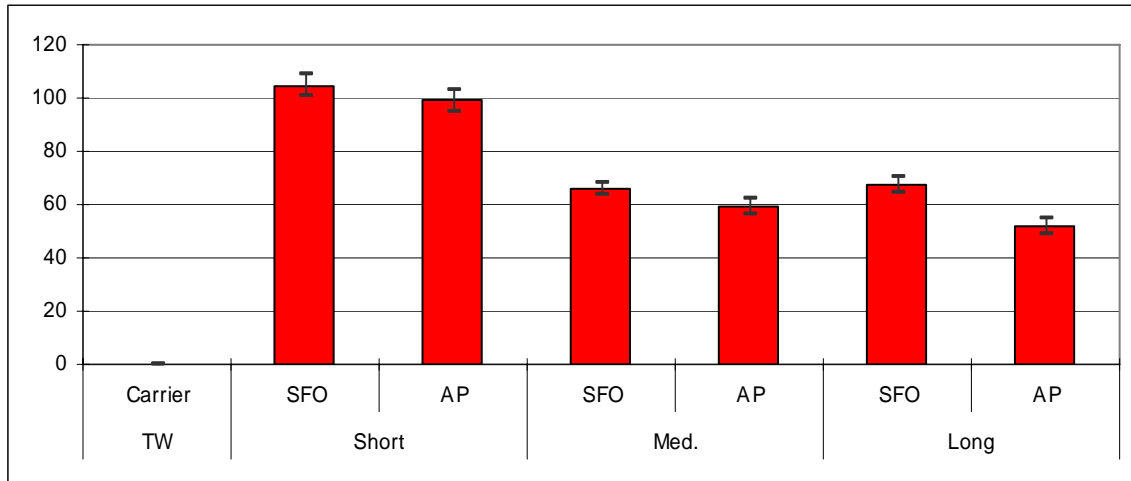


Figure 1 Profits and Significant Intervals (SFO vs. Naive Technology) – Low Arrival Rates

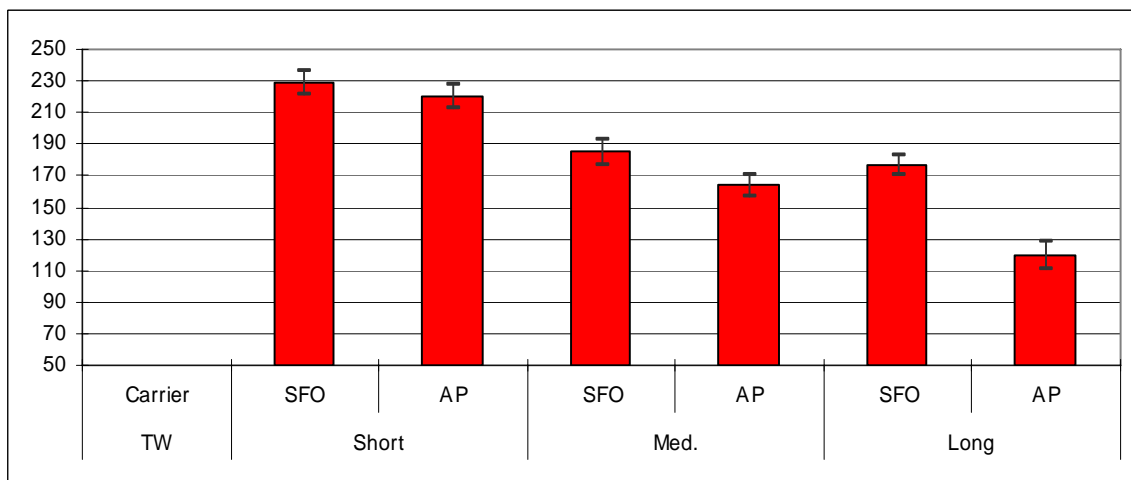


Figure 2 Profits and Significant Intervals (SFO vs. Naive Technology) – Medium Arrival Rates

