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Abstract

Integrating Drayage Truck and Marine Terminal Operations to Improve Intermodal System
Efficiency

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Container terminals are important intermodal interfaces between marine and land transport networks. These interfaces have historically been sources of congestion and logistical inefficiencies. Exacerbated by growing trade volumes, the terminals have become bottlenecks in the port-related supply chain.

This research explores using truck arrival information to integrate drayage truck and container terminal operations and improve intermodal system efficiency. The first part of the dissertation investigates whether and to what extent pre-arrival information regarding drayage trucks can be used to reduce operational inefficiencies and truck delays within the terminal. An advanced container rehandling strategy is proposed for using truck arrival information to reduce container rehandling work, and a computer simulation model is developed for evaluating the impact of truck arrival information on container handling efficiency by adopting the proposed strategy during the import container retrieval operation. In addition, a queuing model is employed to assess the impact of truck information on truck transaction time within a terminal. The research results demonstrate that any amount of information about arrival trucks is effective for improving yard crane productivity and reducing truck transaction time.

The second part of the dissertation investigates the travel time reliability of the port drayage network and evaluates the predictability of drayage truck travel time. A simple but effective method is developed for predicting the 95% confidence interval of travel time between any OD pair and is validated with GPS data. The research results indicate that the proposed travel time prediction method

is quite accurate in estimating the arrival time window of trucks at the terminals. It is therefore sufficient to support the implementation of the proposed container rehandling strategy.

Overall, this research provides terminal operators with insights as to the impact of truck arrival information on system efficiency of drayage truck/terminal operations, travel time prediction method to improve information quality, and operational strategies to effectively utilize such information. The research results can identify terminals likely to experience significant benefits if utilizing truck information, and inform the design of a data sharing system and tools for acquiring better information.

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Chapter 1 Introduction

“Together with enhanced telecommunications, the continued liberalization of trade and international standardization, transportation is regarded as one of the four cornerstones of globalization” (Wang et al., 2005). Among the modes of freight transportation, maritime transportation accounts for two-thirds of world trade in metric tonnes (UNCTAD, 2001). In particular, container transportation has become the predominant mode of world cargo traffic, and over 60 percent of the world’s deep-sea general cargo is transported in containers. Some routes, especially between economically strong and stable countries, are containerized up to 100 percent (Muller G, 1995). As a result, container terminals have been playing an important role as intermodal interfaces between sea and inland transport.

Container terminals are large, interdependent and complex systems, with many processes and activities involved in container movements. They are generally located in urban areas, and have little available land for physical expansion or inland transport network improvement (Rodrigue et al., 2009). Because of growing international trade volumes and increasing pressure to accommodate more container traffic, container terminals have been facing increasing congestion problems and have become bottlenecks in supply chains relying on ports to move goods. In 2004, the largest port complex in U.S., San Pedro Bay Ports reached capacity, which includes the Ports of Los Angeles and Port of Long Beach. During the summer and fall, as many as 50 ships were lined up off the coast near the ports, waiting as long as a week before berthing and unloading (Guido D.W., 2005). Such excessive delays at ports have marginalized lean inventory models, forcing some retailers to carry more supply during peak periods to eliminate out-of-stocks and driving up total supply chain costs. Although the Great Recession of 2008-2009 caused container volumes at the world’s ports to decline, global container volume are forecast to increase by an average of 7.2 percent annually over next five years and port congestion could once again become a problem. It is predicted that global container port volumes will rise by 245 million TEUs between 2009 and 2015, an increase of just over 50 percent in this period, while the capacity of the world’s container terminal is forecast to grow by 143 million TEUs during the same time frame, a rise of just under 20 percent. Port congestion problems could become more serious in fast-growing areas of the Far East and the Middle East, as the average capacity utilization rate of container terminals would increase to 95 percent in those regions (Guido D.W., 2005).

To deal with capacity challenges, container terminals around the world have been pursuing various strategies to improve terminal productivity, such as automation of terminal operations using emerging technologies, implementation of policies to reduce container dwell times, extended gate hours, and gate appointment systems. Some of those strategies have been effective, while others have not met expectations. Having implemented all of these strategies at the Ports of Los Angeles and Long Beach, the San Pedro Bay Ports can serve as an example in examining the effectiveness of these solutions. Gate automation has been pursued at many terminals of the Ports of Los Angeles and Long Beach by employing Optical Character Recognition technology, which speeds up truck processing through the terminal gates (Port of Los Angeles, 2011). Reduced container dwell time has also been achieved at San Pedro Bay Ports by lowering the terminal free time allowance from five to four days for import

containers and from seven to six days for export containers (Le-Griffin and Murphy, 2006). The terminal free time refers to the number of days a container can remain at a container terminal once it has been unloaded from a ship before incurring a storage fee. This strategy has effectively increased the capacity of container storage yards and improved the productivity of terminal equipment. The Ports of Los Angeles and Long Beach have also established and implemented a voluntary program of extended gate hours (PierPASS), which provides five off-peak terminal gates at all 13 terminals within the ports and assesses a Traffic Mitigation Fee on eligible containers moved into and out of the ports during peak hours. The fee excludes containers moved between 6PM and 3AM Monday-Thursday and between 8 AM and 6 PM on Saturdays to encourage more off-peak moves. The PierPass OffPeak program has diverted an average of 40 percent of all container moves to off-peak hours and has reduced truck waiting time inside port terminals and truck traffic during peak daytime commuting periods (Giuliano and O'Brien, 2008). Many terminals at San Pedro Bay Ports have also implemented a gate appointment system for trucks to pick up or drop off containers. However, appointment systems are perceived by the trucking industry as ineffective in reducing truck turn time and a wasted effort by many terminal operators (Giuliano and O'Brien, 2007). Figure 1.1 shows the results of a field survey conducted at the Ports of Los Angeles & Long Beach regarding the effectiveness of gate appointment systems, illustrating that most systems were perceived by trucking firms as less than marginally effective in reducing the truck turn time (Giuliano and O'Brien, 2007). Therefore, the appointment system didn't meet its expectation in reducing port congestion.

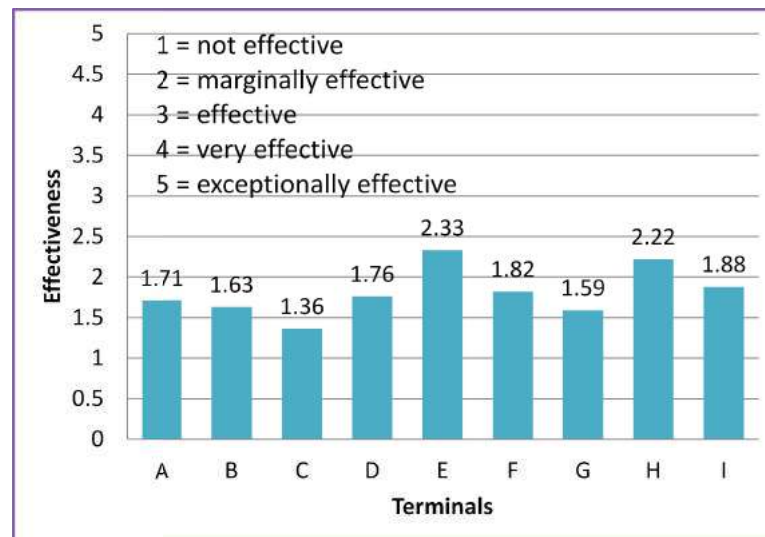


Figure 1.1 Effectiveness of gate appointment systems in reducing truck turn time at Ports of Los Angeles and Long Beach (Giuliano and O'Brien, 2007).

However, if utilized effectively by terminal operators, truck pre-arrival information obtained from the implementation of a gate appointment system could allow for greater terminal operating efficiencies, and therefore an improvement in truck wait times. Such information could also be obtained through GPS technology and other less novel technologies. This dissertation addresses the problem of whether and how truck arrival information can be used to improve the drayage truck/container terminal interface. Additionally, this dissertation explores using historical GPS data to

forecast the truck arrival time at container terminals in order to obtain more accurate truck arrival information.

1.1 Background

A container terminal is comprised of three sub-systems: a landside system, a yard storage and handling system, and a quayside system. Within the landside sub-system containers arrive and depart by trucks or trains, while quayside is where containers are unloaded from and loaded onto ships. Containers are temporarily stored between the landside and quayside sub-systems in container yards and usually separated into areas for export, import, special, and empty containers. The container handling and storage system manages the container storage and transfer between landside and quayside (Elizabeth G. Jones, 1996). Figure 1.2 is a schematic of a container port illustrating both the landside and quayside systems, with the yard storage and handling system in between.

Import containers flow through the terminal in a systematic process. When a ship arrives at the terminal, it is allocated to a berth, and quay cranes are assigned to move the import containers off the ship. Next, the unloaded containers are transported from quay cranes to the storage yard. Upon arrival, a terminal transportation vehicle drops off the container directly, or a piece of yard handling equipment facilitates taking the container off the vehicle, and stores it in the yard. The import containers may be stored in the yard for some length of time before being retrieved and transferred to other modes such as trucks, trains, or barges to depart the terminal (Vis and Koster, 2003). The export containers flow in a reverse direction - containers arrive by other modes, such as trucks or trains; are stored in the yard; and depart by container ships.

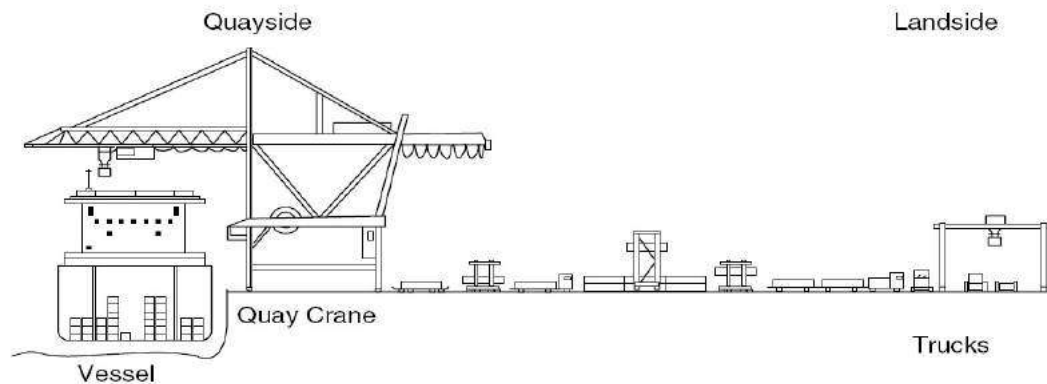


Figure 1.2 A schematic of container terminal (Steenken et al., 2004)

Due to different configurations and operating strategies at different terminals, truck transaction time varies across terminals. Table 1.1 shows the average truck turn time observed at one of the Los Angeles container terminals in 2004, indicating that trucks experienced longer delays at the yard (within the terminal) compared to at gate check-in, especially for container pick-up transactions. There are two approaches to reduce system inefficiencies at the drayage truck/ container terminal interface: (1) improve the gate operations in landside systems where trucks are checked in; and (2) improve the container handling operations in storage systems where trucks pick up or drop off containers. Since gate operation automation has been widely realized at many marine ports through

optical character recognition and other technologies, this research considers the second approach and focuses on using truck arrival information to improve import container retrieval operations and reduce system inefficiencies.

Table 1.1 Average truck turn time by transaction type (minutes) (Giuliano and O'Brien, 2007)

Transaction type	Transaction time at gate	Transaction time within terminal	Total truck turn time
Import container pick-up	4.6	35.6	40.2
Export container drop-off	10.2	27.7	37.9
Dual transaction	10.2	50.3	60.5

Containers are either stored on a chassis or the ground at container yards. In chassis, or wheeled storage, the container is stored on the chassis as a unit (as seen in Figure 1.3). This method of storage allows for easy and fast transfer of containers and reduces labor requirements, but it requires a larger terminal area to store the same number of containers when compared to grounded storage. Wheeled storage has been adopted by some U.S. terminals with large terminal areas and relatively high labor costs. Alternatively, with grounded storage, containers are stored directly on the ground, without a chassis, and may be stacked on top of each other. Containers are moved in and out of stacks by yard handling equipment (as seen in Figure 1.4). Ground stacking of containers reduces the terminal area requirements, but it requires more handling effort and increases transaction times for a truck to retrieve a container. This storage method is popular at European, Japanese and U.S. ports where land is scarce. Ground storage methods increase the complexity of terminal operations because containers are not independent, as accessing one container may require moving others. This research studies terminal types that adopt ground stacking strategies.

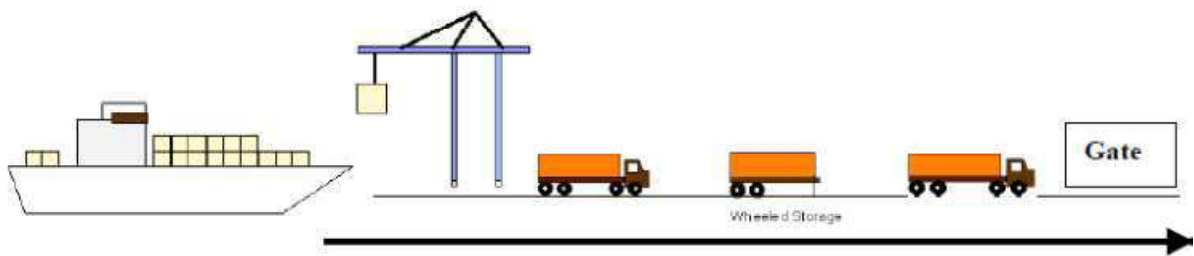


Figure 1.3 Wheeled operation at container terminals



Figure 1.4 Ground stacking of containers at yards

In these terminals containers are often stacked on the ground in several tiers and the entire storage area is separated into blocks. There are various ways of organizing containers, such as classification by size, owner, transaction type or function. Containers can be classified into two groups by transaction type: import containers (those arriving by ship and leaving by landside transport modes) and export containers (those arriving by landside transport modes and leaving by ship). Their storages are typically separated into different areas for logistical simplicity.

