INCREASING PRODUCTIVITY AND SERVICE QUALITY OF THE STRADDLE CARRIER OPERATIONS AT A CONTAINER PORT TERMINAL

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ABSTRACT
The paper presents results of a research designed to evaluate the potential for improving productivity and the quality of service for a straddle carrier operation at an intermodal container port terminal. Straddle carrier is a specialized vehicle for handling containers. It removes the container from a truck-tractor chassis by straddling the chassis, lifting the container using an overhead crane to the desired height (up to four times the container’s height), and drives away with the container in its belly. A methodology was developed to quantify possible savings from redesigning the straddle operation. The main effort was to develop and evaluate a series of algorithms for straddle assignment and control. The algorithms differ in a manner in which the straddles are given assignments to move containers. The algorithms are applied to a case study representing the operation of a major port terminal in the port of New York and New Jersey. The case study results indicate that the use of the proposed algorithms would result in a substantial reduction (in the 17-23% range) in the straddle distance over the current operation. In general, this reduction was accompanied by the slight increase (of 1-2%) in the average truck service time, although a particular algorithm was able to simultaneously reduce both the distance and truck service time. The model shows that the operator can substantially reduce its fleet ownership and maintenance costs by using fewer straddles while maintaining a desired level of truck wait time. The annual cost savings were conservatively estimated to be in the $997,000 to $1,970,000 range. These savings would increase to the $3,370,000 - $6,740,000 range if the operator were to sell the surplus straddles and invest proceeds from the sale at an interest rate of 10%.

KEY WORDS: Container Port Operations, Intermodal Transportation, Straddle Carrier, Port Productivity

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INTRODUCTION

The last decade has seen a remarkable growth in the volume of containerized cargo. On average, the volume grew 6% annually in the US, 1.5% in Canada, and 10% worldwide. This trend is likely to continue in the next decade. Forecasters estimate that by the year 2,010, 90% of the world’s liner cargo will move in containers (USDOT 1998).

This growth has been fueled by the strong US and until recently Asian economies, elimination of international trade barriers, and shifting patterns in global manufacturing and consumption. The growth was also facilitated by the substantial technological developments in maritime intermodal transportation. The main advantage of intermodal is that it brings together the best features of its composite modes: (1) the economy of water in line haul, where a large number of containers can be moved over long distances at the least cost (on per unit basis), (2) the economy of rail in intermediate haul between the ports and urban markets, and (3) the flexibility of truck in local pick up and delivery. The introduction of high-speed hull designs and larger container ships capable of carrying over 3,000 TEU (twenty-foot equivalent units) containers substantially increased the productivity of water line haul. The higher speed resulted in a reduced transit time, and the increased ship size further reduced the average transportation cost. On-dock rail facilities (express rail) facilitated transfer of containers between ship and rail and contributed to the increased productivity of terminal operations and the reduction in truck congestion at the terminal gates. Direct rail access to docks decreased the container handling. A mode shift from truck to rail in the delivery of containers can eliminate approximately 200 trucks for each double stack train that comes to the port. The automation of terminal gates further alleviated truck congestion by providing unimpeded
truck access and equipment interchange. These advances, coupled with the advances in information technology and management of cargo-related information flows, led to a relatively seamless transfer of containers between the modes.

The future of containerized cargo in the US will be shaped by the following factors. The trend of decreasing the average transport cost by water has already lead to the development of megaships capable of carrying over 8,000 TEU containers. The price of a megaship can easily exceed $200M, and such high capital investment requires that the ship’s transit and port turnaround time be kept at minimum. The lower turnaround time means faster ship unloading/loading with the terminals being able to receive and discharge a large number of containers within a short time period. This large influx of containers will place a burden on the terminal capacity and operations.

Megaships will bring about the hub and spoke system with the large ships moving in high density traffic lanes between the hub ports and the smaller ships connecting the hub ports with the feeder ports. What ports will become the hubs will be determined in the next decade. It appears that only those ports that invest in infrastructure and streamline its operating and labor practices in order to increase the efficiency of their container terminals will participate in the new economic activity brought about by megaships. A recent article envisioned a tough competition developing on the Eastern seaboard of the North America among the ports of New York and New Jersey, Halifax, Nova Scotia, and Virginia. The article speculated that only one port would emerge as the dominant hub. The competition is already heating up with Halifax gaining on the port of New York and New Jersey (Kannapell 1998). Although it carries a fraction
(approximately 22%) of the port of New York and New Jersey’s volume, its volume doubled in the last three years.

These changes will present a major challenge to the US ports and their effort to stay competitive in the global market. In order to succeed in this competition, further emphasis will be made on increasing port efficiency and the seamless transfer of cargo. This implies that the port authorities around the country will be ensuring that their channels are sufficiently deep to accommodate megaships and that the wharves can support larger cranes with a longer reach. Terminal operators will invest in cargo handling equipment. The investments range from buying larger cranes to introducing intelligent control systems capable of locating containers and monitoring equipment performance through a host of on-board devices and the Global Positioning System.

The objective of this paper is to look at the issue of container port efficiency, more particularly on the processes that are performed at the port in which real time information on the status of containers and loading equipment is used for intelligent port management. More particularly, the paper presents results of research in improving productivity and service quality of the container straddle carrier operation at an intermodal container port terminal. The straddle carrier is a vehicle specifically designed to receive containers from (and deliver them to) truck or rail, by straddling the truck-trailer chassis or rail car carrying containers.