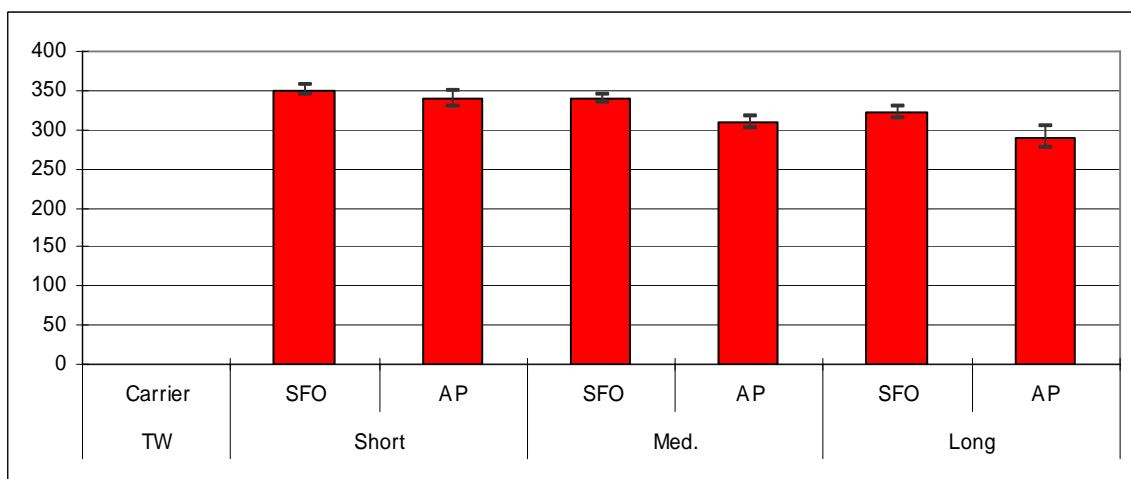


Figure 3: Profits and Significant Intervals (SFO vs. Naive Technology) – High Arrival Rates

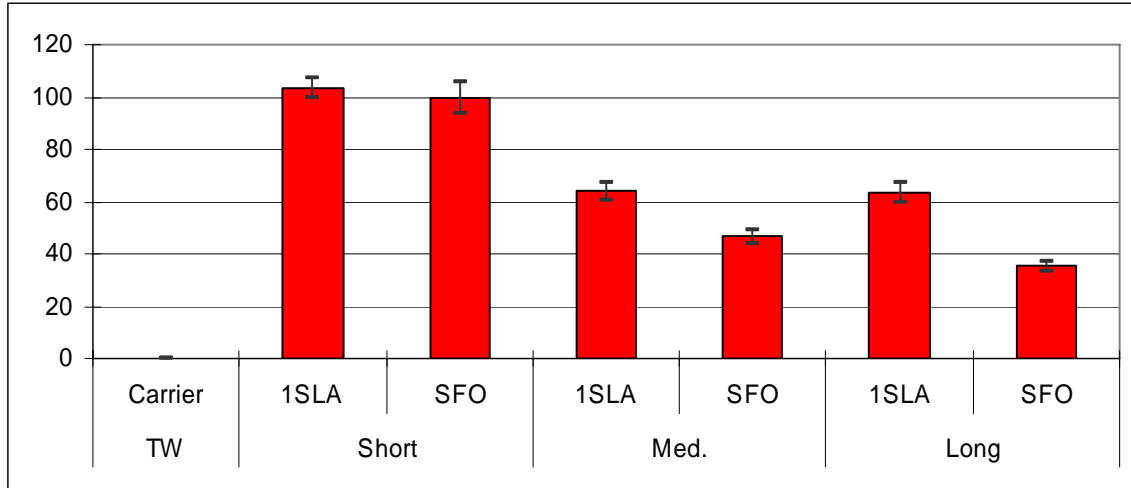


Figure 4: Profits and Significant Intervals (ISLA vs. SFO Technology) – Low Arrival Rates