Often, export container storage is better organized than import container storage. At European terminals 60 to 70 percent of the export containers arrive at the terminal with accurate data with regards to respective vessel, discharge port, and container weight. A common strategy for export planning is to reserve slots within a row for containers of the same type and discharge port, while heavier containers are stacked on lighter ones assuming that they are loaded first because of the ship stability (Steenken et al., 2004). Typical import container storage is less organized because the transport means and date of delivery generally are unknown at the time of discharge (Steenken et al., 2004). Consequently the import container storage configuration seldom matches the real pick up configuration, and containers are often relocated in order to access desired containers, which are often buried underneath other containers. This activity is called container rehandling. In current practice containers are usually relocated to the nearest available stack, limiting the distance traveled by the crane to finish one rehandle operation. Figure 1.5 provides an illustration of container rehandling. To retrieve the red container in the bay, the two containers stacked on top of the desired container need to be relocated to other stacks. After the yellow container is relocated to the left stack and the blue container is relocated to the right stack, the red container becomes accessible and can be picked up by the drayage truck. Container rehandling is often unproductive and requires a significant level of effort in the terminal.

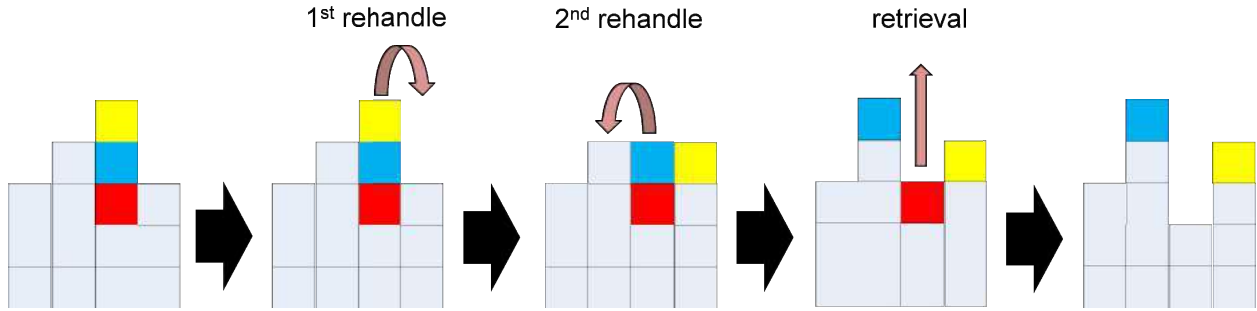


Figure 1.5 An illustration of container rehandling

The above example only required two rehandles to retrieve the desired container, but consider an example with a more significant container rehandling effort. Yard crane efficiency can be defined as the ratio of productive crane moves to total crane moves as follows:

$$\text{crane efficiency} = \frac{\text{productive crane moves}}{\text{productive crane moves} + \text{unproductive crane moves}}$$

Productive crane moves are ones in which a desired container is moved. Unproductive crane moves are rehandles, or moves that relocate an undesired container in the process of obtaining the container of interest. Consider a container bay with eight stacks and six containers in each stack, and assume the containers to be retrieved are randomly distributed and rehandled containers are always relocated to the nearest available stack. If the retrieval order of containers and their positions in the bay are randomly assigned, to pick up all the containers the expected number of unproductive crane moves averaged for a thousand times of container retrieval experiment is 78, while the number of productive crane moves is 48 (equal to the product of stack height and stack numbers, or the total number of containers). Crane efficiency is therefore 38 percent. This case, where there is no pre-planning of container storage, provides a lower bound on crane efficiency and an upper bound on rehandling activity. However, the number of container rehandles and the crane efficiency cannot quantify the impact of container rehandling on the yard throughput and truck wait time. In this dissertation, other metrics will also be used to address this issue, including crane productivity (number of trucks served per hour), and the truck transaction time on yard.

In current terminal operations, rehandles represent a significant level of effort in the terminal, affecting the productivity of container handling equipment and causing long truck transactions and time delays. If the truck arrival sequence and the information of their required containers were known in advance, the storage location of rehandled containers could be carefully determined to avoid a second rehandling. Currently, terminals without an appointment system have no knowledge about the time or date of export container delivery or import container pickup by trucks. Terminals having a gate appointment system, such as Ports of Los Angeles and Long Beach and Port of Oakland, have the expected arrival time window of a truck if the truck driver makes an appointment online or by phone for container pickup or drop off. The information quality depends on the extent to which the appointment system is used, the percentage of appointments kept, and the lead time of appointments

being made. Perfect knowledge can be imagined if truck arrival sequences are dictated by the terminal. Significant improvements could be realized if drayage trucks are equipped with GPS units and location information, along with container details, was shared with the terminal operator.

The truck arrival information could be effectively utilized to reduce the container rehandling work. The pickup sequence of containers or container groups could be obtained by relating the import containers stacked on the yard with their corresponding trucks and used for identifying the optimal storage location of rehandled containers. That is, rehandled containers could be relocated to a stack whose containers are all requested later in time compared to this container to avoid being rehandled again. By reducing container rehandles, the terminal could improve yard crane productivity, reduce truck transaction and delay time, and improve container throughput on the yard.

However, utilizing truck arrival information requires cooperation between the terminal and trucking operations and may raise privacy and other issues. For example, equipping trucks with GPS units and sharing their location with the terminal operators may disclose the shipping and logistics information of businesses and be rejected by shippers. Truck drivers might be unwilling to use the gate appointment system since making and keeping gate appointments could cause additional costs. Also, using truck arrival information requires changes in terminal operations, such as keeping track of the container locations on the yard in real time, incorporating the container rehandling strategy into existing terminal operating system, and dictating the crane operators for each container movement. Since that would increase the complexity of current terminal operations and operating costs, terminal operators are unwilling to make such changes if they are not convinced of the actual benefit being generated.

1.2 Research problem and objectives

The first research problem this dissertation addresses relates to using truck arrival information to reduce container rehandling work and truck transaction time. The first set of research objectives are:

- 1) Develop advanced container handling strategies to effectively utilize truck arrival information for reducing container rehandling work and truck transaction time;
- 2) Assess how truck arrival information with different levels of quality and accuracy can affect the system efficiency at terminals;
- 3) Identify the information requirements to achieve significant improvements in system efficiency;
- 4) Evaluate the impact of different terminal system configurations on the effectiveness of truck arrival information.

The second problem this research addresses involves using historical GPS data to forecast truck arrival time at container terminals. The second set of research objectives are:

- 1) Evaluate the travel time reliability of the port drayage network;
- 2) Develop an effective method to predict the confidence interval of truck travel time between a given Origin-Destination pair;

- 3) Investigate the usefulness of the proposed travel time prediction method for improving truck arrival information.

1.3 Organization

The remainder of this dissertation is organized as follows:

The next chapter provides a general overview of marine container terminal operations and presents the literatures review relevant to this dissertation work.

Chapter three proposes a method for using truck information to improve container handling operations and describes a simulation model developed for evaluating the impact of truck arrival information on container rehandling work. Additionally simulation results are presented and the impact of truck information quality on the container rehandling efficiency is discussed.

Chapter four develops a methodology for evaluating crane productivity and truck transaction time, and presents the estimated improvements in crane productivity and truck transaction time if the truck arrival information is utilized to reduce rehandling work. Experiment results are discussed to identify the impact of different system configurations on the effectiveness of truck arrival information.

Chapter five investigates the effectiveness of using a truck appointment system for improving the efficiency of yard crane service system. It evaluates how the appointment system design and terminal configurations affect the performance of yard crane service system, and quantifies the impact of using inaccurate information on the effectiveness of this truck information.

Chapter six uses the San Pedro port drayage network as a case study for predicting truck travel time. It evaluates the travel time reliability of the port drayage network, examines the relationship between routing choice and route attributes, and proposes a simple method to predict the confidence interval of truck travel time between given Origin-Destination pairs. The potential implementation of this method for improving the truck arrival information is also discussed.

The last chapter presents the key findings from this research, highlights their contribution, and presents areas for future research.

Chapter 2 Literature review

This chapter provides an overview of marine container terminal operations and presents the literatures relevant to this dissertation work. The review is divided into four parts. The first part provides a basic introduction to container terminal operation and an overview on terminal operation researches. The second part presents the studies on container storage and stacking logistics within container terminals. The third part reviews the studies relevant to reducing drayage truck delay at container terminals. Lastly, the fourth part summarizes the studies on travel time forecasting. The goal of this review is to share the current body of literature on container terminal operations and show how this work complements that body of work.

2.1 Overview of marine container terminal operations

Although marine container terminals considerably differ in size, function, layout, they principally consist of the same subsystems: landside system, yard storage and handling system, and quayside system, and the operations in container terminals are of three types: quayside vessel operations, landside receiving/delivery operations for road trucks/ rails, and container handling and storage operations at yard.

Vessel operations include the unloading operation, during which containers in a vessel are discharged from the vessel and stacked on the container yard, and the loading operation, during which containers are handled in the reserve direction of the loading operation (Kim, 2007). Quay cranes are the main quayside handling equipments and transfer containers from a ship to prime movers.

During receiving and delivery operations, when a container arrives at the terminal gate by a drayage truck, the container is inspected to check whether all the required documents are ready and damages to the container are present. Further, information with regard to where to store an export container or where the required import container is located is provided to the drayage truck. Then the drayage truck is directed to a transfer point of the yard, and the yard equipment, a yard crane or straddle carrier, unload a container from truck, which is called the receiving operation, or transfers a container from the stack to the truck, which is called the delivery operation (Kim, 2007).

Container handling and storage operations are performed by yard equipments, such as straddle carriers or yard cranes. The main functions of yard equipments include: (1) picking up import containers delivered by prime movers from quayside or export containers by drayage trucks from landside and stacking them into blocks; (2) retrieving export containers onto prime movers for ship loading or import containers onto drayage trucks from storage area.

Corresponding to different types of terminal operations, the port research topics can be classified into three main categories: ship planning, storage and stacking logistics, and transport optimization (Steenken et al., 2004). The ship planning issues mainly consist of berth allocation (Nishimura et al. 2001; Kim and Moon, 2003), stowage planning (Wilson and Roach, 1999; Avriel et al., 2000), quay crane allocation and scheduling (Gambardella et al., 2001; Park and Kim, 2003). With regard to the transport optimization, two types of transport can be distinguished: the horizontal transport and the

stacking transport carried out by gantry cranes. The horizontal transport problem subdivides into the quayside transport serving ships (Kim and Kim, 1999; Grunow et al., 2004), and the landside transport serving trucks and trains (Kim et al., 2003; Steenken et al., 1993). The crane transport issue mainly includes crane deployment/ scheduling (Zhang et al., 2002), and routing (Kim and Kim, 1997). The storage and stacking logistics is closely related to this dissertation work and a thorough review is provided in next subsection. Most of that work utilizes queuing theory and stochastic models, simulation, and classical operation research techniques and metaheuristic optimization algorithms. More comprehensive literature reviews concerning researches on container terminal operations can be found in (Steenken et al., 2004) and (Vis and Koster, 2003).

2.2 Container storage and stacking logistics

There is an extensive literature which considers improving container handling operations, for example by optimizing container storage and stacking logistics. Common research problems include storage space allocation, storage strategies, and reducing container rehandling during the retrieval process. The main objective of such yard optimization research is to minimize the number of container rehandles or maximize storage space utilization (Steenken et al., 2004). As container rehandling is directly related to this research a brief review of previous research in this area is provided.

McDowell et al. (1985) explored the problem of import container stacking configuration by considering trade-offs of various costs involved such as container storage cost, container rehandle cost, and transtainer operation cost. Watanabe (1991) suggested a simple method called the selectivity index to estimate the number of rehandles on container yards; Kim (1997) proposed a formula for estimating the expected number of rehandles to pick up all the containers in a bay randomly, and showed his method performs more accurately than Watanabe's.

Kim et al. (2000) proposed a dynamic programming model to determine the optimal storage location of arriving export containers to minimize the number of rehandles expected for the loading operation. The rehandles occur when lighter containers are stacked on top of heavier containers in a yard, since the heavier ones are usually loaded first to the ship. The configuration of the container stack, the weight distribution of containers in the yard-bay, and the weight of an arriving container are considered in the model. A decision tree is developed from the set of the optimal solutions provided by dynamic programming to support real time decisions.

Kim and Hong (2006) proposed two methods for determining the locations of rehandled containers to minimize the number of rehandles during the pickup operation given the container retrieval sequence. First a branch-and-bound algorithm is suggested and then a decision rule is proposed by using an estimator for an expected number of future rehandles to be added for a stack. Although in numerical experiments the branch and bound (B&B) algorithm outperforms the heuristic algorithm, the computational time of the B&B algorithm exceeds the level of real time usage when problem size increases. Aydın (2006) studied the same problem as Kim and Hong (2006), but he considered minimizing not only the total number of rehandles, but also the total distance travelled by the crane. He first solved the problem using the B&B algorithm and the heuristic algorithm proposed

by Kim, and also suggested two other alternatives, a greedy heuristic and the difference heuristic. His experimental results indicate that the solution gap between the heuristic and optimal algorithms is within 8%.

The most closely related paper was written by Jones and Walton (2002). 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 ship unloading process. While the overall intent is the same, to reduce rehandling activity, Jones and Walton study a different component of the terminal operations (unloading container to stacks), and solve a different mathematical problem. This research assumes the truck arrival time is obtained after import containers have been stored on the yard, to mimic the practice of having real-time, rather than strategic information.

2.3 Drayage truck transaction within the container terminal

Some researchers have studied how to reduce the truck transaction time at a container yard by better utilizing the current system or improving operational methods. Huynh and Walton (2008) studied regulating the number of trucks that can enter the terminal to make the gate appointment system effective. He proposed a methodology, which is a combination of mathematical formulation and computer simulation, to determine the maximal number of trucks allowed to enter the terminal while maintaining a target truck transaction time.

