Impact of Truck Arrival Information on System Efficiency at Container Terminals

Wenjuan Zhao and Anne V. Goodchild

This paper quantifies the benefits to drayage trucks and container terminals from a data-sharing strategy designed to improve operations at the drayage truck–container terminal interface. This paper proposes a simple rule for using truck information to reduce container rehandling work and suggests a method for evaluating yard crane productivity and truck transaction time. Various scenarios with different levels of information quality are considered to explore how information quality affects system efficiency (i.e., truck wait time and yard crane productivity). Different block configurations and truck arrival rates are also investigated to evaluate the effectiveness of truck information under various system configurations. The research demonstrates that a small amount of truck information can significantly improve crane productivity and reduce truck delay, especially for those terminals operating near capacity or using intensive container stacking, and that complete truck arrival sequence information is not necessary for system improvement.

Marine container terminals are important intermodal interfaces between marine and surface transportation. Efficient operation of container terminals can improve port productivity, reduce drayage truck wait time, and reduce the social cost of the intermodal system. Recently, container terminals on the West Coast of the United States have improved operations by automating gate transactions, establishing gate appointment systems, and extending gate hours. Some of those measures have been effective; others have not. For example, some gate appointment systems have been reported to have not reduced truck queuing or transaction times (*1*).

This research addresses the problem of whether and how truck arrival information can be used to improve the drayage truck–container terminal interface, using a mechanism that is aligned with both the container terminal and drayage trucks' incentive schemes. This research also considers how to use truck information to improve import container retrieval operation. The objective of this research is to identify the information required to achieve a significant improvement in truck transaction time and terminal handling efficiency and evaluate the impact of different yard configurations on the effectiveness of this truck information.

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LITERATURE REVIEW

There is a wide body of literature that considers improvements to marine terminal operations; only research closely related to the present study is described here. Holguín-Veras and Walton studied improving the level of service for containers with a higher priority at container terminals by implementing priority systems (*2*). They considered a group of priority systems, including locating high-priority containers on special hatches, storing them on chassis, or using automatic equipment identification devices at gates and assessed the impacts on different users using a computer simulation. They concluded that the implementation of priority service significantly improves the performance of high-priority containers without overly penalizing the level of service for low-priority containers or the terminal's operating costs.

Some researchers have studied how to reduce truck transaction time at a container yard by better utilizing the current system or improving operational methods. Huynh and Walton studied regulating the number of trucks that can enter the terminal to make the gate appointment system effective (*3*). They proposed a methodology that is a combination of mathematical formulations and computer simulations to determine the maximum number of trucks allowed to enter the terminal while maintaining a target truck transaction time. Kim et al. studied sequencing trucks for container transfer operations to minimize truck delay at the container yard (*4*). A due time for transfer service is assumed for each truck, and the delay of a truck beyond the due time results in a penalty cost. A dynamic programming model was developed to minimize the total delay cost, and a learning-based method for deriving decision rules was suggested to solve the model. Kim and Kim also studied optimizing the size of the terminal storage space and number of yard cranes for handling import containers and developed an analytical cost model that addresses terminal space cost, the investment and operating cost of yard cranes, and the waiting cost of outside trucks (*5*). In that model, truck cost was estimated based on truck transaction time, and transaction time was evaluated by formulating the container transfer operation for trucks as an M/G/1 queuing model.

The most closely related paper was written by Jones and Walton (*6*). They studied whether and how more accurate and timely information about the departure times of containers can be used to more efficiently and effectively manage import containers in stacked storage. They developed an event-based simulation model capturing the interactions among a port's various subsystems to evaluate the impact of using this departure information on the number of container rehandles, ship turnaround time, and average cost per container moved through the port. Their study assumes that the import container departure time has been acquired by the terminal operator prior to the ship unloading, and they used this information to determine the container stacking sequence on the yard during the ship unloading process. With the same overall intent of reducing rehandling activity, Jones and Walton also studied a different component of terminal operations (unloading containers to stacks) and solved a different mathematical problem. This paper assumes that truck arrival time is obtained after import containers have been stored in the yard, mimicking the practice of having real-time rather than strategic information.

Zhao and Goodchild addressed the problem of using truck arrival information to reduce import container rehandling work at the terminal (*7*). The research presented in this paper develops that work for import containers, identifying the improvements in truck transaction time and yard crane productivity from the same strategy proposed previously, which uses truck arrival information to reduce container rehandling work (*7*).

The paper is organized as follows. The first section introduces research assumptions, basic scenarios, and operation rules for using truck information. The next sections describe the method used to evaluate crane productivity and truck transaction time and provide the results of numerical experiments. Conclusions are then presented.