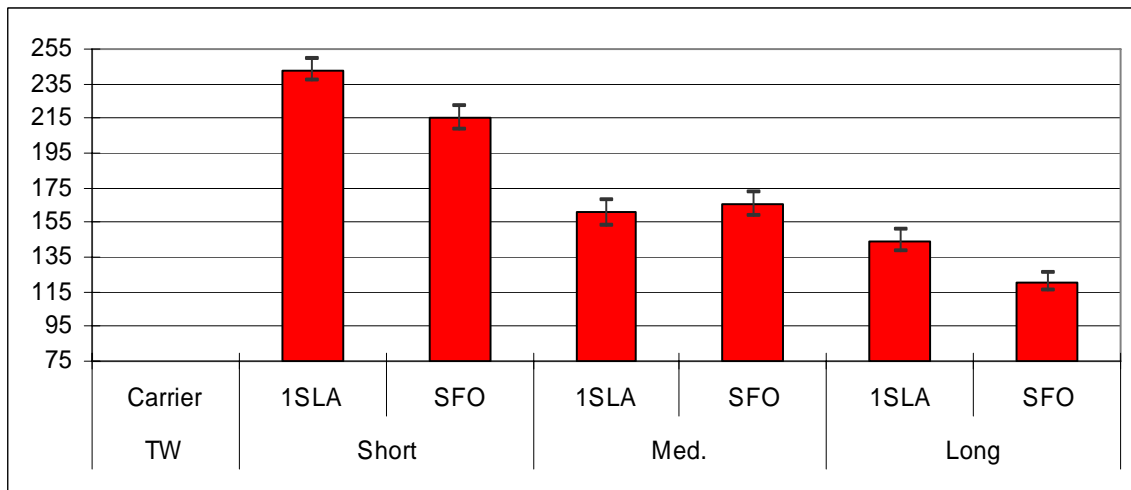


Figure 5: Profits and Significant Intervals (ISLA vs. SFO Technology) – Medium Arrival Rates

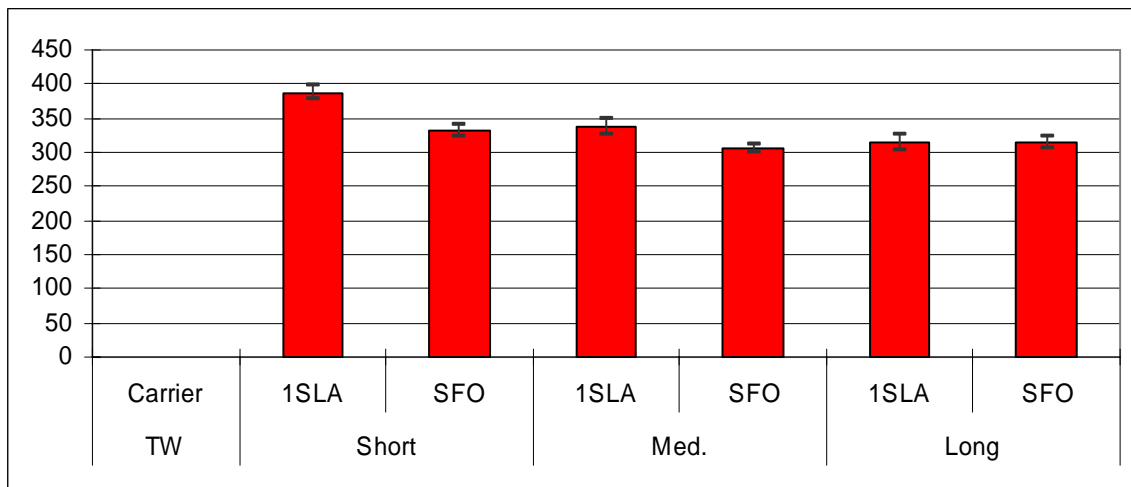


Figure 6: Profits and Significant Intervals (ISLA vs. SFO Technology) – High Arrival Rates