Kim et al. (2003) studied sequencing trucks for container transfer operations to minimize truck delay at the container yard. A due time for transfer service is assumed for each truck, and delay of a truck beyond the due time incurs 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 (2002) studied optimizing the size of terminal storage space and number of yard cranes for handling import containers and developed an analytical cost model which addresses terminal space cost, investment and operating cost of yard cranes, and waiting cost of outside trucks. 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.

Holguín-Veras and Walton (1997) studied improving the level of service for containers with a higher priority at container terminals by implementing priority systems. He considered a group of priority systems, such as 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 based on computer simulation. He 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.

2.4 Travel time prediction

Significant research has addressed travel time prediction. With regard to methodological approaches, they can be categorized as follows: regression, time series estimation, and artificial intelligence. With regard to input data, the travel time data is acquired through various technologies and can be divided into three categories: sensor-based, site-based, and vehicle-based measurement. Sensor-based methods estimate travel time by collecting spot speed data from stationary sensors such as loop detectors installed on roadways. Site-based methods use fixed-location equipment such as automatic vehicle identification systems to identify and track a subset of vehicles in the traffic stream, and estimate spatial travel times by matching the unique vehicle identifications. A vehicle-based method collects travel time data directly from a fleet of vehicles using GPS devices or automatic vehicle location systems. In this section, a review is provided on the literature employing different approaches for estimating or predicting vehicle travel time. This review is mainly focused on the research using traffic data collected by site-based or vehicle-based method as input sources because the raw traffic data collected by these methods is similar to the GPS data used for this research.

Before discussing the literature, several terms which are widely used in travel time prediction research need to be defined. Short-term travel time prediction refers to prediction of travel time within a small time window, say, 15 minutes. Real-time traffic data refers to the traffic information collected in real-time to capture current traffic condition; historical traffic data refers to the traffic information collected in previous time intervals which captures the historic traffic condition.

Lee et al. (2009) proposed a real-time knowledge based travel time prediction (TTP) model for an urban network. This model utilizes the raw data collected from site-based methods and, predicts travel time by integrating the historical traffic data, real-time traffic information and real-time external information sources. The basic idea of the proposed TTP model is that the travel time along a selected path can be estimated by summing up the link travel times with intersection delays. This model is a linear combination of historical and real-time travel time predictors, in which the historical predictor infers the travel time on a candidate path on historical traffic patterns, and the real-time predictor estimates the current travel time based on real-time travel speed. The two predictors are combined with weights which are adjusted dynamically according to the external traffic events. The proposed TTP model was implemented for a real-time taxi dispatching system, and the results demonstrated that the precision within a tolerable range can be achieved.

You and Kim (2000) developed and evaluated a hybrid travel time forecasting model for predicting link travel times in congested road networks. This hybrid forecasting model has been developed and tested by deploying GIS technologies in the following areas: (1) storing, retrieving, and displaying traffic data to assist with forecasting procedures, (2) building road network data, and (3) integrating historical databases and road network data. The hybrid model uses a non-parametric regression as its core forecasting algorithm to reduce computation time and increase forecasting accuracy, which adopts the k-nearest neighbor smoothing method. The model is designed to predict

future travel times for a period of 15-60 minutes, and was applied for highway corridors using loop detector data and also an arterial network using probe vehicle data for forecasting travel times. The performance evaluation results indicates that the hybrid model is accurate to less than 10% in mean absolute percent error, and the model performs better with the highway data than with the arterial data.

Chien and Kuchipudi (2003) developed dynamic models to predict short-term travel times with real-time and historic data. The data was collected from roadside terminals along a stretch of freeway. The Kalman filtering algorithm was adopted as the core prediction algorithm because it enables the prediction of the state variable to be continually updated as new observations become available. The aggregated historic travel time data and previous time interval data were used to generate a historical seed, and the prediction model was implemented to predict both the path-based and link-based travel times. Results revealed that during peak hours, the historic path-based data used for travel-time prediction outperformed the link-based estimate due to smaller travel-time variance and larger sample size.

Rice and Zwet (2004) proposed a method to predict vehicle travel time on a freeway segment when its departure is at a certain time in the future. The prediction is based on current traffic conditions in combination with historical data, and the prediction method uses the empirical fact that there is a linear relationship between any future travel time and the current status travel time. Consequently, a linear regression model with time varying coefficients is developed for predicting travel times on freeways.

Park et al. (1999) use real-time information collected from ITS technology to predict link travel times for one through five future time periods (of 5-min duration). They employ a spectral basis artificial neural network (SNN) that utilizes a sinusoidal transformation technique to increase the linear separability of the input features. Actual link travel times from Houston that were collected as part of the AVI system of the Houston Transtar system were used as a test bed. It was found that the SNN outperformed a conventional artificial neural network and gave similar results to that of modular neural networks. The results of the best SNN were compared with conventional link travel time prediction techniques including a Kalman filtering model, exponential smoothing model, historical profile, and realtime profile, and it was found that the SNN gave the best overall results.

2.5 Summary

This chapter provides an overview of researches related to container terminal and travel time prediction. Overall, few researches have explored using truck arrival information to integrate container terminal/ drayage truck operations, which is the first research problem of this dissertation. The most relevant research was done by Jones and Walton, in which they studied using the departure times of containers to manage import containers in stack storage. However, they examined a different component of terminal operations, the process of discharging containers from the ship to stacks. The first part of this dissertation considers the container retrieval process on the yard to investigate the scenario of having real-time, rather strategic information.

With regard to travel time prediction studies, most of the studies develop models to predict short-term travel time on a given path or network link for ITS applications, such as in-vehicle route guidance system and advanced traffic management system. These models require extensive historical traffic data as well as real time information for model training. However, the second part of this dissertation is not intended to provide real-time travel time prediction or routing guidance for truck drivers; instead, one of the main objectives is to provide the terminal operators with information about the truck arrival time window at the terminal gates to support the implementation of improved container handling in the terminal. Travel time prediction methods proposed in previous studies are not applicable for this research and a new method will be developed to forecast the confidence interval of truck travel time between the given Origin-Destination pair.

Chapter 3 The Impact of Truck Arrival Information on Container Terminal Rehandling

This chapter addresses the problem of utilizing truck arrival information to reduce container rehandling work by improving terminal operations. The objective of this chapter is to assess how truck arrival time information with different levels of quality can affect container handling efficiency, identify the requirement on information quality to achieve a significant benefit, and evaluate the impact of bay configuration on the effectiveness of truck arrival information.

3.1 Problem description and assumptions

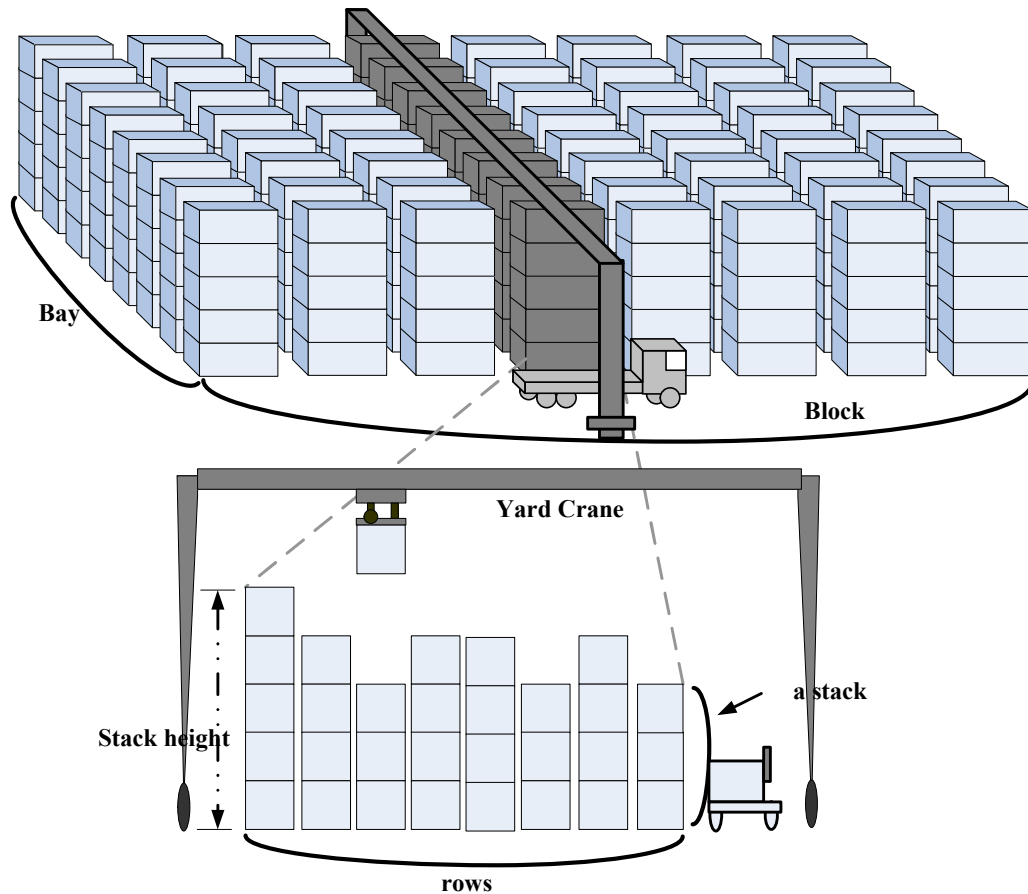


Figure 3.1 Container stacks and yard cranes in operation (Source: Port of Charleston)

Before describing the research problem in more detail, a brief introduction is provided to the container yard layout and container pickup process. Within the terminal, areas of stacked container storage are divided into rectangular regions called blocks. As shown in Figure 3.1, each block consists of many parallel bays; each bay is composed of several stacks; and each stack stores several containers. The truck lane occupies the space beside the block and serves as the truck transfer area. This research assumes containers are retrieved from the block and transferred to trucks by a yard crane (Figure 3.1). The yard crane straddles the block and truck lane. When a truck arrives at the

block, the required container is not always located on top of a stack, and relocations of containers above it occur. In many terminals containers above the required container are relocated to the nearest available stack to minimize the travel distance of yard crane. This strategy, of relocating containers to the nearest stack with an available storage location will be called the nearest relocation strategy in the dissertation.

Currently, terminals have limited knowledge of the truck arrival sequence. Figure 3.2 provides an example of available truck information if a truck appointment system is utilized, and appointments are met. Truck 1 and 2 will arrive within time window A, prior to truck 3, 4, and 5 which will arrive within time window B, but the exact order of truck arrivals within time window A or B is unknown. This illustrates that truck information could be available in terms of truck groups. If much narrower appointment time windows are adopted, or the terminal tracks the real time location of each truck and can estimate arrival times, a more complete truck arrival sequence will become available. Accordingly, this chapter will look at two problems: the problem with incomplete truck arrival information, and the problem with complete truck arrival sequence information.

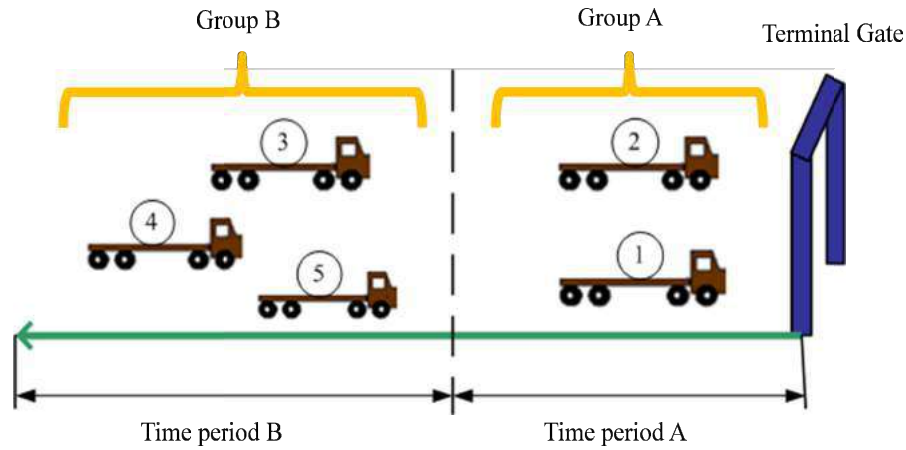


Figure 3.2 Container block, bay configuration and yard crane positioning

Information quality varies in the case of incomplete truck information. To explore the impact of information quality on terminal operational efficiency, we consider two subproblems: a) one where only truck group information is available (i.e. the arrival time window of each group is known rather than the actual arrival time/sequence of each truck in each group), and b) one where, for some of the truck groups, the arrival time /sequence is known for each truck within the group. Since the information quality could be further improved by updating information in real time, the subproblem with real-time updated information is also discussed.

The sequence of truck arrivals is considered for container retrieval within one bay. The following additional assumptions are made:

- (1) No inter-bay container rehandles occur;
- (2) No additional container is added to the bay during the container retrieval process;
- (3) Re-handles occur during the container retrieval process;

(4) The location of each container in the bay is known in advance and tracked throughout the pickup process.

These assumptions are the same as those made in Aydın (2006), and Kim and Hong (2006). Inter-bay container rehandles do not occur during container retrieval from bays due to safety concerns. During this time trucks are moving between bays and conflicts may occur (Port of Seattle, personal conversations). In addition, terminals have little incentive to do so, as the gantry travel of a transfer crane (to move container between bays) is much slower than traverse travel (to move container between rows within the same bay) (Kim, 1997). For several reasons, it is typical that containers are not retrieved from stacks until all containers from the vessel have been loaded into these stacks (Port of Seattle, personal conversations). This includes the time to clear paperwork, and concerns about conflicts between moving vehicles in the yard. The third assumption is driven by the intent of our analysis, which is to consider real-time information about truck arrivals, rather than strategic information. Finally, we assume the location of each container in the bay is known. The application of Real-Time Location Systems and Global Positioning System (Morais and Lord, 2006) has been integrated in many Terminal Operating Systems and enables the container terminal to locate and track their containers. Analysis of the impact of lost containers on the results presented in this chapter is beyond the scope of this dissertation. Under the first assumption container bays are independent of each other; and our analysis of one bay of containers also holds for problems with multiple bays in one block.