Possible gains from the improved productivity of port operations, terminal access and services are likely to be shared among a number of entities. The lower transportation cost will make the shipper’s goods more competitive in the current markets or enable them to move longer distances from their origins. An increase in port traffic translates to
an increase in jobs not only for the port operator but for the regional economy as well. Using information technology to manage truck fleets and rail carriers serving the port may result in a more productive use of equipment (trucks, chassis, rail cars) and reduced congestion at the port through better scheduling of port calls by the truckers. Society may benefit from the reduced congestion and pollution.

The paper proceeds as follows. Section 2 gives a detailed description of the container terminal operations. The focus is on the straddle carrier operations. Section 3 presents the research problem and discusses the global issues of productivity and service quality and how they apply to the straddle operation. It also provides insight into the economics of the straddle operations. Section 4 discusses the methodological framework used to ascertain the magnitude of potential savings from redesigning straddle operations planning. Section 5 discusses the results of a case study. Section 6 presents conclusions and directions for future research.

2 CONTAINER TERMINAL OPERATIONS

There are two types of container moves: exports and imports. Export containers are those that arrive at the terminal by truck or rail for the outbound movement by ship, while import containers arrive by ship and are taken out of the terminal by truck or rail. Both, export and import containers can be either loaded or empty.

Conceptually, the processes at a port are: 1. delivering an export container by truck arrival to the terminal. 2. removing (or stripping) the container from the truck chassis. 3. taking the container to the yard for storage until the voyage time 4. delivering the container to the crane, and 5. loading the container into the ship. Very rarely will the
truck deliver the container directly under the crane. The processes are reversed for import containers. The distribution of empty containers is usually handled in a separate terminal area and will not be the subject of this study.

The focusing is on the truck operation in processes 1-3. The delivery and pick up by truck is quite different than that of rail because of the random nature of truck arrivals. The rail schedule is more or less known and can be timed to fall within a period of low truck activity.

The process starts when the truck hauling a loaded container approaches the terminal gate. At the state-of-the-art terminal, a grid of high-resolution digital cameras, strobes and sensors captures the images of the container and chassis numbers as the truck is driven through the grid. Based on the image, the computer character recognition (CCR) process retrieves the relevant information for the captured container number from the bill of lading in the main database. This bill had been transmitted previously via Electronic Data Interchange (EDI). If everything checks out, the driver receives a magnetic card. The card contains the entry number, equipment location, and exit authorization. The driver then proceeds to the truck slotting area. As the driver approaches the slotting booth, the attendant calls a program that assigns the truck to an individual slot and assigns the container to a yard location to which it will be delivered. (The slotting can be completely automated if not for the current labor rules that require that the slot booth be staffed.)

An instruction is sent to the straddle to come to the slot number and remove (receive or strip in the terminal parlance) the container and deliver it to the assigned yard location. For each voyage, the export containers are organized by the port of call close to the berth where the ship will be anchored. The central control system allocates several
rows (or streets) to each port of call. The containers are stored in these by height and weight criteria, and they can be stacked up to four containers high. The street location can be either fixed or dynamic (i.e., gets created as the loads are arriving at the terminal) depending on the land availability. Each container is assigned an address, i.e., an actual location in the street, by the central control system.

The process is similar for the trucks arriving at the terminal to pick up an import container. However, it has far more stringent control on authorizing the trucker to obtain custody of the container. After going through the gate, the truck with a chassis goes straight to the slotting area. The truck without a chassis goes to the chassis pool to pick one up. At the slotting booth it gets the slot assignment, while simultaneously the straddle control module assigns a straddle to retrieve the container. The straddle delivers the container to the slot and loads it onto the chassis. The driver then leaves the slotting area for the exit gate. At the gate, the chassis and the container are inspected. The inspector has a hand-held radio frequency data terminal that can transfer the inspection results immediately to the central system so that they can appear on the driver’s receipt. As the driver surrenders his magnetic card, the digital cameras take his picture and compare it with the picture of his port access card that was issued by the local port authority. (Each company driver must be authorized to enter the port.) A clerk verifies visually that the pictures match. These are then saved in the database. The system also checks that all release forms are valid and that the customer has paid freight charge to the steamship line for that container. It also verifies that all US Customs documents are in order and that this particular trucking company is indeed authorized to haul freight for that particular customer. This includes the verification of insurance limits and credit data that the trucker
has with the customer, the steamship line, and the port authority. The driver is issued a trailer interchange receipt (or equipment interchange receipt) and leaves the terminal. The receipt contains the date of visit, the type of movement (pick up/drop off), container status (empty/full), steamship line name, container number, chassis number, seal number, vessel/voyage booking number, origin port, inspection findings of damage if any, weight, entry time, exit time and the time lapsed between the entry and the exit. It also contains the names of the people involved in the transaction. The receipt is also electronically transmitted to the customer so that it knows that the truck has left the port with the container and can begin to schedule for the unloading of the container at its facility.

2.1 Straddle Operation

The focus is on operation that deals with the removal of export containers from the truck and their delivery to the yard, and delivery of import containers from the yard to the truck. The yard location of the container is known and will be considered a fixed input in the straddle operation.