ANALYSIS FRAMEWORK

Assumptions and Scenario Definitions

This study considers the retrieval of import containers by the yard crane within a container block to serve drayage trucks (Figure 1). Several assumptions are made:

1. The yard crane serves the drayage trucks using the first-in-first-out (FIFO) rule;
2. Rehandled containers are relocated to a slot within the same bay;
3. No additional containers are added to the block during the container pick-up process;
4. Truck arrivals can be modeled by a Poisson process;
5. The location of the container requested is randomly distributed;
6. The location of each container in the block is known in advance and tracked throughout the pickup process; and
7. Truck arrival information includes the container to be retrieved.

Under the second assumption, container bays are independent of each other; thus, the analysis for container rehandling work is performed for one bay by one crane, and the result is the same for any bay within the block. This research on the operation of one yard crane within a container block can be extended to the whole container yard, with multiple yard cranes given identical assumptions for each crane. In that situation, the container yard can be segregated into multiple subareas, with each subarea assigned to one yard crane and with each crane modeled as an independent system. The third assumption posits that containers unloaded from arriving ships are not stored on top of existing containers unloaded from ships that had previously arrived. Mixing containers with different arrival times in such a way causes excessive container rehandling work and should be avoided. If such a mixing strategy exists, this research would underestimate the number of rehandles, and the actual benefit to the terminal and trucks would be larger than the estimate presented in this paper.

Truck information is considered for container retrieval within the same bay. Currently, terminals have limited knowledge of truck arrival sequences. For those terminals in which a gate appointment system is implemented and appointments are met, the arrival time window of trucks is available and could be translated into arrival groups. If a much narrower appointment time window were adopted or if the terminal tracked the real-time location of each truck and could estimate arrival times, a more complete truck arrival sequence would be available. On the basis of the amount of known truck information

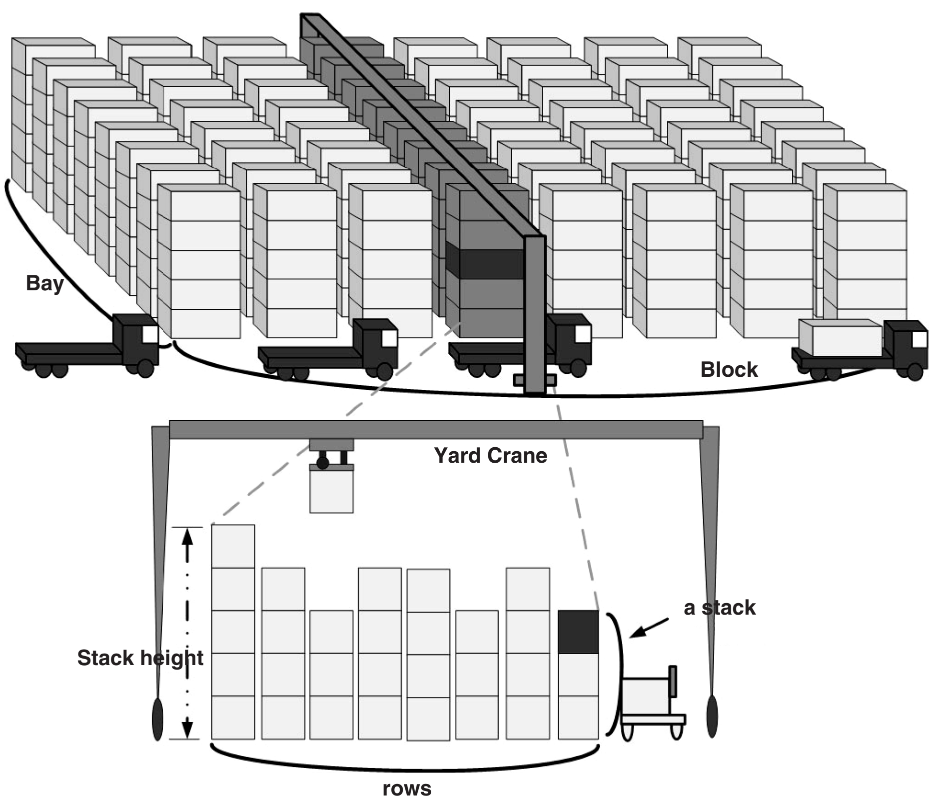

FIGURE 1 Container block configuration and terminology.