Besides the information quality, bay configuration (number of stacks, stack height, loading degree and balancing) is also considered to assess whether and how bay design affects the effectiveness of information in improving container handling efficiency.

3.2 Solution approach

Given the truck arrival sequence, there are two ways to reduce rehandling work. One is to carefully determine the storage location of rehandled containers to avoid future rehandles. The second is dictating the container pickup sequence for trucks so that it matches the container stacking sequence as closely as possible. This research considers both approaches.

As to the first approach, Kim and Hong (2006) propose the exact, branch and bound algorithm, and Aydın (2006) defines the Difference Heuristic Algorithm and two other heuristics to determine the location of rehandled containers given the arrival sequence. In this research a new algorithm is introduced, referred to as the Revised Difference Heuristic (RDH), which extends the Difference Heuristic Algorithm so that it can be used to address the problem with incomplete information. In the scenario with complete information, our RDH works the same as Difference Heuristic and generates the same results. Aydın (2006) has benchmarked the three heuristics in his research and concluded that the Difference Heuristic outperforms the other two heuristics, and its optimality gap is only 2% compared to the exact algorithm. Therefore, the performance of our RDH is guaranteed in the scenario with complete information. For the scenario with incomplete information, there is no existing optimal solution, but the performance of the RDH under the scenario with complete information can provide some confidence for its usage in this scenario.

The idea behind the RDH is to check each alternative location for the container to be rehandled and place the container in a location that would cause minimal additional relocations in future. This algorithm requires each container's retrieval order number as input (Figure 3.3). The retrieval order number can be obtained by relating the truck arrival sequence (or groups) to their container of interest. Given truck arrival information, the RDH can be applied to determine the location of rehandled container. Let X denote the order number of the container to be rehandled, the flowchart of the RDH is illustrated in Figure 3.4 and the algorithm is described below.

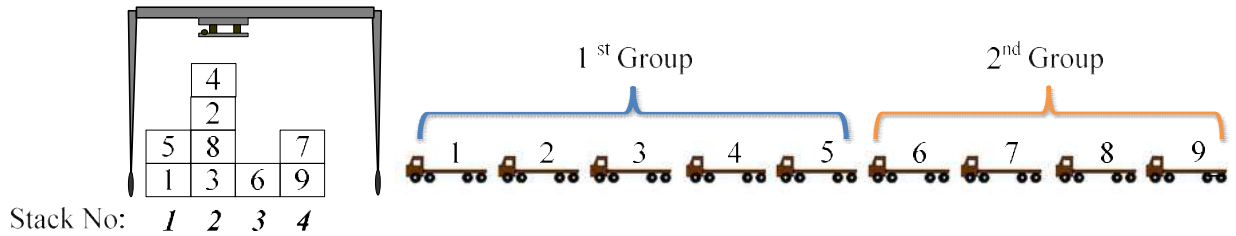


Figure 3.3 An illustration of truck information availability at terminals with a truck appointment system

Revised Difference Heuristic (RDH)

- Step 1: When relocating container X , search for a stack with container Y whose order number is smallest in its stack and 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 smallest Y is chosen. If such 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 stack does not exist, go to step 3.
- Step 3: Search for a stack with container Z which is accessible by the crane and has an order number smaller than X . If multiple stacks are found, then the one with largest Z is chosen to minimize the difference between X and Z . If such stack does not exist, go to step 4.
- Step 4: Search for a stack to minimize the difference in order number between its top container and X . Decisions are made sequentially regarding relocations using the RDH, 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.

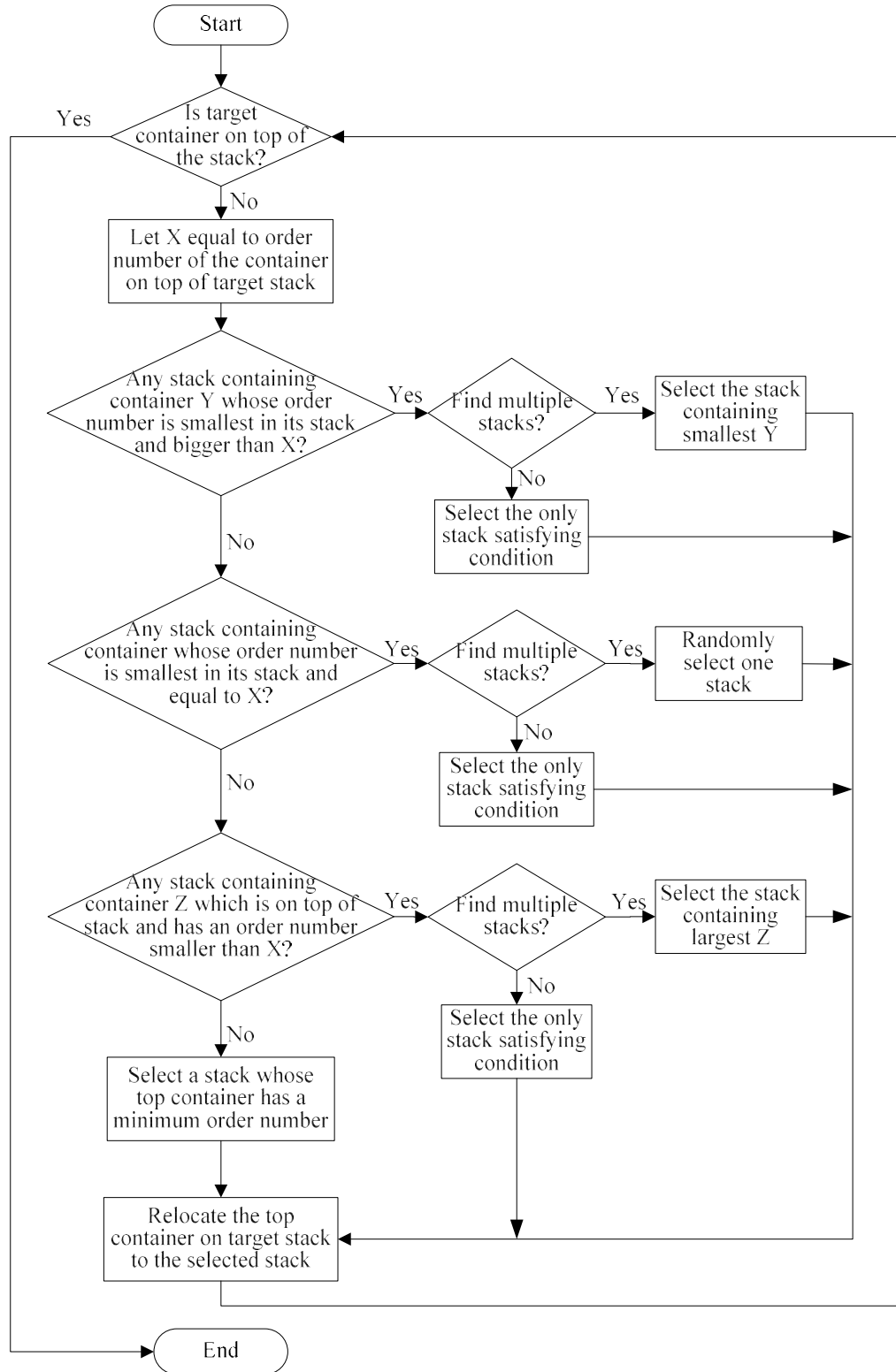


Figure 3.4 Implementation of RDH during container retrieval operation

As for the second approach, the idea is to change the container pickup sequence to match the container stacking sequence. This research considers this approach only within the first group of

arriving trucks so as not to cause excessive delay to any one truck. If the Pickup Sequence Dictation Approach is applied to more groups of trucks, although a greater reduction in rehandles can be achieved, longer time delay will be incurred to some trucks. For example, because of the service sequence change, the first truck to arrive might be the last one served. Therefore, to avoid deterioration in level of customer service, this research only considers the proposed approach for the first group of truck. Further, we expect that better arrival time estimates are available for trucks that are closer to the terminal. It will be more difficult to determine arrival sequences for trucks beyond the first group.

The pickup sequence for the first group is then dictated to minimize number of rehandles and also the number of trucks affected by such operation. By reducing the number of rehandles, the time for transfer crane to serve one truck will be reduced, consequently reducing the average truck delay. This approach benefits both the container terminal and drayage trucks, and avoids excessive delay for any one truck by limiting the dictation to the first group.

Let Q denote truck arrival sequence, with each truck represented by the retrieval order number of its required container; let P denote container pickup sequence, and let $S_j\{1 \leq j \leq a; a \text{ is the number of rows in the container bay}\}$ denote the container stacking sequence of stack j . The procedure of pickup sequence dictation approach is illustrated in Figure 3.5 and the approach could be described mathematically as follows:

Pickup Sequence Dictation Approach:

Step 1: Set $P = Q$;

Step 2: Define p_j^1 as a subsequence of P , whose elements are containers from stack j and belonging to the first group, for all j ;

Step 3: Define s_j^1 as a subsequence of S_j , whose elements are containers belonging to the first group, for all j ;

Step 4: Set $p_j^1 = s_j^1$ for all j .

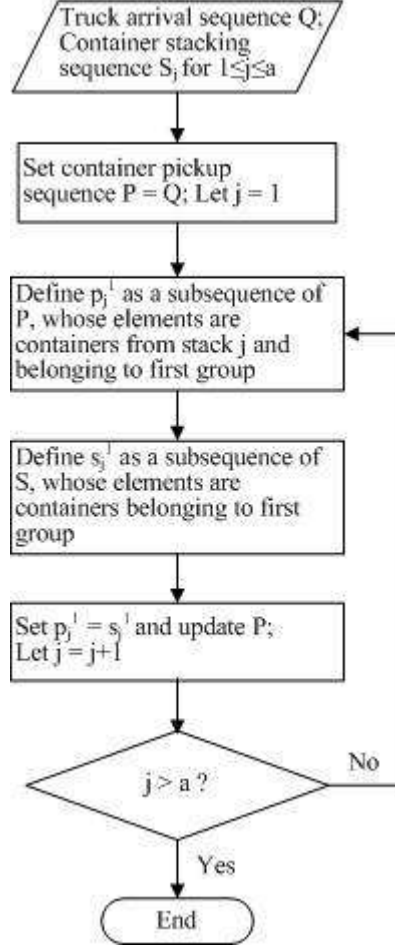


Figure 3.5 Flowchart for the Pickup Sequence Dictation Approach

A numerical example is provided to illustrate the usage of Pickup Sequence Dictation Approach. The input data from Figure 3.3 is used, with $Q = (1, 2, 3, 4, 5, 6, 7, 8, 9)$, $S_1 = (5, 1)$, $S_2 = (4, 2, 8, 3)$, $S_3 = (6)$, $S_4 = (7, 9)$. The first five trucks in the arrival sequence belong to the first group.

Step 1: P is set as $(1, 2, 3, 4, 5, 6, 7, 8, 9)$;

Step 2: $p_1^1 = (1, 5)$, $p_2^1 = (2, 3, 4)$, $p_3^1 = ()$, $p_4^1 = ()$;

Step 3: $s_1^1 = (5, 1)$, $p_2^1 = (4, 2, 3)$, $p_3^1 = ()$, $p_4^1 = ()$;

Step 4: Set $p_j^1 = s_j^1$ for all j from 1 to 4, and thus P becomes $(5, 4, 2, 3, 1, 6, 7, 8, 9)$. The algorithm ends.

3.3 Computer simulation

Computer programs were developed to generate sequences of arriving trucks, and to calculate the number of rehandles required to retrieve containers with this sequence of truck arrivals. Three scenarios were defined with regard to truck information quality:

- Scenario with complete sequence -- the complete sequence of truck arrivals is assumed to be known.
- Scenario with group information -- only the arrival groups of trucks are known, which means only the information which of several groups a truck will arrive in is known but the exact order of truck arrivals within any group is not available.
- Scenario with partial sequence -- the arrival groups are known, and the arrival sequence within the first group is known.

The parameters used to model information quality and bay configurations are described in table 3.1 and 3.2.

Table 3.1 Parameter setting for truck arrival information under different scenarios

Scenarios	Parameters			
	Length of known subsequence	Number of groups	Group size	Information updating rule
Complete sequence	(Number of stacks)*(stack height)	--	--	--
Group information	0	Within [2, total truck pool size]	Within [1, total truck pool size]	No update for static case; updated in terms of group size for dynamic case
Partial sequence	Equal to the size of first truck group	Within [2, total truck pool size]	Within [1, total truck pool size]	No update for static case; updated in terms of truck unit for dynamic case

Table 3.2 Parameter setting for container bay designs

Description	Parameter setting
Number of stacks	Within the range [2, 12]
Stack height	Within [2, min(number of stacks, 6)]
Stack storage capacity	Maximum stack height + 1
Bay balancing condition	Balanced bay, or unbalanced bay
Bay loading percentage	33.3%, 50%, 66.7%, 83.3%, 100%

The parameters listed in table 3.1 and 3.2 are user-defined inputs into the programs. Four parameters are considered for each scenario to define the information quality (table 3.1): the length of known subsequence, which refers to the number of trucks within the known arrival sequence; the number of groups; each group size; and the information updating rule, representing whether the information is real-time updated or not. The information updating rule for scenarios with group information differs from the updating rule for scenarios with partial sequence information. With groups, information is updated only after all the trucks in the first group are exhausted, and the updated amount of information is equal to the size of first group. With partial sequence information, information is updated every time a truck is served, and the updated information is one truck.

Another five parameters are required to define the bay configuration (table 3.2): number of stacks, stack height, stack storage capacity, bay balancing condition, and bay loading percentage. As for number of stacks, 12 is chosen as upper bound because double-wide yard cranes can span two parallel container blocks, with six stacks in each block bay. A balanced bay has the same initial stack height

for all stacks; an unbalanced bay has randomly generated stack heights that range from 0 to stack storage capacity. Bay loading percentage represents the utilization of bay storage capacity, which is calculated by:

$$\text{Bay loading percentage} = \frac{\text{number of containers stored in the bay before pickup operation}}{\text{number of stacks} * (\text{stack storage capacity} - 1)}$$

Different loading percentages are considered to test whether the availability of more storage space affects the amount of rehandle work.