The straddle, shown in Figure 1, is an eight-wheel vehicle (four wheels on each side) whose sides are connected by lateral braces at the top. It straddles the container, grabs it using an overhead crane, lifts it to the desired height (up to four times the height of a container), and drives away with it in its belly. The driver sits sideways in a cabin on the top (i.e., perpendicular to the direction of vehicle movement) in order to have a better view of the container below. The structural design, height, and forces that impact its movement require significant skill and training is required to operate it.
After the trucker has been slotted, the central control system looks at the list of all available straddles and their operational status. Based on the location of the last job, the program determines which straddle should be assigned to the truck/container and sends the instruction to the straddle via a radio frequency link. The instruction is displayed on an on-board terminal screen. The driver confirms that he has received the instruction via keyboard. The instruction has the truck slot number and the yard address. If the driver enters any of the emergency codes (e.g., mechanical failure), the container job gets re-assigned to the next available straddle.

For a delivery move, the address may be incorrect, because the container may have been moved a moment earlier by another straddle trying to access its container directly below. The driver must then search for the container number in that row. The use of a GPS system for monitoring container and straddle locations may alleviate this problem. After the job is finished, the driver sends an acknowledgment via keyboard and the new job is given to the straddle. Due to the union rules a three-man crew operates two straddles. The drivers change every hour.

3 RESEARCH PROBLEM

The terminal operator has two primary concerns when it comes to the straddle carrier operation: to increase the productivity of its straddles, while providing high quality service to its customers. The main measure of customer service is the truck service time, or the time from the moment the truck is slotted to the moment it is given a container, or having a container removed.
It is clear from the previous section that the terminal operator has realized that effective handling of real time information has a major impact on efficient handling of cargo and has made a substantial investment in the technology that uses real time information for operations management. A preliminary investigation of a candidate terminal however, indicated that despite significant technological improvements, and the improvements in maintenance plans that essentially had eliminated straddle breakdowns, the productivity and service quality remained the same. The question arose, whether the current productivity of the straddle carrier operations can be improved while either improving or maintaining the current level of service quality to trucks.

3.1 Definition of Productivity

In order to understand the economics of straddle operations, a brief discussion on productivity is given. The discussion is similar to the one presented in Morlok et al. (1995). In general, productivity in transportation is measured as a ratio of transportation output to input. (An alternate definition of productivity is a ratio of transportation output to the cost of resources used in the production process.) In this paper the productivity of straddle operation is defined as a ratio of number of containers handled (received from or delivered to the trucks) to straddle carriers used in the operation (i.e., number of lifts per straddle hour).

It is commonly misconstrued that in order to improve productivity one needs to degrade service quality. While this may be true for some types of transportation facilities where an increase in throughput can only be achieved by increasing delays, and thus causing a degradation in service, there can be an operating regime that may result in the
improvements in both productivity and service quality. The following discussion illustrates this premise.

3.1.1 The Port Operator’s Perspective

A simple model was developed with the purpose of providing insights in the relationship between the cost of operation and the operating parameters such as time or speed. It assumes that \( Q \) containers need to be moved by straddles within an operating period (e.g., one hour). Each container either must to be stripped from the truck or delivered to the truck. Either move has several components, each requiring certain time for completion. It has a loading component or lift time \( (T_l) \), a one-way movement (and related travel time \( (T_m) \)) between the truck slotting area and the yard location, and an unloading component or drop time \( (T_d) \). In addition to these, a typical straddle operation consist of a certain time for empty straddle repositioning between a strip and a delivery move \( (T_e) \), and idle time between the completion of one job and the start of the next job \( (T_i) \). Essentially, the time between the moment a straddle has received an assignment until it becomes available for a new assignment can be thought of as cycle time \( (T_c) \).

\[
T_c = T_l + T_m + T_d + T_e + T_i
\]  

(1)

Given the fact that a straddle can carry only one container per cycle, the number of straddles \( N \) required in the operation during a given period is given as:

\[
N = \left( Q \times T_c \right)^+ \tag{2}
\]

where the plus sign indicates that the number in the brackets is rounded up to the nearest integer. Eq. 2 indicates that if the number of containers is kept constant, the number of vehicles will decrease with a decrease in the cycle time.
The travel time is a function of distance \((L_c)\) and average speed \((V_m)\), the straddle carrier travels with a loaded container. The speed includes the speed during acceleration, cruise and deceleration phases of the movement:

\[
T_m = \frac{L_c}{V_m}
\]  

(3)

Also, for the empty movement, the travel time is a function of distance \((L_e)\) and average speed \((V_e)\) the straddle travels with an empty container. Its is given as:

\[
T_e = \frac{L_e}{V_e}
\]  

(4)

The operator’s cost consists of the fleet ownership and maintenance cost, as well as operating cost. If the fleet size decreases the ownership and maintenance cost will decrease as well. Since the crew size is related to the fleet size, the labor cost will also be reduced. The operating cost, however, will increase because a smaller number of vehicles will have to move faster to complete the assignments. This translates to an increase in operating cost due to the increased fuel consumption, wear and tear of the tires and the engine.

The relationship between the fleet ownership cost and the cycle time, shown in Part a of Figure 2, indicates that the fleet cost will decrease when the cycle time is reduced. It also shows that the operating cost increases as the cycle time decreases. The minimum total cost may not necessarily coincide with the value of the cycle time for which the fleet and operating costs are equalized. (The same graph will hold if the \(x\) axis were to present the increasing speed instead of decreasing cycle time.) The graph is developed by assuming that 300 containers move during one hour, and the fleet size requirement and fleet and cost are then calculated for the cycle times between 15 and 3
minutes. The cost values used for calculations are similar to those used for calculating the savings in the results section below.