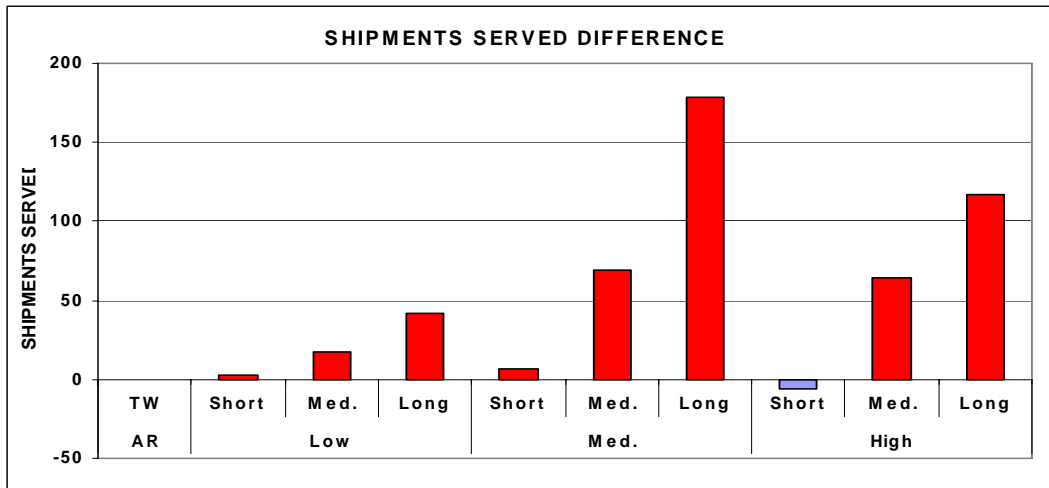


Figure 7 Shipments Served Difference SFO vs. Naïve Technology

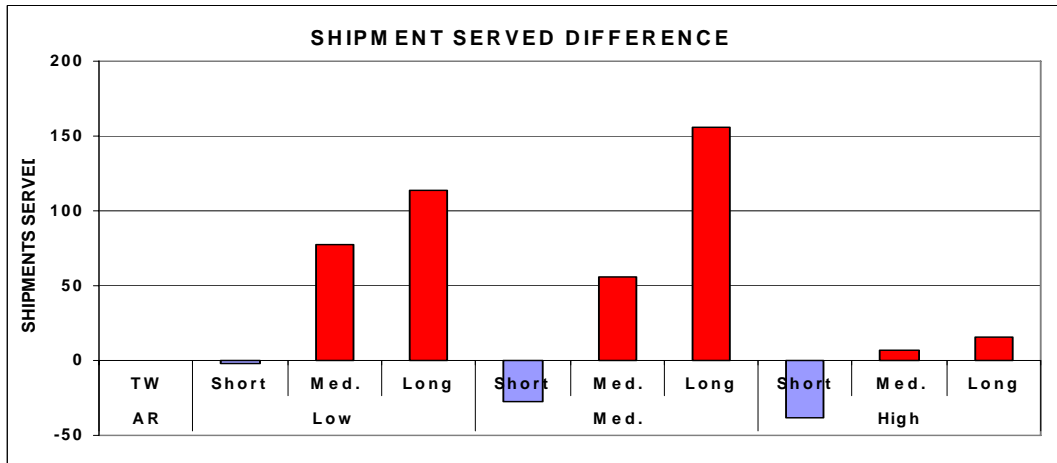


Figure 8 Shipments Served Difference ISLA vs. SFO Technology

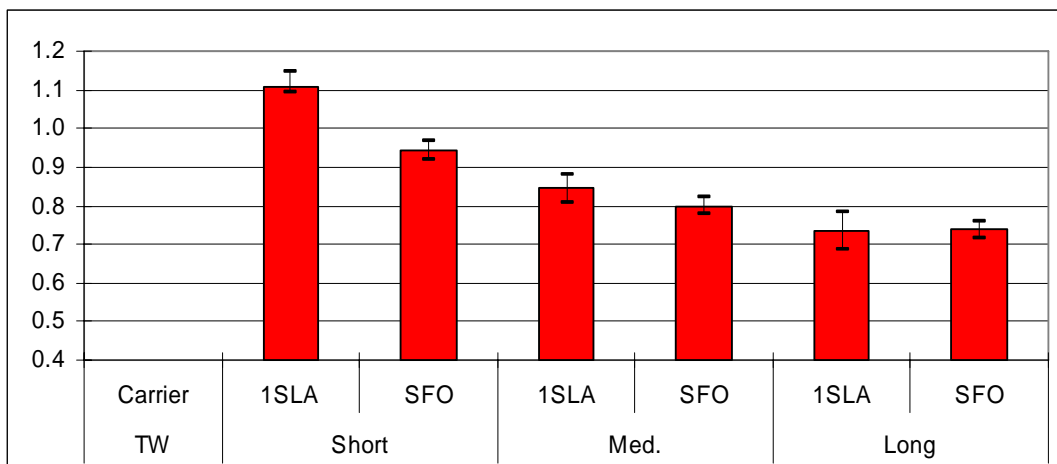


Figure 9: Average Payment Value and Significant Difference (ISLA vs. SFO) – High Arrival Rate