For scenarios with complete truck sequences, the nearest relocation strategy and the RDH are used as solution approach. For the scenario with group information, another hybrid method which combines the RDH and pickup sequence dictation approach is also adopted for the scenarios where the sequence is dictated for the first group.

Two metrics are used to evaluate the container rehandling effort: the number of container rehandles; and the horizontal distance, which is the total distance travelled by yard crane between rows of the bay during the container relocating process, and measured in terms of the container width (one unit distance equals to the width of one container). Recall this is travel only between rows in one bay, not between bays. The number of container rehandles is used as the metric to evaluate the benefit of using RDH while the horizontal distance is used as the metric to evaluate the cost of using RDH, because the RDH tends to increase the horizontal distance traveled by crane and consequently increase the container handling time compared to current operation rule (nearest relocation strategy). Although minimizing the total distance traveled by crane is not our research objective, using both two metrics enables us to more comprehensively assess the effect of RDH.

The computer programs are written in Matlab, and the container bay is modeled using arrays to represent the storage locations. The stacking sequence of containers in the bay is randomly generated, with containers represented by retrieval orders and stored in an array. The truck arrival sequence or groups are generated according to the specified value of parameters (those in table 3.1). Three different functions are written for determining the storage location of the rehandled container, respectively representing the nearest relocation strategy, RDH, and the hybrid method of RDH and pickup sequence dictation approach. The main program simulates the container pickup operation under each solution approach by calling the corresponding function when a container is required to be rehandled and updating its storage location in the array. Two counters are used to respectively track the total number of rehandles carried and the horizontal distance traveled, and updated whenever a rehandle occurs. Many problem instances can be specified, and the average results of these instances provided. This includes the average number of rehandles and the average horizontal distance under each solution approach, the average efficiency gain in terms of rehandle reduction and the average efficiency change in terms of horizontal distance from our proposed solution approach compared to nearest relocation strategy.

3.4 Experiments, result and analysis

This section presents the benefit of utilizing truck arrival information estimated through simulation. The results for complete sequence information are presented first to provide an upper bound on the benefit realized.

3.4.1 Simulation results for the scenario with a complete truck arrival sequence

At least one thousand instances were tested for each combination of stack number, stack height, balancing, and loading conditions. Two performance measures are tracked in each experiment: the number of total rehandles and the horizontal distance traveled by crane during container relocation operation. Results are summarized below.

Result 1: Larger reduction in rehandles for bay configuration with more rows and higher stacks

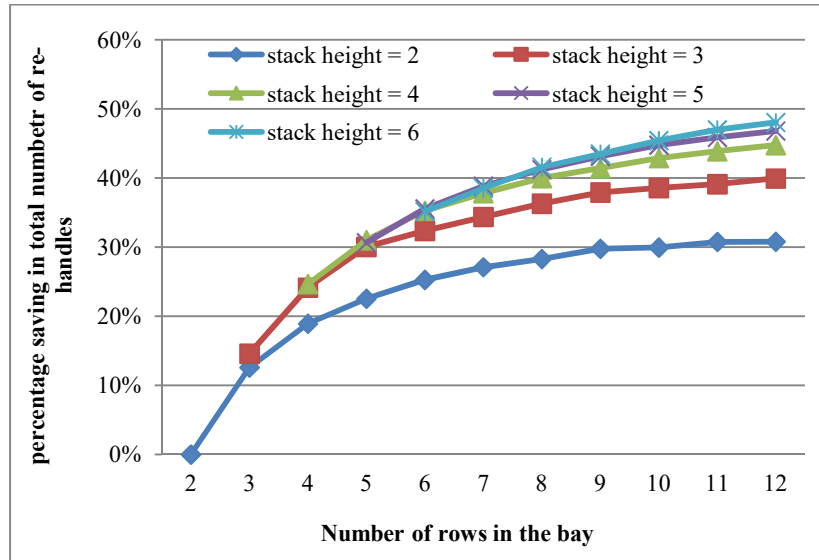


Figure 3.6 Performance comparison of RDH and nearest relocation strategy in terms of the number of re-handles

Figure 3.6 shows how the percentage savings in total number of rehandles of using RDH over nearest relocation strategy is affected by the bay layout. The figure indicates that the total number of rehandles could be significantly reduced under various combinations of stack height and row numbers if the complete sequence is known and utilized. Such efficiency gain grows with the stack height and number of stacks, and reaches 48% when the bay is twelve-stack wide and six-container high. Lesser rehandles could be translated into shorter container handling time and increased productivity of yard cranes.

Result 2: Increase in horizontal movement using RDH

The RDH searches for the storage location incurring minimal rehandles and tends to relocate rehandled container to farther stack than the nearest relocation strategy. The total horizontal distance traveled under the RDH is showed in Figure 3.7. One unit of horizontal distance represents the width

of one container. Figure 3.7 indicates that the horizontal distance travelled under the RDH increases exponentially with the stack height and the number of stacks in the bay.

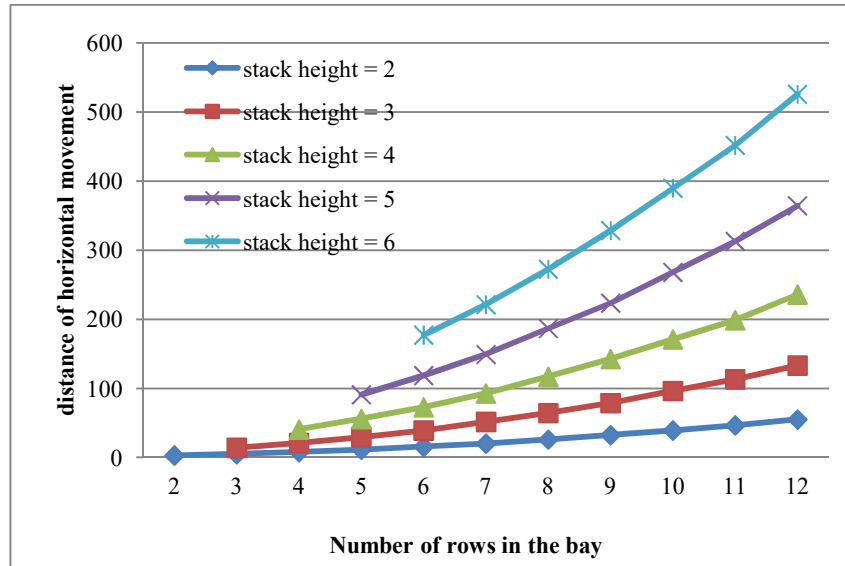


Figure 3.7 Performance of RDH in terms of horizontal distance

Figure 3.8 shows how the percentage increase in horizontal distance is affected by the bay layout. It grows linearly with the number of stacks in the bay, but decreases non-linearly with the initial stack height.

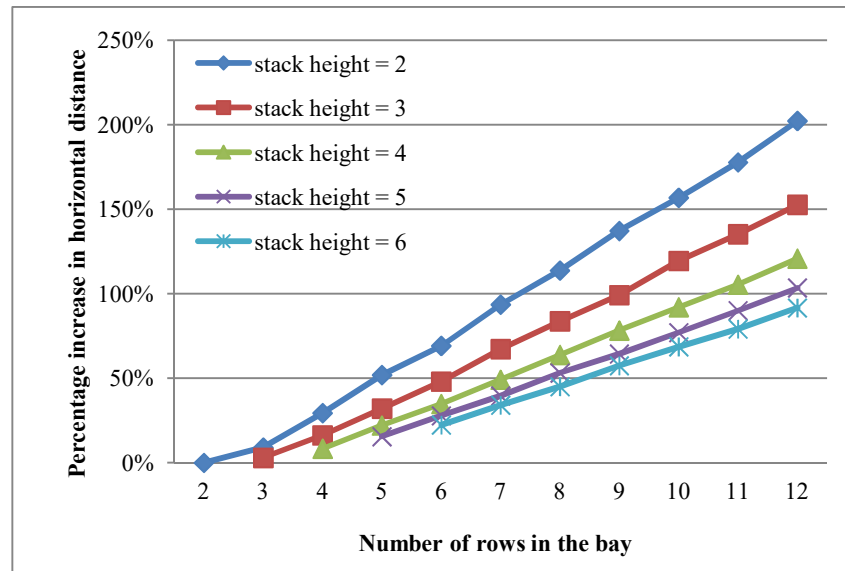


Figure 3.8 Performance comparison of RDH and nearest relocation strategy in terms of horizontal distance

Longer horizontal movement could lengthen container handling time and weaken the benefit of using the RDH in saving container handling time. The extent to which depends on the relative cost of horizontal travel to rehandles.

Result 3: the cost of reducing rehandles increases with number of stacks but decreases with stack height

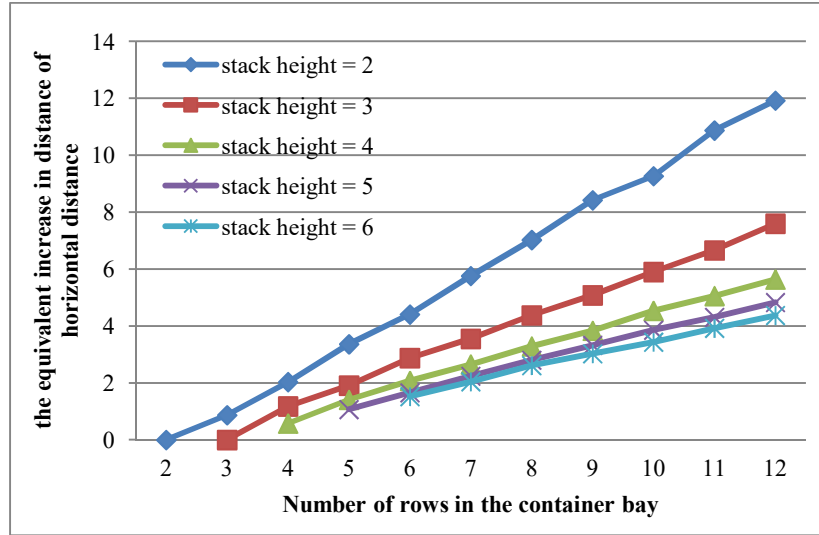


Figure 3.9 Comparison between increase in horizontal distance and reduction in number of re-handles

Figure 3.9 shows the equivalent increase in horizontal distance resulting from one reduction in number of rehandles using the RDH. It illustrates the cost of reducing rehandles is directly associated with the bay layout -- it increases linearly with the number of rows, and decreases with the initial stack height.

Figures 3.6 and 3.9 illustrate how the benefit and the cost of using RDH are influenced by the bay configuration. For the container bay with more stacks, the rehandle reduction achieved by RDH is larger but associated unit cost also becomes higher; for the container bay with higher stacks, the efficiency gain is larger while the unit cost becomes lower.

Result 4: Impact of bay balancing and loading percentage on rehandle reductions

The impact of loading percentages on the reduction of rehandles under balanced bay configuration is shown in Figure 3.10.

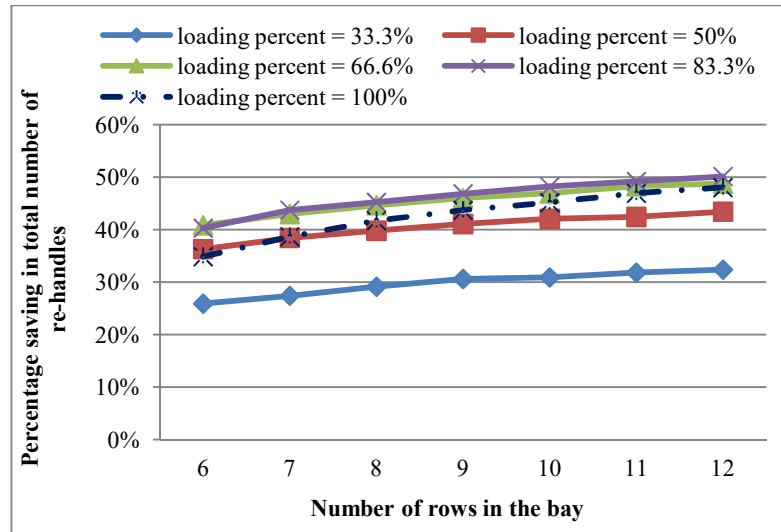


Figure 3.10 Performance of RDH under balanced bay with different loading percentages

Note: the initial stack height is 6.

Figure 3.10 illustrates that the benefit gained from using the RDH first increases with the loading percentage, but drops off when the loading percentage reaches 100%. If the bay is not fully loaded, there are more available location choices for the rehandled container. This increases the likelihood of finding a storage location that incurs fewer rehandles. However, if the loading percentage is too small, the stack is short and the rehandles are less necessary. Consequently the opportunity to further reduce rehandles is small even there are many location choices. Those two mechanisms affect the performance of the RDH at the same time and generate the benefit curve shown in Figure 3.10.

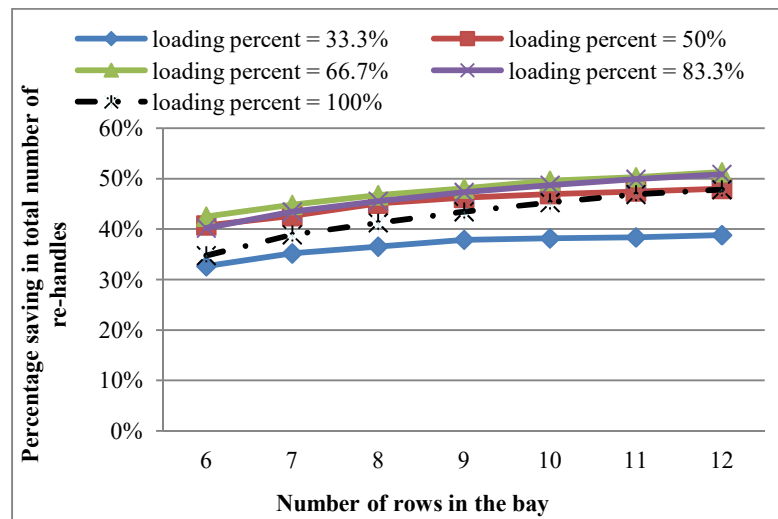


Figure 3.11 Performance of RDH under unbalanced bay with different loading percentages

Note: the initial stack height is 6.