### 3.1.2 The Shipper’s Perspective

For the shipper, the time goods spend in transit represents the cost of capital tied up in the shipment, a form of inventory cost. The shipment’s value directly impacts the shipper’s choice of transportation service; the higher value will induce the shipper to select faster modes in order to decrease the inventory cost. One of the shipper’s primary concerns is to move goods from an origin to a destination so as to minimize the transit time.

As transit time is reduced, inventory costs are reduced as well. The change in shipper’s inventory costs resulting from a decrease in the cycle time is shown in Part b of Figure 2. The figure also shows the total combined operator and shipper cost. Note that for this particular example, the minimum total cost occurs at a generally higher level of service (lower cycle time) than the one that minimizes the operator’s cost.

It is important to note that moving toward the optimal value of the cycle time would make both the operator and the shipper better off: the operator will have minimized its cost, while the shipper will have received improved service. Operating a fleet size that is larger than the optimum may not only result in a wasteful use of resources for the operator, but also may translate into a poor level of service for the shipper.

### 3.4 Economics of Straddle Operation
Three components of the cycle time (Eq. 1) can be considered constant. Usually a fixed amount of time is required for a straddle to lift or drop a container. Since the container locations in the yard are determined by the ship loading/unloading and are known before the straddle operation begins (i.e., determined externally and are thus treated as fixed input to the model), and since all containers must be moved, the distance (and time) the straddles travel carrying loaded containers between the yard and the slotting area is also fixed. The only variables that will impact the duration of the cycle time, and thus the truck service time is the time the straddles move empty between jobs ($T_e$) and the time they sit idle waiting for an assignment ($T_i$).

3.4.1 Potential for Improvements - Reduction in Operating Cost and Truck Service Time

The manner in which the straddles are assigned the jobs of moving containers is of critical importance for the productivity (and thus cost) and customer service quality. The following example is developed to demonstrate that an intelligent assignment will decrease the operator’s cost as well as improve the customer service. The example, shown in Part a of Figure 3, has two loaded containers to be delivered from the yard to the trucks in the slotting area. Assume that truck 1 (T1) arrived and was slotted at 8:00 a.m. while truck 2 (T2) arrived one minute later. Truck 1 is picking up container 1 (C1), while truck 2 needs to pick up container 2 (C2). Straddle 1 (S1) has just finished a job and is ready for the new assignment, while straddle 2 (S2) will be available for the new assignment in one minute. If the straddles are assigned on the first-come-first-serve (or the closest container) basis, straddle 1 will be assigned to move container 1 while straddle 2 will be
assigned to move container 2. Assuming an average speed of 10 mph, the total distance and time of the empty moves for this assignment would be 0.6 miles and 216 sec. The figure shows that if the assignment decision was postponed for 1 minute and then both straddles assigned simultaneously in order to minimize the combination of travel distance and truck service time, a superior solution would have been reached. This solution assigns straddle 1 to move container 2 and straddle 2 to move container 1. It has the total distance of 0.4 miles and combined travel and wait time of 204 seconds (144 plus 60). As the result of this assignment the total empty travel distance has been reduced by 33% while the truck service time decreased by 6%. Therefore, redesigning the way the straddles are assigned jobs provides an opportunity to improve the productivity and service quality of the straddle carrier operations.

3.4.2 The Trade-Off between Operator Cost and Truck Service

Looking at Part b of Figure 2, the optimal cycle time that minimizes the operator’s cost in on the left of the one that minimizes the total combined operator and shipper costs. The operator can reduce costs by moving toward this optimum. That can be done in two ways. First, the empty straddle distance can be reduced through a better assignment method that would match strip and delivery moves. Looking for the matching possibilities within a time window may increase the straddle idle time and thus the duration of the cycle time. Second, the removal of straddles from the operation will increase the duration of the cycle time.

The following example, shown in Part b of Figure 3, may yield even more dramatic cost savings for the operator while keeping the customer time either constant or
slightly worse. Here, container C1 needs to be stripped and delivered to the yard location L1. Three minutes later a truck (T2) is slotted to receive container C2.

Two solutions to this scheduling problem and their distance and time are shown in the figure. The assignment scheme (S1-C1 and S1-C2) eliminates one straddle from the operation while performing the jobs with a marginal increase in the truck service time of 36 sec. The removal of a straddle would certainly result in a substantial reduction in the operator’s ownership and maintenance cost.

4 METHODOLOGY

A study was undertaken with the purpose of answering the specific question:

• Can the operator reduce either the fleet ownership or operating costs, or both, by using the smaller number of straddles while maintaining certain service quality?

If the answer to the question was yes, then the magnitude of the possible gains needed to be estimated as well. A related question is whether is it necessary for the operator to redesign the straddle carrier operations planning modules to extract the savings?

The overall approach to answering this question is shown in Figure 4. First, the data on a representative operation were collected. The case study was based on the actual operation of a Port New York/New Jersey container terminal. A schematic layout of the terminal area is shown in Figure 5. The case study was based on a 5-day operation in October and November 1997. The operation was representative of the fluctuating traffic volume that varied from heavy (with 739 container arrivals) to light (with 523 containers). It also reflects the peaking nature of seasonal traffic. Since the size of the fleet is governed by the peak demand, any reduction in the fleet ownership cost due to the
elimination of a straddle from the peak period service can be maintained in the off-peak period as well.