TABLE 1 Scenario Definitions

Scenario	Definition
No truck information	No truck information is available.
Static group information	The terminal knows in which of several groups a truck will arrive, but not the exact order of truck arrivals within any group. For example, trucks can be assigned to one of two groups, A or B. The terminal knows which trucks are in Group A and which trucks are in Group B, and that all trucks in Group A will arrive before any truck in Group B. But the exact arrival sequence of trucks within Group A or B is not available. "Static" means information is provided before any truck arrives, and is not updated over time.
Static partial sequence	The terminal knows in which of several groups a truck will arrive, and the exact order of truck arrivals for the first group. Information is not updated over time.
Dynamic group information	The terminal knows in which of several groups a truck will arrive, and the group information is updated over time. Every time all the trucks in the first group are exhausted, the terminal receives information about the arrival group of the next *N* trucks, where *N* is the number of trucks in the original first group. Figure 2*a* is provided as an example. After the two trucks in group A have been served, information about a new arrival group of the next two trucks becomes available, which emerges from Group B and forms a new Group A, with its size equal to the old Group A. The updating process continues until no trucks remain in Group B.
Scenario with dynamic partial sequence	The terminal knows in which of several groups a truck will arrive, and the arrival sequence of the first group. After a truck in the first group is served, information about the first truck within the next group becomes available, and this truck joins the first group. Take Figure 2*b* as an example. After Truck 1 has been served, information about the first truck in Group B becomes available, and Truck 3 enters Group A. The size of Group B shrinks. The updating process continues until no trucks remain in Group B.
Scenario with complete sequence	The complete sequence of truck arrivals is known.

and whether the information is static or updated in real time, six scenarios are defined to represent situations with various information qualities (see Table 1 and Figure 2). A more general definition of scenarios with regard to truck information quality and a detailed explanation is presented in previous work by the authors (*7*).

Truck arrival information is useful in reducing number of container rehandles by carefully determining the storage location of rehandled containers. The next subsection introduces the rules of container relocation for this strategy. This information is contained in the authors' previous work (*7*).

Rules for Using Truck Information

Without truck arrival information, rehandled containers can be relocated to the nearest available stack. This strategy minimizes the travel distance of the yard crane and is used widely in container terminals. This strategy will be referred to as the "nearest relocation rule" and applied to the scenario with no truck information for container relocation.

The revised difference heuristic is applied to all the other scenarios with some truck information. This rule is extended from Aydin's work (*8*). Aydin proposed the difference heuristic algorithm to address the container relocation problem given a complete truck arrival sequence; this algorithm is improved to address the problem of incomplete truck information and is referred to as the "revised difference heuristic." This algorithm requires each container's retrieval order number as input. The retrieval order number can be obtained by relating the truck arrival sequence (or group) to the container of interest. Given truck arrival information, the revised difference heuristic can be applied to determine the best storage location of the rehandled container (i.e., the location that incurs fewest future

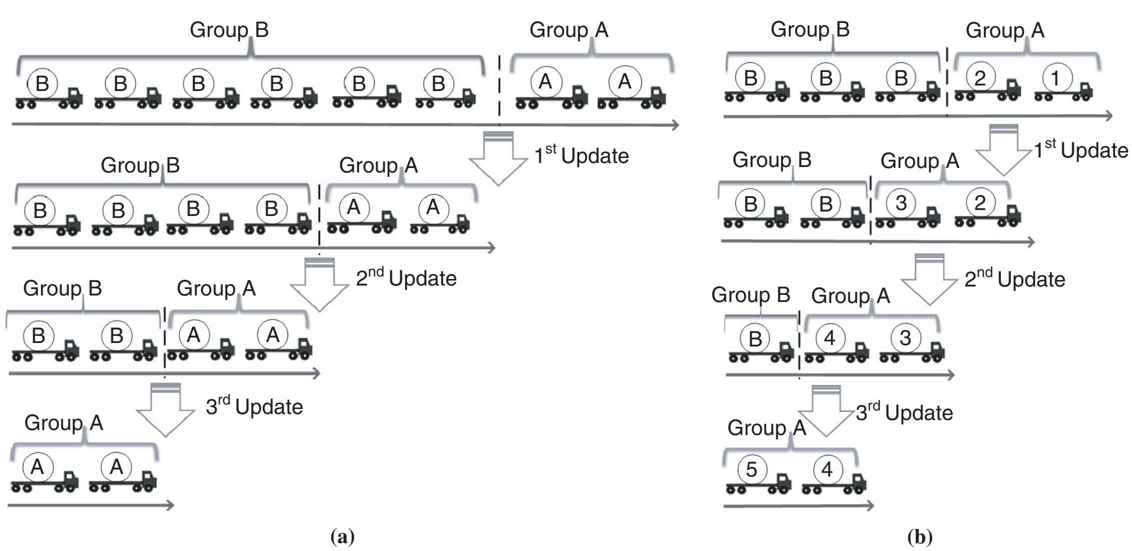

FIGURE 2 Information updating rule for dynamic scenarios: (*a*) dynamic group information and (*b*) dynamic partial sequence.

rehandles). The revised difference heuristic is described below, with *X* denoting the order number of the container to be rehandled.