The impact of loading percentages on the number of rehandles under unbalanced bay configuration is shown in Figure 3.11. Figure 3.11 illustrates the same trend in benefit as under the

balanced bay configuration—the benefit gained from using the RDH first increases with the loading percentage, but drops off when the loading percentage reaches 100%. The comparison between Figure 3.10 and Figure 3.11 also indicates the impact of bay balancing condition on possible efficiency gain—an additional 5% savings in rehandles is generated with the unbalanced bay compared to balanced bay when the bay loading percentage does not exceed 50%. However, it makes no difference while the bay loading percentage is higher than 50%.

Overall the balancing condition of the initial container bay has very limited impact on the performance of the RDH in reducing total number of rehandles; bay loading percentage has more impact on rehandle reductions, and higher benefit is resulted if the loading percentage is above 50% but lower than 100%.

3.4.2 Simulation result for the scenario with incomplete truck arrival information

The results above provide insight into the benefit from complete truck arrival information. They illustrate how the bay configuration impacts the reduction in rehandles and the increase in horizontal distance traveled. In this section the scenarios with different levels of information quality are modeled to identify how information quality affects rehandle reductions.

Our experiments considered two basic scenarios: the scenario with group information (called scenario 1) and the scenario with partial sequence (called scenario 2). For each scenario three sets of parameters were considered: the information updating rule, the amount of known truck information, and the bay configuration. With regard to information updating rule, the static case without updating information and the dynamic case employing specific updating rules were considered. With regard to the amount of known truck information, three specific parameters were used to define the information quality: the length of known truck subsequence, the number of truck groups, and the group size (parameter values are showed in table 3.1). With regard to the bay configuration, two parameters were considered: the stack height and the number of stacks. For stack height, two parameter values were tested --3 and 6 which respectively represent the upper bound and the lower bound. In the same manner two parameter values were tested for the number of stacks, which are 3 and 12 respectively. Some combinations of above parameters were tested in our experiments, and 1000 instances were generated for each combination.

For the first scenario, both the nearest relocation strategy and RDH were adopted as solution approaches to relocate containers. For the second scenario with partial sequence, a third approach, using the RDH and pickup sequence dictation approach simultaneously, was employed. The experiments are designed in such a way to examine how much additional benefit could be obtained by knowing more accurate truck information based on the same operation strategy, and also how much additional benefit could be generated by dictating truck sequence under the same information quality.

3.4.2.1 Simulation result with static truck information

Result 1: rehandle reductions when trucks are assigned to two groups

The simulation results when all the trucks retrieving containers in the bay are assigned to two groups are shown in Figure 3.12. As expected, knowing more information results in larger benefits; dictating the truck sequence also brings additional benefits which grow exponentially with the length of known truck subsequence. Four additional observations can be made from the simulation results.

First, with two groups, the percentage saving is convex with the size of the first truck group (scenario 1), and reaches maximum when the two truck groups have the equal size.

Second, knowing the partial truck sequence generates little additional benefit when the length of known subsequence is small. Notice in Figure 3.12 that the three scenario curves overlap when the number of trucks in the first group is small. Recall that the length of known truck subsequence is set the same as the size of the first group. Within the scenarios tested, until the number of trucks in the subsequence reaches about 1/7 of the total number of trucks, there is no value for knowing and using sequence information.

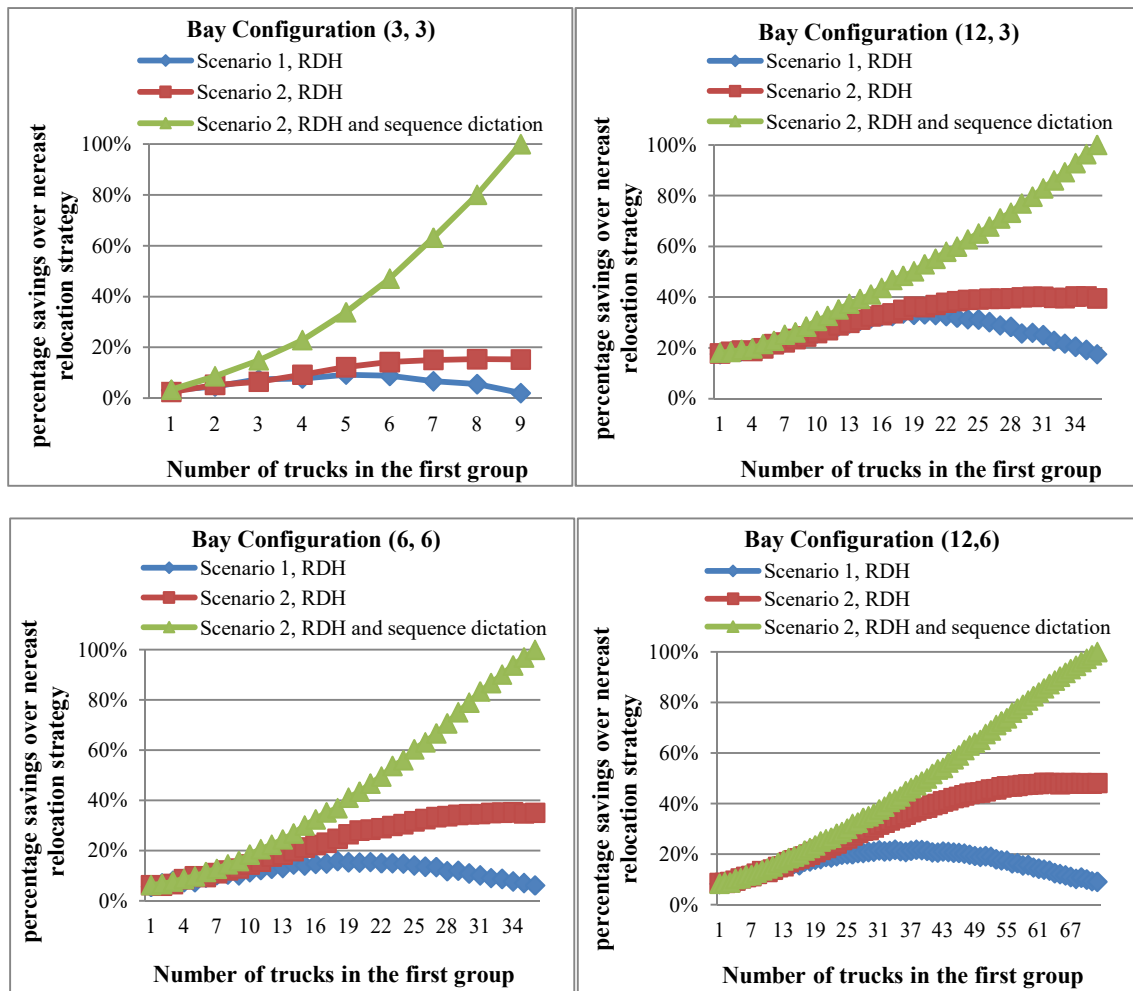


Figure 3.12 Comparison of RDH, pickup sequence dictation approach to nearest relocation strategy under various truck group sizes and lengths of known subsequence

Note: (a, b) above each graph represents the bay configuration, with a as number of stacks, and b as stack height.

Third, the maximum benefit under the RDH can be achieved without the complete sequence. In Figure 3.12 the curve corresponding to scenario 2 under the RDH gradually grows and then becomes flat, which implies after the length of known subsequence reaches a certain value, knowing more sequence information does not generate additional rehandle reductions. The minimum length requirement of known subsequence to achieve peak benefit is estimated and summarized in table 3.3. The results show that under various bay configurations at least 67% of the total truck sequence is required to obtain the maximum benefit, and after the length reaches 75% of the total sequence no additional value is obtained.

Table 3.3 The critical length of known truck subsequence to obtain maximum benefit under RDH for various bay configurations

Stack height	Number of stacks	
	3, or 6	12
3	67%	64%
6	75%	75%

Note: the peak benefit is perceived as being achieved at a certain length of subsequence when the difference between the percentage saving resulted from available subsequence information and the maximum saving is within 2%. The length is calculated as the proportion of truck numbers in known truck subsequence to the total truck numbers.

Fourth, dictating the truck arrival sequence generates little benefit when the length of known truck subsequence is small. The curve corresponding to scenario 2 in Fig. 13 which uses the RDH and pickup sequence dictation approach simultaneously first overlaps with the curve corresponding to scenario 2 which uses the RDH, and later grows exponentially with the number of trucks in the first group. Until the length of known subsequence reaches 1/3 of the whole sequence, the additional benefit generated from dictating truck sequence is still within 8% for three-container-high bay and 5% for six-container-high bay.

Result 2: rehandle reductions when trucks are assigned to more groups

Our experiments also tested the impact of group numbers on the performance of proposed solution approaches by dividing the whole truck pool into several equally sized groups. Simulation results when trucks are assigned to different groups are shown in Figure 3.13, and two observations can be made from the results:

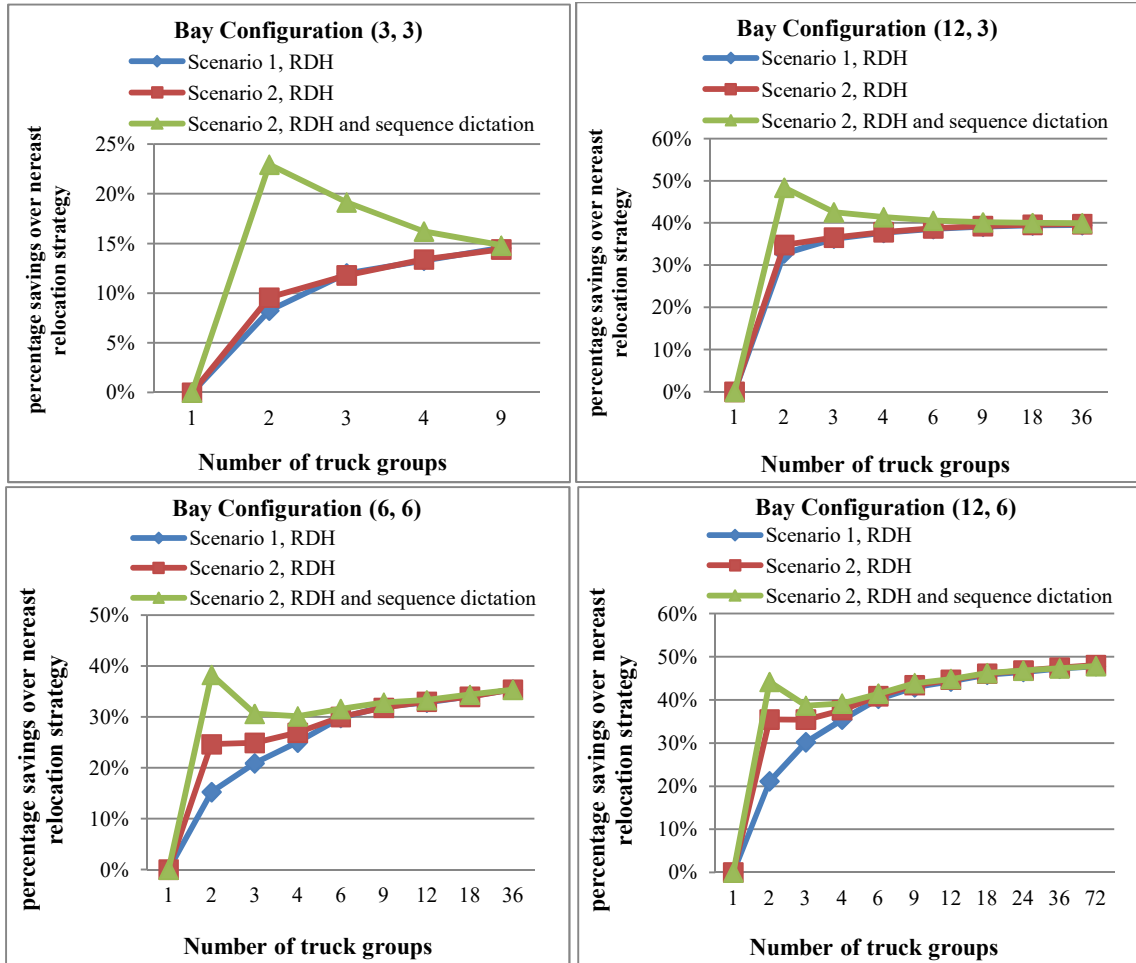


Figure 3.13 Comparison of RDH, retrieval sequence dictation approach to nearest relocation strategy under various truck group numbers and lengths of known subsequence

Note: (a, b) above each graph represents the bay configuration, with *a* as number of stacks, and *b* as stack height.

First, group information can be very valuable in reducing number of rehandles. Significant benefit can be obtained from only two truck groups, and the magnitude of benefit grows with the number of groups (Figure 3.13). Table 3.4 shows the fraction of benefit provided from knowing just the group number (two equal groups) as compared to knowing the entire sequence. At least 43% of the maximum benefit is realized with small blocks, with the value increasing with the number of stacks. 82% of the maximum benefit can be achieved with just two groups for the bay with a width of twelve stacks and a height of three containers.

Table 3.4 The comparison of benefit obtained from knowing only which of two groups the truck will arrive in as compared to the maximum benefit achieved from having the complete sequence

Stack height	Number of stacks	
	3, or 6	12
3	56%	82%
6	43%	44%

Note: each value in table above indicates the ratio of percentage saving in re-handle reductions obtained from grouping arrivals in two groups as compared to the maximum benefit obtained from the complete sequence.