The record for each individual container movement was obtained from the terminal operator as a machine-readable file. Each record had the container arrival number, arrival time, type of movement (e.g., pick-up/delivery), container ID number, yard location, assigned straddle ID, and job competition time.

These records represent the data input into a straddle assignment module. The productivity and service quality measures, more specifically, total straddle distance, and average truck service time were estimated for the original baseline operation and the redesigned operation. An optimization model with animation capability, shown in Figure 6, was developed to display the container arrivals and yard locations and the actual and optimized assignment of straddles to containers.

4.1 The Logic of the Assignment Algorithms

The main part of this modeling effort developed and evaluated the algorithms for assigning straddles to containers. The discussion from the previous section illustrates the fact that the manner in which the straddles are assigned container jobs impacts the cost and service quality of operation. An extensive literature review was performed to identify if similar work has been done elsewhere. The review revealed only two papers. Kim et al. (1995) presented a load sequencing problem of delivering export containers to be loaded onto a ship in which the total travel distances of straddle carriers in the yard was minimized. A mathematical model and a heuristic were formulated for multiple straddle carriers as well as a single carrier. Ballis and Abacoumcin (1996) developed a computer
simulation model with on-screen animation graphics to simulate the operations of
drives calling trucks to be served directly in the container yard. They used the model to
evaluate different terminal configurations.

In marked contrast, the algorithms develop in this research considered both the
operator’s costs and the truck service time cost. In general, the problem of assigning
straddles to containers can be formulated as the assignment problem, a mathematical
programming problem. It is of the following form:

\[ \text{Min } Z = \sum_{i} \sum_{j} c_{ij} x_{ij} \]  \tag{5} 

s.t.

\[ \sum_{i=1}^{n} x_{ij} = 1, \text{ for } j=1,2,\ldots,n \]  \tag{6} 

\[ \sum_{j=1}^{n} x_{ij} = 1, \text{ for } i=1,2,\ldots,n \]  \tag{7} 

where:

\( i,j = \) indices,

\[ x_{ij} = \begin{cases} 1 & \text{if the feasible assignment of container } i \text{ to straddle } j \text{ is selected} \\ 0 & \text{otherwise} \end{cases} \]  \tag{8} 

\( c_{ij} = \) cost of the \((i,j)\) assignment

Equation 5 is an objective function that minimizes costs. Constraints 6 and 7 are typical
assignment problem restrictions that ensure that a straddle can be assigned to only one
container and vice versa.
Various heuristics can also be used to provide a good solution to the problem. One of the obvious approaches (Approach 1) would be simply to go down the list of containers and assign them to the first available straddle and remove this pairing from further consideration. Another approach (Approach 2) would be to list all pairings between a container and all available straddles and rank these pairings in the ascending order of their cost. Then, going down the list of containers, for each container the least cost pairing is chosen and the container-straddle pair is removed from further consideration. The most efficient method would be to solve the assignment problem (Eq. 5-8) to optimality by looking at all pairings simultaneously. This can be done efficiently using the Hungarian method (Winston 1995).

The following example demonstrates the differences in the approaches. In the example, there are four (4) containers to be moved. There are four (4) straddles in the operation and they are currently occupied but will be available for assignment within a short period of time. They will be available in the following order A,B,C and D. The system knows the exact location where the straddles will complete their jobs and become available for a new assignment. The matrix with distances between the location of a straddle’s last job completion and the location of containers to be moved is shown in Part a of Table 1. Part b of Table 1 shown the solution of the algorithms when only straddle travel distance is considered. Solving the problem to optimality using the Hungarian method results in a 10% reduction in travel distance compared to the results of Approach 1, and approximately 3% compared to the second best result from Approach 2.

4.2 Algorithms
Based on the above, the following algorithms were considered:

Original - this algorithm assumes the first-truck-in-first-truck-out principle. Thus, the emphasis is on truck service and no attempt is made to minimize the straddle distance by pairing container stripping and delivery moves.

Baseline – the algorithm recognized that the straddle distance must to be minimized. This is accomplished by employing the following rules:

1. a strip move should follow a delivery move,
2. the straddle that has just completed a delivery will strip the truck closest to its last delivery move, and
3. the straddle that has just completed a strip move will be assigned the closest delivery move according to a pre-specified search pattern of the yard sectors.

Algorithm 1. Each time a straddle becomes available a list of its assignments to all containers to be moved is generated and the least cost assignment is selected. If more than one straddle is available, the algorithm picks one straddle arbitrarily to start the assignment process. While the algorithm selects the best assignments for each straddle, the arbitrary selection of straddles does not guarantee the optimality of solution.
Algorithm 2. This algorithm solves the assignment problem (Eqs. 5-8) to optimality using the Hungarian method. The algorithm is run each time a new container move is requested.

Algorithm 3. This is a more complex version of Algorithm 2, because the algorithm attempts to find the minimum cost assignment by considering not only the next straddle move but also the move that will occur immediately after that. (It looks 2 steps ahead; not only what the next optimal assignment is but also how this assignment impacts the subsequent moves.) When a straddle is available in the truck slotting area, and there are several containers waiting to be stripped, a series of the straddle assignments to all containers is performed first. The time of delivering these containers to their respective yard locations is estimated. Then, the distances from the yard locations to the locations of the containers waiting to be delivered from the yard to the trucks in the slotting area are calculated. A new assignment is then performed that considers the total distance and time of both assigning the straddles to the stripped moves, and then the assignment of straddles to the delivery moves.