Revised Difference Heuristic

Step 1. When relocating container *X*, search for a stack with container *Y* whose order number is the smallest in its stack and yet still bigger than *X*. In this way, no additional rehandles will be necessary for container *X*. If multiple stacks satisfy this condition, then the stack containing the smallest *Y* is chosen. If such a stack does not exist, go to step 2.

Step 2. Search for a stack in which the container with the smallest order number is the same as *X*. If multiple stacks satisfy this condition, then randomly select one. If such a stack does not exist, go to step 3.

Step 3. Search for a stack with container *Z* that is accessible by the crane and has an order number smaller than *X*. If multiple stacks are found, choose the one with largest *Z* to minimize the difference between *X* and *Z*. If such a stack does not exist, go to step 4.

Step 4. Search for a stack with the goal of minimizing the difference in order number between its top container and *X*.

Decisions are made sequentially regarding relocations using the revised difference heuristic, from the top container on the target stack (the stack in which the requested container is located) to the one just above the required container.

RESEARCH METHODOLOGY TO EVALUATE CRANE PRODUCTIVITY AND TRUCK TRANSACTION TIME

In this section, the method used to estimate crane service time is first described, and a queuing model is presented to evaluate truck transaction time. Crane productivity is the reciprocal of the average crane service time. Truck transaction time depends on the interarrival time of trucks and the service time of the yard crane.

Crane Service Time Estimation

Crane service time includes the travel time between yard bays, the rehandling time required to move containers on top of the target container, and the handling time for the target container. One container block filled with 40-ft standard containers is considered, and the following notation is used to estimate the crane service time (see Figure 1 for the definition of bays, blocks, stack, and row).

Other terms are defined as follows:

c = number of bays in the block;
a = number of stacks in each bay;
b = initial number of containers in each stack;
h_1 = horizontal distance traveled by the trolley to relocate the rehandled container;
d_1 = vertical distance traveled by the trolley to pick up the rehandled container;
d_2 = vertical distance traveled by the trolley to drop the rehandled container;
h_2 = horizontal distance traveled by the trolley to handle the required container;
d_3 = vertical distance traveled by the trolley to pick up the required container;
d_4 = vertical distance traveled by the trolley to drop the required container on the drayage truck;
v_t = average travel speed of the crane across the yard bays;
v_f = average hoist speed of the trolley when moving a container;
v_e = average hoist speed of the trolley when not moving a container;
v_h = average horizontal travel speed of the trolley;
R = number of rehandles to serve one truck;
T_t = crane travel time between yard bays;
T_r = rehandling time;
T_d = required container handling time; and
T_o = time needed to perform one container rehandle.

Crane Travel Time Estimation (T_t)

Under the assumption that trucks are served following the FIFO rule and that the requested container location is randomly distributed, the expected distance between two random retrievals is $c/3$, and the variance can be derived as $c^2/18$. Thus, the mean and variance of the travel time across container bays to pick up one import container are as follows:

$$E(T_t) = \frac{c}{(3v_t)} \tag{1}$$

$$V(T_t) = \frac{c^2}{(18v_t^2)} \tag{2}$$

Crane Rehandling Time Estimation (T_r)

The number of rehandles and the time needed to rehandle one container are assumed to be independent. Consequently, the expected rehandling time can be calculated as the product of the expected number of rehandles and the expected time to rehandle one container.

Estimation of Time to Rehandle One Container (T_o) One rehandle is defined as a complete cycle: the trolley reaches the container to be rehandled, moves it to another stack, and returns it to the original stack. The trolley first travels vertically and horizontally with the container and then travels back empty. An upper bound for the cycle time can be derived by assuming the horizontal movement and vertical movement are carried separately. As illustrated in Figure 3,