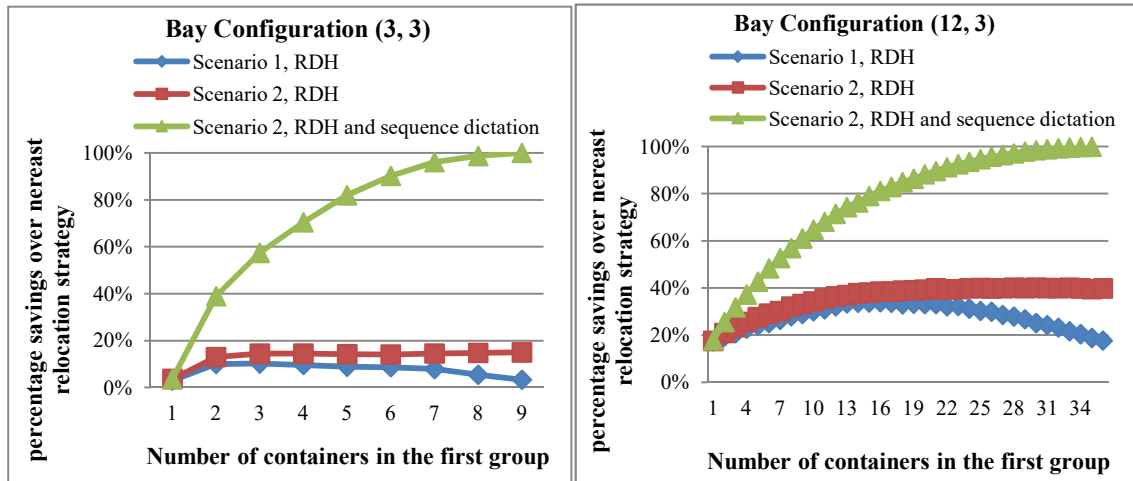
Second, the value of partial sequence information decreases with shorter subsequence and more groups. Figure 3.13 shows that the gap between three scenario curves diminishes with the increase in number of truck groups and the curves start overlapping when the group number reaches six. Such result is quite consistent for different bay configurations. It indicates that when the group number increases to 6 and the length of known subsequence decreases to 1/6 of whole sequence, partial sequence information does not generate additional benefit.

Third, pickup sequence dictation approach is much more effective given a longer partial sequence. Notice that there exists an initial jump on curves of scenario 2 for which the RDH and pickup sequence dictation approach are used simultaneously. At the beginning of the curve corresponding to scenario 2 in which two approaches are employed simultaneously, the length of partial sequence accounts for 1/2 of the whole sequence, the pickup sequence of many trucks could be dictated and a lot of rehandles could be directly eliminated; approaching the end of the curve, less trucks can be dictated and mainly the RDH functions which could only avoid future rehandles for relocated containers. Therefore, such curves are not smooth and have jumps at the beginning.

3.4.2.2 Simulation result while the truck information is dynamically updated

Result 1: rehandle reductions when trucks are assigned to two groups

The simulation results when trucks are assigned to two groups and truck information is dynamically updated are shown in Figure 3.14.



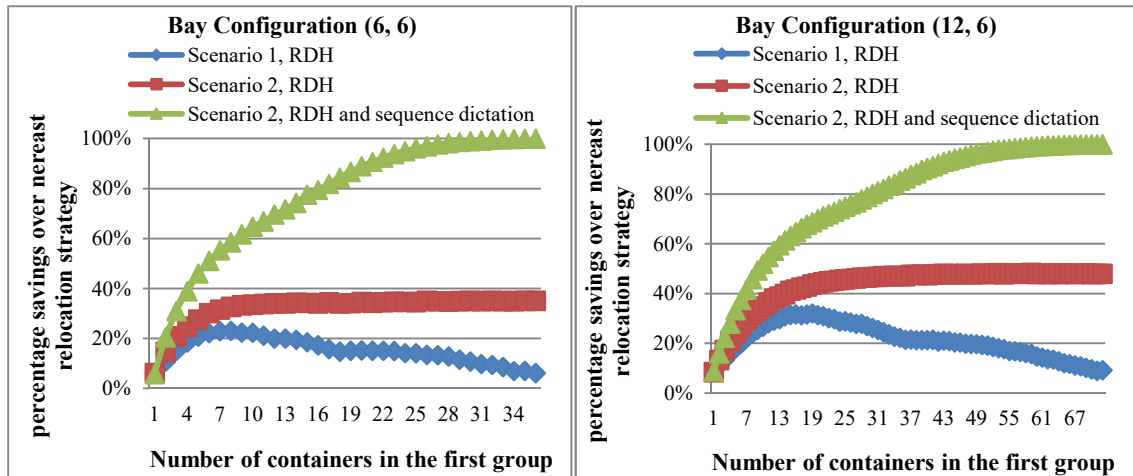


Figure 3.14 Comparison of proposed solution approaches to nearest relocation strategy under various truck group sizes and lengths of known subsequence, and accessibility to dynamically updated information

Note: (a, b) under each graph represents the bay configuration, with *a* as number of stacks, and *b* as stack height.

Comparing Figure 3.14 with Figure 3.12, four observations can be made:

First, in the scenario with group information, updating information in real time can generate greater maximum benefit, and peak benefit occurs at a much smaller first group size than in the static case. For a three-container-high bay, the largest benefit is achieved when the size of the first group captures 33%-44% of the complete truck sequence; however it is only 1% higher than the maximum percentage saving obtained at the static case. For a six-container-high bay, the largest benefit is achieved when the size of the first group hits 22% of the whole truck sequence, and is at least 7% higher than the maximum percentage saving obtained in the static case.

Second, when real-time information is available, partial sequence information can generate significant benefits. Compared to the scenario with group information, knowing 1/3 of the truck arrival sequence could generate an additional 4% reduction in rehandles for a three-container-high bay, and 14%-16% additional percentage savings for six-container-high bay with the RDH.

Third, for the scenario with partial sequence information, updating in real time provides maximum benefit with the RDH in a much shorter known subsequence. Table 3.4 shows that only 22%-42% of the whole sequence is required to obtain the same benefit as the scenario with the complete sequence. The comparison between table 3.3 and 3.5 shows updating information in real time could reduce the information need by 22% - 50% of total truck sequence.

Table 3.5 The critical length of known truck subsequence to obtain maximum benefit under RDH given real-time updated information

Stack height	Number of stacks	
	3, or 6	12
3	22%	42%
6	25%	36%

Note: the peak benefit is perceived as being achieved at a certain length of subsequence when the difference between the percentage saving resulted from available subsequence information and the maximum saving is within 2%. The length is calculated as the proportion of truck numbers in known truck subsequence to the total truck numbers.

Fourth, dictating the truck arrival sequence can generate significant benefit with a small known truck sequence. The additional percentage reduction in rehandles generated from dictating the truck arrival sequence is above 2% when there are only two trucks in the known subsequence, and exceeds 28% when the length of known subsequence reaches 1/3 of the total truck sequence.

Result 2: rehandle reductions when trucks assigned to two and three groups

Our experiments also tested the impact of updating truck information on the magnitude of benefit achieved from assigning trucks into different groups. The case of assigning trucks into two groups and the case of assigning trucks into three groups are tested. For the case of three groups, the first two groups have the same size. Different numbers of trucks within the first group are considered. The results shown in Fig. 15 suggest that with the RDH the maximum benefit can be achieved when the first group reaches the critical size and that no additional benefit can be generated from a larger group. Such critical size of the first group is used as the upper bound for its size in this experiment for scenarios in which the RDH is used as the solution approach. For scenarios in which the hybrid method of RDH and sequence dictation approach is used, $\frac{1}{2}$ of the total truck sequence is used as the upper bound for the size of the first truck group. Various bay configurations were considered. The results for using group information under two different configurations of container bay are shown in Figure 3.15.

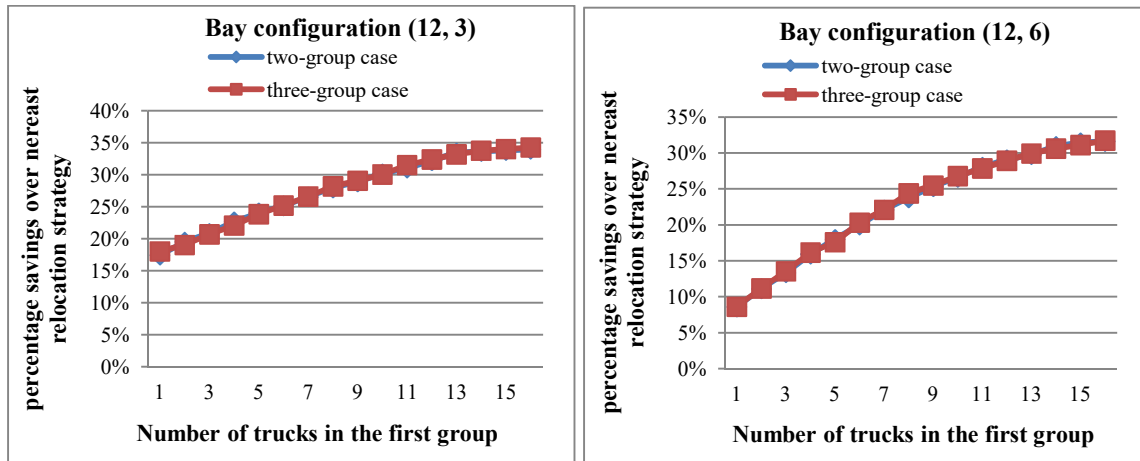


Figure 3.15 Comparison of RDH to nearest relocation method in the scenario only truck group information is available

Note: (a, b) under each graph represents the bay configuration, with a as number of stacks, and b as stack height.

Figure 3.15 shows that when two truck groups are known and the information is updated, having an additional group does not generate additional rehandle reductions. The results are consistent when different truck subsequence lengths or different solution approaches are adopted, or under various bay

configurations. Again such simulation results verify that updating information in real time lowers the information needed to realize significant reductions in rehandles.

3.5 Summary

The contributions of this chapter to the literature are:

- Two strategies for reducing container rehandles during the drayage truck retrieval process. These strategies are designed to be used real-time, allowing for information updates during the retrieval period.
- Analysis of the rehandle reductions expected from these strategies under a variety of information quality scenarios including complete and incomplete information.
- Analysis of how the container bay configuration affects the container handling efficiency under these scenarios.

Through these contributions we can conclude that potential rehandle reductions in all cases are significant. Complete truck sequence information is not required to significantly reduce the number of rehandles using the RDH. Significant reductions can be obtained from knowing which of several groups a truck will arrive in. Updating information in real time significantly lowers the information need for achieving a certain amount of benefit, and only requires knowing about 20%-40% of the total truck sequence to maximize the benefit under the usage of RDH. In addition, using the pickup sequence dictation approach and RDH simultaneously further enhances the magnitude of benefit. For a specific bay, the simulation tools developed allow for specification of clear thresholds on data quality, for example, if the real time information is available, that the investment needed to obtain information regarding three groups over two groups would not be rewarded with additional reductions in rehandles. More significant rehandle reductions can be obtained from bay configurations with taller stacks and a larger number of rows. Such benefits are significant even for a small number of short stacks, and increase more modestly for increasing bay sizes. Whether the container bay is initially balanced or not almost has no impact on the magnitude of the benefit, while bay loading condition has more impact and a larger benefit can be obtained from not full, but more than half loaded bays.

In summary, significant reductions in rehandles can be obtained with small improvements in terminal information regarding truck arrivals. Just splitting the truck arrivals into two groups allows for significant reductions in rehandles. In fact, any amount of information about arrival trucks during container pickup is beneficial, only reducing the container rehandling work. Technology investments such as equipping trucks with GPS units to keep track of truck location in real time are not necessarily required to obtain this truck information. In fact truck information could be obtained in a variety of ways including existing gate appointment systems, which could provide some information about truck arrival time windows, or phone calls from approaching trucks. Utilizing such currently available information does not incur much effort or cost; however, it does require cooperation, and collaboration between the terminal and trucking operations.

Chapter 4 The Impact of Truck Arrival Information on System Efficiency at Container Terminals

This chapter addresses the problem of evaluating the impact of truck arrival information on crane productivity and truck transaction time at container yards. The objective of this chapter is to identify the information requirement for achieving a significant improvement in the performance of yard crane service system, and evaluate the impact of different yard configurations on the effectiveness of this truck information.

This chapter considers the retrieval of import containers by the yard crane within a container block to serve drayage trucks (Figure 3.1). The set of assumptions introduced in chapter three (see section 3.1) also holds here; two additional assumptions are introduced here:

- (1) The yard crane serves the drayage trucks by the first-in-first-out rule (FIFO);
- (2) Truck arrivals can be modeled by a Poisson process.