The Original algorithm was taken out of consideration because it did not consider the operator’s costs. The remaining four algorithms were implemented within a computer model.
5 RESULTS OF THE ANALYSIS

The results, shown in Table 2, indicate that the use of Algorithms 1, 2 and 3 would result in a substantial reduction in the straddle travel distance (and thus operating cost due to the less fuel consumed and less tire and engine wear) over the Baseline operation. The average reduction is in the 9%\(^1\) to 23%\(^2\) range and has been accompanied by the 1-2% increase in the average truck service time. However, it should be noted that Algorithm 2 succeeded in reducing the distance without increasing the truck time for half of the time (e.g., Days 2, 3 and 6). For this reason, Algorithm 2 is deemed the most promising. Also, it requires less computational effort than Algorithm 3 in reaching the optimal solution.

Next, the impact of reducing the number of straddles in the operation on the distance and average truck service time was evaluated. Two algorithms, the Baseline and Algorithm 2, modeled the Day 2 operation (with 718 containers) using progressively smaller number of straddles. The results, shown in Part a of Table 3, indicate how the straddle distance and average truck service time changed when the number of straddles was reduced from 14 to 8. The results are very revealing. In general, when a straddle is removed from an efficient operation its workload needs to be carried out by the remaining straddles, and it is expected that the total straddle distance and the average truck time would likely increase. Note that just the opposite happened with the distance when a straddle was removed in the Baseline operation; running the operation with 13 straddles reduced the total distance by 1% (from 298 to 295 miles) while the truck service time increased 5% (from 6.3 to 6.6 min.). This means that the Baseline operation is inherently

\(^1\) For Algorithm 1 and Day 2 with 718 and Day 6 with 523 container arrivals
inefficient with an unnecessarily large number of straddles literally interfering with each other. The objective of increasing the efficiency of operation was being eluded by the straddles “snatching” the loads from one another and thus eliminating the opportunity for matching the receiving and delivery moves.

When a straddle was removed from the Algorithm 2 operation, the distance remained essentially the same while the average truck service time increased 3%. The removal of 2 straddles (and thus running the operation with 12 straddles) resulted in an insignificant increase in the distance while the truck service time increased 8%. The operation could not be run with less than 10 straddles without causing the truck service time to exceed 20 minutes. Such a high service time is deemed unacceptable in practice. Finally, the comparison of Algorithm 2 with 12 straddles and the Baseline operation with 14 straddles revealed that Algorithm 2 had 16% less travel distance and 9% higher truck service time.

The above results imply two conclusions. The operator can reduce its fleet ownership and operating costs by running the Baseline operation with 13 instead of 14 straddles while only marginally increasing the truck service time. This can result in the daily cost savings of $913\textsuperscript{3}. Running the operations with 12 straddles would result in the cost savings of $1,830. If it were to implement Algorithm 2 running 12 straddles, the operator would have a daily cost saving of $1,866 compared to the Baseline.

6 CONCLUSIONS AND FUTURE RESEARCH

\textsuperscript{2} For Algorithm 2 and 3 and Day 3 with 711 container arrivals
\textsuperscript{3} The purchase price of a new straddle of $1 million with the useful life of 15 years, 10% rate of return, and 260 operating days per year translates in the daily ownership cost of $505 per straddle. The operating cost is assumed to be $1 per mile. The operator's
The port terminal operator clearly recognizes the value of using real time information for increasing the productivity of its straddles and improving the quality of service to its customers. The results of the analysis indicate the potential for significantly improving the productivity of the straddle operation. The results indicate that the use of Algorithms 2-3 in straddle assignment would result in a substantial reduction in the straddle distance (and thus the operating cost) over the Baseline operation. In the case study presented in this paper, the distance was reduced on average by 19% and this reduction was accompanied by an average increase of 1% in the truck service time.

The annual operator’s cost savings are conservatively estimated to be in the $237,000 - $475,000 range. These savings can be extracted if the operator were to reduce the number of straddles in operation from 14 to 13, and then to 12, and continue to run the Baseline algorithm. The annual operator’s cost savings increase substantially if the operator sells the straddle carriers that are removed from the operation. The savings are estimated to be in the $987,419 - $1,975,608 range. These savings jump to the $3,370,356 - $6,741,480 range if the operator invests proceeds from the sale at an interest rate of 10%. The removal of straddles would not require an investment to redesign the straddle assignment and control software.

The operator can further reduce the cost by additional $10,000 by using Algorithm 2 and operating only 12 straddles. However, these savings would be somewhat reduced...
since the straddle control algorithm had to be re-designed and re-programmed. Although, it is recognized that the investment in the design and development of a new straddle control module may be significant, the estimated levels of savings are more than sufficient to justify this investment. The redesigned operation will benefit both the terminal operator and the shipper, because the savings can be used to further improve service quality and the productivity of other processes at the terminal.

The future research efforts should include in the model the random equipment breakdowns and other emergencies (e.g., bad weather) that may impact the operation. The model output needs to be captured to better analyze the straddle productivity statistics on hourly basis.

The current research focused solely on trucks. The productivity of the whole pool of straddles should be analyzed. This should include the straddles servicing on-dock rail, the cranes during ship loading and unloading as well as re-warehousing of containers in the yard.

\[9 \text{ Baseline algorithm with 12 straddles, and the 13}^{\text{th}} \text{ and 14}^{\text{th}} \text{ straddle were sold for $750,000 each, with the proceeds invested at 10\% interest rate.}\]
ACKNOWLEDGMENT

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REFERENCES


2. Kannapell, A. “If only one east coat port can be No. 1, which one will it be?”, New York Times- New Jersey Section, December 14, 1997.