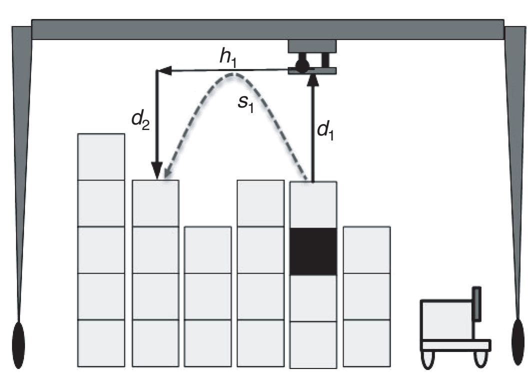

FIGURE 3 Trolley movements in one rehandle cycle.

the trolley travels along the path $d_1 \rightarrow h_1 \rightarrow d_2$. The upper bound can therefore be estimated as

$$T_o^u = \frac{d_1}{v_f} + \frac{d_2}{v_f} + 2 \cdot \frac{h_1}{v_h} + \frac{d_2}{v_e} + \frac{d_1}{v_e} \tag{3}$$

A lower bound for the cycle time can be derived by assuming that the horizontal movement and vertical movements are carried simultaneously. This is also illustrated in Figure 3, in which the trolley travels along trajectory s_1. The lower bound can be estimated as

$$T_o^l = \max\left(\frac{d_1}{v_f} + \frac{d_2}{v_f}, \frac{h_1}{v_h}\right) + \max\left(\frac{d_2}{v_e} + \frac{d_1}{v_e}, \frac{h_1}{v_h}\right) \tag{4}$$

The average of the upper and lower bounds is used to estimate the expected time to rehandle one container. Because the variance of T_o is small, its impact on the model outcome can be neglected, and the variance of T_o is assumed to be zero.

Estimation of Number of Rehandles (*R*) The expectation and variance for the number of rehandles can be estimated based on the probability distribution of the number of container rehandles. A computer-based simulation is developed to model the container pickup operation and is used to derive the probability distribution of the number of rehandles for one import container pickup under different scenarios. The computer system simulates the container retrieval process for a bay of containers under specified rules of container relocation and keeps track of the number of rehandles performed and the horizontal distance traveled by the trolley. The program is able to evaluate the amount of rehandling work under various truck information qualities and bay configurations. A detailed description of the computer simulation can be found in Zhao and Goodchild (*7*).

The expectation and variance of rehandling time can be calculated as follows:

$$E(T_r) = E(T_o) \cdot E(R) \tag{5}$$

$$V(T_r) = E(T_o)^2 \cdot V(R) \tag{6}$$

Crane Handling Time Estimation (T_d)

One handle for an inbound container is defined as a cycle that starts with the trolley above the truck lane, moves to reach the required container, travels back to drop it on a drayage truck, and returns to its initial position. The expected handling time for one container can be estimated by deriving an upper bound and a lower bound for handling time; the variance is assumed to be zero.

The upper bound and lower bound of T_d is estimated following the same logic used to evaluate T_o. The upper bound of T_d can be written in the same format as Equation 3, but replacing d_1, d_2, h_1 with d_3, d_4, h_2; the lower bound of T_d can be expressed as

$$T_d^l = \max\left(\frac{d_3}{v_f}, \frac{h_2}{v_h}\right) + \max\left(\frac{d_3}{v_e} + \frac{d_4}{v_e}, \frac{h_2}{v_h}\right) + \frac{d_4}{v_e} \tag{7}$$

Estimated Crane Service Time and Crane Productivity (T_c)

Because the handling time for an import container, the rehandling time, and the travel time can all be assumed to be independent of each other, the expectation and variance of crane service time can be estimated as

$$E(T_c) = E(T_t) + E(T_r) + E(T_d) \tag{8}$$

$$V(T_c) = V(T_t) + V(T_r) \tag{9}$$

Crane productivity can be estimated as the reciprocal of average crane service time.

Truck Transaction Time Estimation

Assume truck arrivals follow a Poisson process with the arrival rate λ. For a yard crane working within a block of inbound containers, the container retrieval operation can be modeled as an M/G/1 queuing system, with the yard crane being the single server and the arriving trucks as customers (Figure 1). The traffic density is

$$\rho = \lambda \cdot E(T_c) \tag{10}$$

Expression 11 can be used to calculate the expected truck transaction time (*9*):

$$E(W) = E(T_c) + \frac{\lambda \cdot V(T_c) + \rho \cdot E(T_c)}{2(1-\rho)} \tag{11}$$

NUMERICAL EXPERIMENTS

This section presents the estimated improvements in crane productivity and truck transaction time if a terminal utilizes truck arrival information to reduce rehandling work. The impact of various information qualities, truck arrival rates, and block configurations on drayage truck–yard crane system performance was evaluated to identify the effectiveness of truck information under different system configurations. The parameter values of the yard crane are listed in Table 2 and were used for the numerical experiments.