Table 1. Example Problem

a. Distance matrix

<table>
<thead>
<tr>
<th>Containers</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>6</td>
<td>5</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>8</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>10</td>
<td>9</td>
<td>6</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>9</td>
<td>13</td>
<td>9</td>
</tr>
</tbody>
</table>

b. Potential assignments of straddles to containers

<table>
<thead>
<tr>
<th>Approach 1</th>
<th>Approach 2</th>
<th>Hungarian</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-A</td>
<td>1-B</td>
<td>1-A</td>
</tr>
<tr>
<td>2-B</td>
<td>2-D</td>
<td>2-C</td>
</tr>
<tr>
<td>3-C</td>
<td>3-C</td>
<td>3-D</td>
</tr>
<tr>
<td>4-D</td>
<td>4-A</td>
<td>4-B</td>
</tr>
</tbody>
</table>

Distance = 32  Distance = 29  Distance = 28
Table 2. Results of Operation with 14 straddles

<table>
<thead>
<tr>
<th>Days (# Jobs)</th>
<th>Performance Measure</th>
<th>Baseline</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (739)</td>
<td>Straddle Travel Distance (miles)</td>
<td>333</td>
<td>293</td>
<td>274</td>
<td>279</td>
</tr>
<tr>
<td></td>
<td>(% change)</td>
<td>-12</td>
<td>-18</td>
<td>-18</td>
<td>-16</td>
</tr>
<tr>
<td></td>
<td>Av. Truck Service Time (min/truck)</td>
<td>6.2</td>
<td>6.1</td>
<td>6.4</td>
<td>6.3</td>
</tr>
<tr>
<td></td>
<td>(% change)</td>
<td>-2</td>
<td>3</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>2 (718)</td>
<td>Straddle Travel Distance (%)</td>
<td>298</td>
<td>273</td>
<td>249</td>
<td>246</td>
</tr>
<tr>
<td></td>
<td>Av. Truck Service Time (%)</td>
<td>6.3</td>
<td>6.5</td>
<td>6.3</td>
<td>6.5</td>
</tr>
<tr>
<td>3 (711)</td>
<td>Straddle Travel Distance (%)</td>
<td>307</td>
<td>263</td>
<td>238</td>
<td>236</td>
</tr>
<tr>
<td></td>
<td>Av. Truck Service Time (%)</td>
<td>6.1</td>
<td>6.2</td>
<td>6.0</td>
<td>6.2</td>
</tr>
<tr>
<td>4 (612)</td>
<td>Straddle Travel Distance (%)</td>
<td>262</td>
<td>237</td>
<td>208</td>
<td>205</td>
</tr>
<tr>
<td></td>
<td>Av. Truck Service Time (%)</td>
<td>5.6</td>
<td>6.0</td>
<td>5.8</td>
<td>5.8</td>
</tr>
<tr>
<td>5 (558)</td>
<td>Straddle Travel Distance (%)</td>
<td>226</td>
<td>204</td>
<td>187</td>
<td>186</td>
</tr>
<tr>
<td></td>
<td>Av. Truck Service Time (%)</td>
<td>5.9</td>
<td>6.1</td>
<td>6.1</td>
<td>6.0</td>
</tr>
<tr>
<td>6 (523)</td>
<td>Straddle Travel Distance (%)</td>
<td>218</td>
<td>198</td>
<td>177</td>
<td>175</td>
</tr>
<tr>
<td></td>
<td>Av. Truck Service Time (%)</td>
<td>5.8</td>
<td>5.8</td>
<td>5.8</td>
<td>5.7</td>
</tr>
<tr>
<td>Total (3861)</td>
<td>Weighted Change in Travel Distance (%)</td>
<td>-11</td>
<td>-19</td>
<td>-19</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weighted Change in Av. Truck Service Time (%)</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>

10 (Baseline distance - Algorithm distance)/Baseline distance
11 (Baseline truck service time - Algorithm truck service time)/Baseline truck service time
12 The change in the distance was weighted by the number of containers
13 The change in the truck time was weighted by the number of containers
Table 3. Impacts of reducing number of straddles on straddle distance and truck service time (Day 2 with 718 containers)

a. for each algorithm

<table>
<thead>
<tr>
<th>Straddles</th>
<th>Productivity</th>
<th>Distance (miles)</th>
<th>Change</th>
<th>Time (min)</th>
<th>Change</th>
<th>Distance (miles)</th>
<th>Change</th>
<th>Time (min)</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Baseline</td>
<td></td>
<td>Algorithm 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>89.8</td>
<td>259</td>
<td>-13</td>
<td>20.0</td>
<td>222</td>
<td>8</td>
<td>--</td>
<td>6.3</td>
<td>--</td>
</tr>
<tr>
<td>9</td>
<td>79.8</td>
<td>270</td>
<td>-9</td>
<td>13.0</td>
<td>106</td>
<td>9</td>
<td>--</td>
<td>6.6</td>
<td>--</td>
</tr>
<tr>
<td>10</td>
<td>71.8</td>
<td>278</td>
<td>-7</td>
<td>9.7</td>
<td>54</td>
<td>10</td>
<td>--</td>
<td>7.0</td>
<td>--</td>
</tr>
<tr>
<td>11</td>
<td>65.3</td>
<td>282</td>
<td>-5</td>
<td>7.9</td>
<td>25</td>
<td>11</td>
<td>--</td>
<td>7.0</td>
<td>--</td>
</tr>
<tr>
<td>12</td>
<td>59.8</td>
<td>288</td>
<td>-3</td>
<td>7.0</td>
<td>11</td>
<td>12</td>
<td>--</td>
<td>7.0</td>
<td>--</td>
</tr>
<tr>
<td>13</td>
<td>55.2</td>
<td>295</td>
<td>-1</td>
<td>6.6</td>
<td>5</td>
<td>13</td>
<td>--</td>
<td>6.6</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>51.3</td>
<td>298</td>
<td>--</td>
<td>6.3</td>
<td>--</td>
<td>14</td>
<td>--</td>
<td>6.4</td>
<td>--</td>
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</table>