For any given bay configuration, the parameter values for d_1, d_2, d_3 are calculated by subtracting the average stack height ($b/2$) from the crane lifting height, and d_4 is calculated by subtracting the truck chassis height from the crane lifting height. Here, 1.450 m is used as the chassis height (*11*). For a scenario without truck information, h_1 is estimated based on the simulation result regarding the average horizontal distance traveled by a trolley for one rehandle; for all other scenarios, h_1 is estimated as being one-half of the block width

TABLE 2 Specifications for Rubber-Tired Gantry Crane (*10*)

Parameter	Value
Gantry travel speed (v_t)	115 m/min
Hoist speed with full load (v_f)	30 m/min
Hoist speed with empty load (v_e)	63 m/min
Trolley travel speed (v_h)	70 m/min
Crane lifting height	12.34 m for two-container-high block 15.24 m for three-container-high block 18.14 m for four-container-high block 21.04 m for five-container-high block 23.94 m for six-container-high block

(a/2). h_2 is also estimated as being one-half of the block width (a/2). The container dimension is the standard 40 ft.

Performance Analysis Under Various Information Qualities

A block with $a = 6$, $b = 5$, $c = 40$, and $\lambda = 6$/h is considered. Arrival trucks retrieving containers from the same bay are assigned into two groups, and the impact of truck group size on the performance of the yard crane service system is shown in Figures 4 and 5.

Figures 4 and 5 demonstrate that truck information can generate significant benefit for both the marine terminal and trucks. Notice the similarities between the two figures, indicating that the change in truck group sizes has similar impacts on both crane productivity and truck transaction time. Two other observations can be made from Figures 4 and 5.

First, given static information, the value of truck group information is maximized when the sizes of the two groups are equal. The value of partial sequence information grows steadily with the length of the sequence.

Second, updating information in real time can lower the requirement for information quality. For the scenario with dynamic group information, the peak benefit is realized at a much smaller first group; for the scenario with dynamic partial sequence information, significant benefit is achieved from knowing one-sixth of the total sequence, and little additional value is generated from a longer sequence. Therefore, a complete sequence is not required to significantly improve system performance if real-time information is available.

Performance Analysis Under Various Truck Arrival Rates

Consider a block with $a = 6$, $b = 5$, and $c = 40$. It is assumed that arriving trucks retrieving containers from the same bay are assigned into two groups, with the first group accounting for one-third of the total number of arriving trucks. The change in truck arrival rate has no impact on crane service time but affects the truck waiting time within the system. The truck transaction time is evaluated under a range of arrival rates from 4/h to 10/h, and the result is presented in Figure 6.

Figure 6 shows that truck time savings resulting from any level of information quality grows exponentially with truck arrival rates. Especially when the truck arrival rate is approaching the crane service rate, a 35% reduction in transaction time can be realized from knowing truck arrival groups only. Therefore, the truck information is more valuable for the system operating near capacity, and a small amount of truck information can be very effective in reducing truck delay.

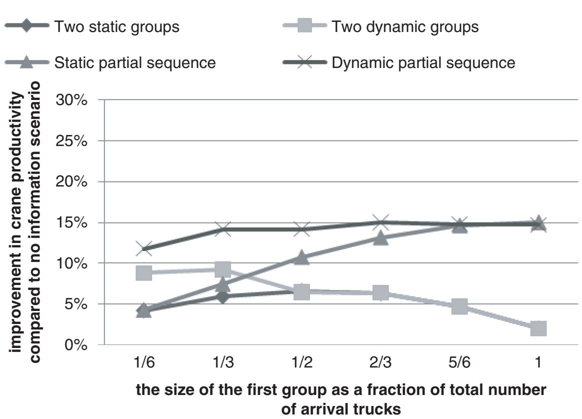

FIGURE 4 Improvements in crane productivity under various first truck arrival group sizes.

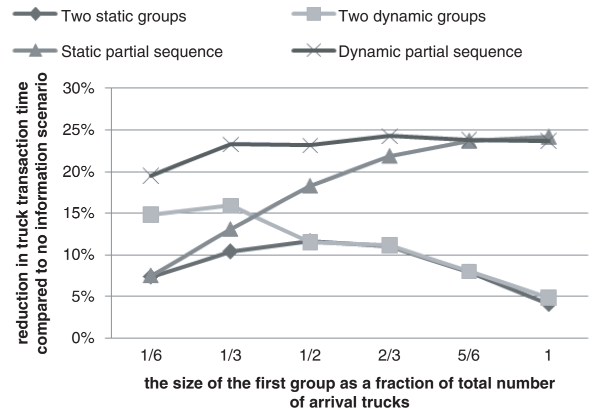

FIGURE 5 Percentage savings in truck transaction time under various first truck arrival group sizes.