b. comparison of Algorithm 2 and Baseline

<table>
<thead>
<tr>
<th>Straddles</th>
<th>Distance (miles)</th>
<th>Change</th>
<th>Time (min)</th>
<th>Change</th>
<th>Distance (miles)</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Baseline</td>
<td></td>
<td>Algorithm 2</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>259</td>
<td>4</td>
<td>20.0</td>
<td>215</td>
<td>8</td>
<td>--</td>
</tr>
<tr>
<td>9</td>
<td>270</td>
<td>8</td>
<td>13.0</td>
<td>103</td>
<td>9</td>
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</tr>
<tr>
<td>10</td>
<td>278</td>
<td>11</td>
<td>9.7</td>
<td>52</td>
<td>10</td>
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</tr>
<tr>
<td>11</td>
<td>282</td>
<td>13</td>
<td>7.9</td>
<td>23</td>
<td>11</td>
<td>--</td>
</tr>
<tr>
<td>12</td>
<td>288</td>
<td>16</td>
<td>7.0</td>
<td>9</td>
<td>12</td>
<td>--</td>
</tr>
<tr>
<td>13</td>
<td>295</td>
<td>18</td>
<td>6.6</td>
<td>3</td>
<td>13</td>
<td>--</td>
</tr>
<tr>
<td>14</td>
<td>298</td>
<td>20</td>
<td>6.3</td>
<td>-2</td>
<td>14</td>
<td>--</td>
</tr>
</tbody>
</table>

14 (718 containers/ No. of Straddles in Operation)
15 (Baseline distance with N straddles - Baseline distance with 14 straddles)/(Baseline distance with 14 straddles)
16 (Baseline truck service time with N straddles - Baseline truck service time with 14 straddles)/(Baseline truck service time with 14 straddles)
17 (Algorithm 3 distance with N straddles - Algorithm 3 distance with 14 straddles)/(Algorithm 3 distance with 14 straddles)
18 (Algorithm 3 truck service time with N straddles - Algorithm 3 truck service time with 14 straddles)/(Algorithm 3 truck service time with 14 straddles)
19 (Baseline distance with N straddles - Algorithm 3 distance with 14 straddles)/(Algorithm 3 distance with 14 straddles)
20 (Baseline truck service time with N straddles - Algorithm 3 truck service time with 14 straddles)/(Algorithm 3 truck service time with 14 straddles)
21 (Algorithm 3 distance with N straddles - Algorithm 3 distance with 14 straddles)/(Algorithm 3 distance with 14 straddles)
22 (Algorithm 3 truck service time with N straddles - Algorithm 3 truck service time with 14 straddles)/(Algorithm 3 truck service time with 14 straddles)
Figure 1. Straddle carrier
Figure 2. Relationship between costs and cycle time

a. Impact of cycle time on fleet ownership and operating costs

![Total Cost vs Cycle Time](image1)

- Fixed Cost
- Op. Cost
- Total Cost

b. Impact of cycle time on total combined operator and shipper cost

![Total Combined Carrier and Shipper Cost](image2)

- Shipper Cost
- Carrier Cost
- Total Cost
Figure 3. Assignments of straddles to containers

a. minimizing the combination of empty straddle distance and truck service time

<table>
<thead>
<tr>
<th>Assignment</th>
<th>Distance (miles)</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-C1 and S2-C2</td>
<td>0.5+0.1 = 0.6</td>
<td>180+36=216</td>
</tr>
<tr>
<td>S1-C2 and S2-C1</td>
<td>0.3+0.1 = 0.4</td>
<td>108+36+60=204</td>
</tr>
</tbody>
</table>

b. minimizing the fleet size

<table>
<thead>
<tr>
<th>Assignment</th>
<th>Distance (miles)</th>
<th>Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1-C1 and S2-C2</td>
<td>0.1+0.3 = 0.4</td>
<td>144</td>
</tr>
<tr>
<td>S1-C1 and S1-C2</td>
<td>0.1+0.4 = 0.5</td>
<td>36+144=180</td>
</tr>
</tbody>
</table>
Figure 4. Methodological framework

Temporal Data on Container Demands for Pick-Up and Delivery at the Terminal

Current Straddle Operation - Baseline

Current Travel Distance

Current Service Quality

Optimized Straddle Operations - Algorithms 1-3

Optimized Travel Distance

Optimized Service Quality

Minimum Service Quality for Delivery and Pick-Up

Potential Savings
Figure 5. Terminal layout
Figure 6. Starting screen for the animation of the optimization model