Figure 6 also demonstrates the consistent effect of truck information quality on truck transaction time under different truck arrival rates. In general, having information for two static truck groups can generate almost one-half of the truck time savings achieved from having a complete sequence; having dynamic group information is more valuable than knowing one-third of the truck arrival sequence and can result in an additional 2% to 4% in time savings. Dynamic partial sequence information can provide almost the same amount of benefit as complete sequence information. Therefore, better information quality can further reduce truck transaction time, but the complete sequence is not required.

Performance Analysis Under Different Block Configurations

Consider a block with 1,200 containers, $\lambda = 6$/h, and a block with $a = 6$, $b = 5$, and $c = 40$ as the base configuration. It is assumed that arriving trucks retrieving containers from the same bay are assigned into two groups, with the first group accounting for one-third of the total number of arrival trucks.

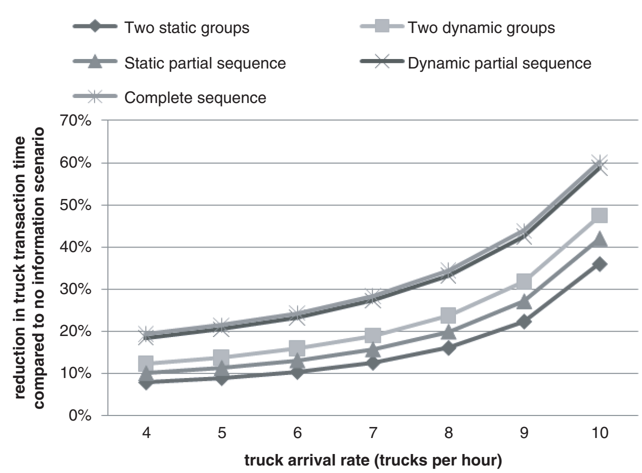

FIGURE 6 Percentage savings in truck transaction time under various arrival rates.

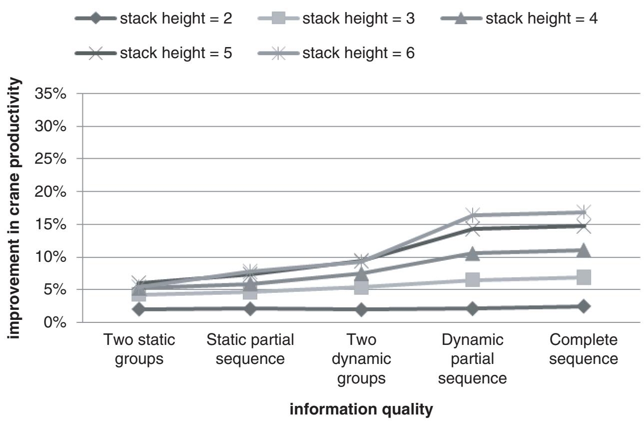

FIGURE 7 Crane productivity under various configurations of stack height and bay numbers.

Figures 7 and 8 illustrate the performance of the yard crane service system under various block configurations with six rows ($a = 6$). Different combinations of stack height and bay numbers have a similar effect on crane productivity and truck transaction time. Two observations can be made. First, given the same level of information quality, the truck information generates a bigger benefit for the block configuration with higher stacks and fewer bays. Second, better information quality can bring additional benefit for the block configuration with higher stacks and fewer bays; however, its value decreases with the stack height. Static group information is sufficient for system improvement for the block configuration with shorter stacks and more bays.

Figures 9 and 10 illustrate system performance under the block configuration with an initial stack height of five ($b = 5$). Again, different combinations of the number of rows and bays have a similar impact on both crane productivity and truck transaction time. Two observations can be made. First, given the same level of information quality, the information provides larger benefit for the block configuration with more rows and fewer bays. Second, the magnitude of benefit grows steadily with better information quality for any combination of row numbers and bay numbers. A comparison between Figures 7 and 8 and Figures 9 and 10 shows that stack height has more impact on the effectiveness of utilizing arrival information than other block configuration factors.

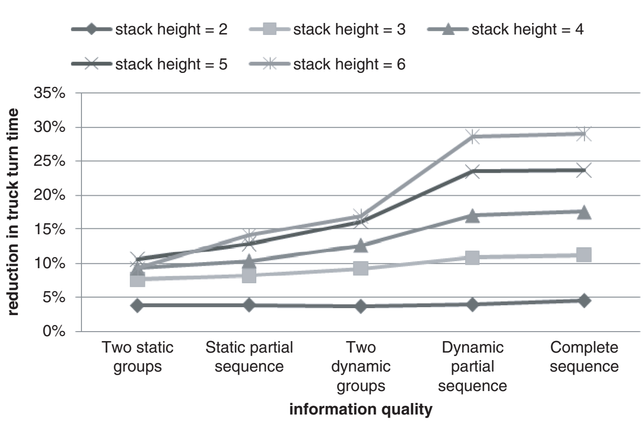

FIGURE 8 Truck transaction time under various configurations of stack height and bay numbers.

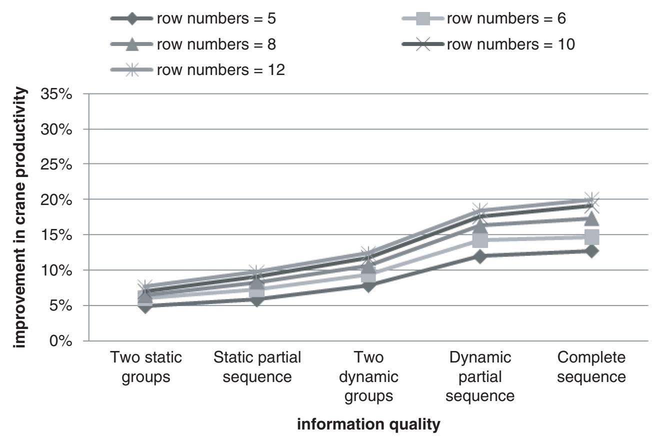

FIGURE 9 Crane productivity under various configurations of row numbers and bay numbers.

CONCLUSION

This paper presents the impact of truck arrival information on the drayage truck–yard crane system. A simple rule for using truck information is adopted to reduce container rehandles, and an M/G/1 queuing model is used to model the interaction between the yard crane and arriving trucks. The model is designed to evaluate how strategic factors such as the level of truck information quality and container block design affect system improvements achieved by utilizing truck information. These results can identify terminals likely to experience significant benefits and can inform the design of a data-sharing system. For very detailed estimates of improvements at a particular terminal, a microsimulation model should be developed that captures the unique terminal configuration, flow rates, and processing times.

These research results demonstrate that truck arrival information is effective for improving crane productivity and reducing truck transaction time. Group information alone can effectively improve system performance; updating information in real time lowers the information requirement and provides significant benefit with a small amount of information. In fact, real-time partial sequence information can generate about the same benefit as the complete arrival sequence, even if the partial sequence is for just one-third of the total number of trucks. Complete sequence information is not required to maximize the benefit.

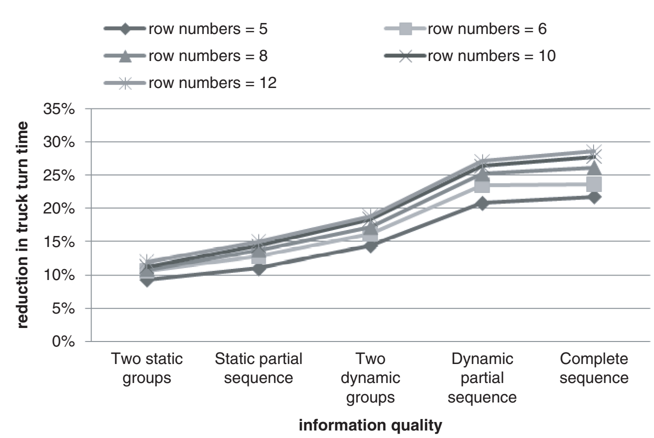

FIGURE 10 Reduction in truck turn time under various configurations of row numbers and bay numbers.

The results also shed light on the relationship between benefits and block configuration. For those terminals with limited yard space and high stacking, truck information is more effective for system improvement, and better information quality is useful for further enhancing the magnitude of benefit. For those terminals with more yard space, the static truck group information can moderately improve system efficiency. Truck information is especially valuable for the system operating near capacity.

The work illustrates that utilizing truck information can benefit both the marine terminal through reduced rehandling work and drayage trucks through reduced turn times. These benefits are naturally aligned with each party's interests. Having any amount of information is useful for improving system performance. Truck information could be obtained in a variety of ways, including using existing gate appointment systems, which could provide some information about truck arrival time windows, or receiving phone calls from approaching trucks. Utilizing currently available information such as this does not require much effort or cost; however, it does require cooperation between the terminal and trucking operations.

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