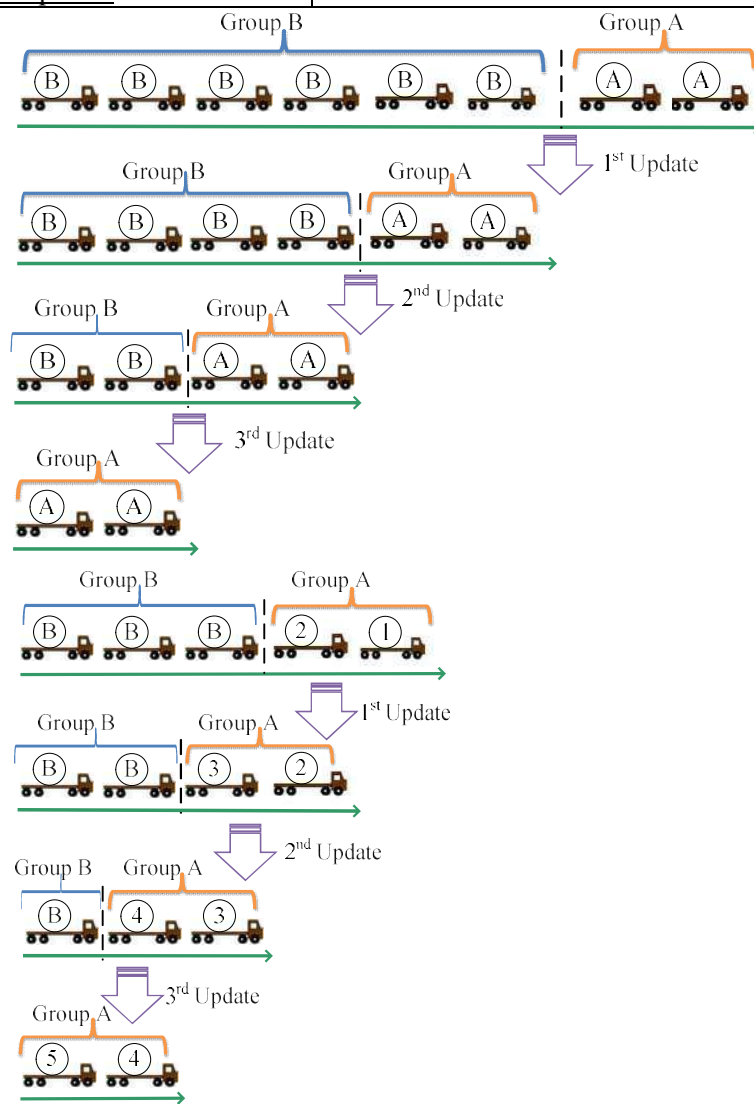
Truck information is considered for container retrieval within the same bay. Since container bays are independent of each other, the analysis for container re-handling work is performed for one bay by one crane and the result is the same for any bay within the block. This research on the operation of 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 sub-areas and each sub-area is assigned to one yard crane, with each crane modeled as an independent system.

Based on the amount of known truck information and whether the information is static or updated in real time, six scenarios are defined to represent situations with various information qualities (Table 4.1).

Table 4.1 Scenario Definitions

Scenario	Definition
<u>No truck information</u>	No truck information is available.
<u>Static group information</u>	The terminal knows which of several groups a truck will arrive in, but not of the exact order of truck arrivals within any group. For example, trucks can be assigned to two groups, A, and 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.
<u>Static partial sequence</u>	The terminal knows which of several groups a truck will arrive in, and the exact order of truck arrivals for the first group. Information is not updated over time.
<u>Dynamic group information</u>	The terminal knows which of several groups a truck will arrive in, 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 4.1(a) is provided as an example. After the two trucks in group A have been served, information about a new arrival group of 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.
<u>Scenario with dynamic partial sequence</u>	The terminal knows which of several groups a truck will arrive in, and the arrival sequence of the first group. After a truck in the first group is served, information about the first truck within next group becomes available, and this truck joins the first group. Take figure 4.1(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.
<u>Scenario with complete sequence</u>	The complete sequence of truck arrivals is known.



(a)

(b)

Figure 4.1 Information updating rule for dynamic scenarios: (a) Information updating for dynamic group information, (b) information updating for dynamic partial sequence

As demonstrated in chapter 3, truck arrival information is useful in reducing number of container re-handles by carefully determining the storage location of re-handled containers to avoid future re-handles. The revised difference heuristic proposed in section 3.2 is applied in this chapter for using the truck arrival information to improve yard operations. This chapter is organized as follows. Section 4.1 describes the proposed methodology for evaluating the crane service time and truck transaction time. Section 4.2 presents the experimental results on the impact of various information qualities on yard crane service system performance. Section 4.3 summarizes the key findings.

4.1 Research methodology to evaluate crane productivity and truck transaction time

In this section, the method to estimate the 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 inter-arrival time of trucks and the service time of yard crane.

4.1.1 Crane service time estimation

Crane service time includes the travel time between yard-bays, the re-handling time 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 3.1 for definition of bays, blocks, stack, and row):

- c -- the number of bays in the block;
- a -- the number of stacks in each bay;
- b -- the initial number of containers in each stack;
- h_1 -- horizontal distance traveled by trolley to relocate the re-handled container;
- d_1 -- vertical distance traveled by trolley to pick up the re-handled container;
- d_2 -- vertical distance traveled by trolley to drop the re-handled container;
- h_2 -- horizontal distance traveled by trolley to handle the required container;
- d_3 -- vertical distance traveled by trolley to pick up the required container;
- d_4 -- vertical distance traveled by trolley to drop the required container on drayage truck;
- v_t -- average travel speed of the crane across yard bays;
- v_f -- average hoist speed of trolley when moving a container;
- v_e -- average hoist speed of trolley when not moving a container;
- v_h -- average horizontal travel speed of trolley;
- R -- number of re-handles to serve one truck;
- T_t -- crane travel time between yard bays;

T_r -- re-handling time;

T_d -- required container handling time;

T_o -- time for performing one container re-handle.

4.1.1.1 Crane travel time estimation

Under the assumption that trucks are served FIFO and 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:

$$E(T_i) = c / (3v_i) \quad (1)$$

$$V(T_i) = c^2 / (18v_i^2) \quad (2)$$

4.1.1.2 Crane re-handling time Estimation

It is assumed that the number of re-handles and the time to re-handle one container are independent. Consequently the expected re-handling time can be calculated as the product of expected number of re-handles and the expected time to re-handle one container.

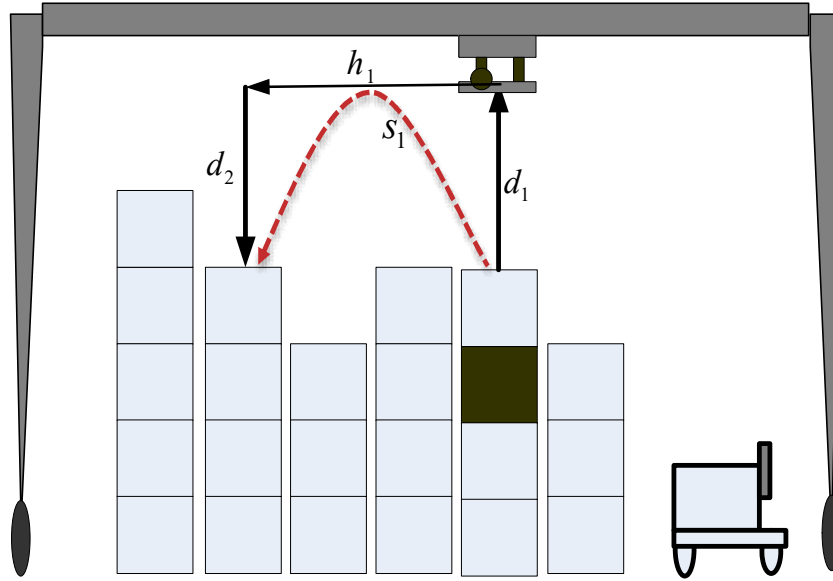


Figure 4.2 Trolley movements in one re-handle cycle

(1) Estimation of time to rehandle one container (T_o)

One re-handle is defined as a complete cycle: the trolley reaches the container to be re-handled, moves it to another stack, and returns 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 the vertical movement are carried separately.

As illustrated in figure 4.2, the trolley travels along the path $d_1 \rightarrow h_1 \rightarrow d_2$. The upper bound can therefore be estimated as:

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

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 4.1, in which the trolley travels along trajectory s_1 . The lower bound can be estimated as:

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

The average of the upper and lower bound is used to estimate the expected time to re-handle 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.

(2) Estimation of number of re-handles (R)

The expectation and variance for the number of rehandles can be estimated based on the probability distribution of the number of container re-handles. A computer-based simulation is developed to model the container pickup operation and is used to derive the probability distribution of the number of re-handles 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 re-handles performed and the horizontal distance traveled by the trolley. The program is able to evaluate the amount of re-handling work under various truck information qualities and bay configurations. A detailed description of the computer simulation can be found in section 3.3.

The expectation and variance of re-handling time can be calculated as:

$$E(T_r) = E(T_o) \cdot E(R) \quad (5)$$

$$V(T_r) = E(T_o)^2 \cdot V(R) \quad (6)$$

4.1.1.3 Crane handling time estimation

One handle is defined for an inbound container as a cycle that starts with the trolley above the truck lane, moves to reach the required container, travels back to drop it on 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 (3) , only replacing d_1, d_2, h_1 with d_3, d_4, h_2 ; the lower bound of T_d can be expressed as:

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

4.1.1.4 Estimated crane service time and crane productivity

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

$$E(T_c) = E(T_t) + E(T_r) + E(T_d) \quad (8)$$

$$V(T_c) = V(T_t) + V(T_r) \quad (9)$$

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

4.1.2 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 3.1). The traffic density is:

$$\rho = \lambda \cdot E(T_c) \quad (10)$$

Expression (11) can be used to calculate the expected truck transaction time (Ross, S.M., 2009):

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

4.2 Numerical results

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 impacts of various information qualities, truck arrival rates, and block configurations on drayage truck/ yard crane system performance are evaluated to identify the effectiveness of truck information under different system configurations. The parameter values of the yard crane are listed in Table 4.2, and are used for numerical experiments.

Table 4.2 Specifications for the rubber-tired gantry crane (Konecranes, 2009)

Parameters	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	12.34m for two-container-high block, 15.24m for three-container-high block, 18.14m for four-container-high block, 21.04m for five-container-high block, 23.94m for six-container-high block

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 crane lifting height, and d_4 is calculated by subtracting the truck chassis height from crane lifting height. Here 1.450m (11) is used as chassis height. For scenario without truck information, h_1 is estimated based on the simulation result about the average horizontal distance travelled by trolley for one rehandle; for all the other scenarios, h_1 is estimated as $\frac{1}{2}$ of the block width ($a/2$). h_2 is estimated as $\frac{1}{2}$ of the block width ($a/2$). The container dimension is standard 40 ft.

4.2.1 Performance analysis under various information qualities

A block with $a = 6, b = 5, c = 40$, and $\lambda = 6$ per hour is considered. When arrival trucks retrieving containers from the same bay are assigned into two groups, the impact of truck group size on the performance of yard crane service system is shown in figure 4.3 and 4.4.

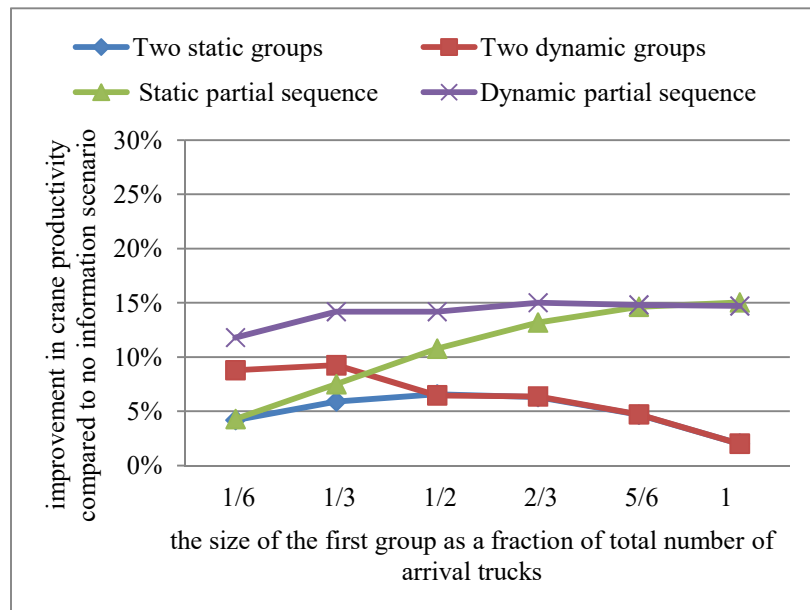


Figure 4.3 Improvements in crane productivity under various first truck arrival group sizes

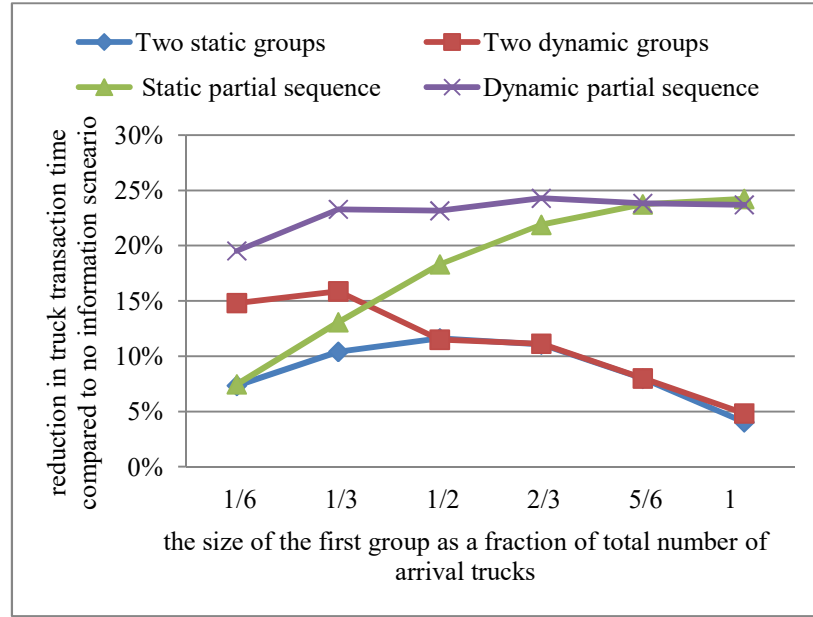


Figure 4.4 Percentage savings in truck transaction time under various first truck arrival group sizes

Figures 4.3 and 4.4 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 figure 4.3 and 4.4.

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

Second, updating information in real time can lower the requirement on information quality. For the scenario with dynamic group information, peak benefit is realized at a much smaller first group; for the scenario with dynamic partial sequence information, significant benefit is achieved from knowing 1/6 of the total sequence and little additional value is generated from a longer sequence. Therefore, a complete sequence is not required for significantly improving system performance if real time information is available.

4.2.2 Performance analysis under various truck arrival rates

Consider a block with $a = 6$, $b = 5$, $c = 40$. It is assumed that arriving trucks retrieving containers from the same bay are assigned into two groups, with the first group accounting for 1/3 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 per hour to 10 per hour, and result is presented in Figure 4.5.

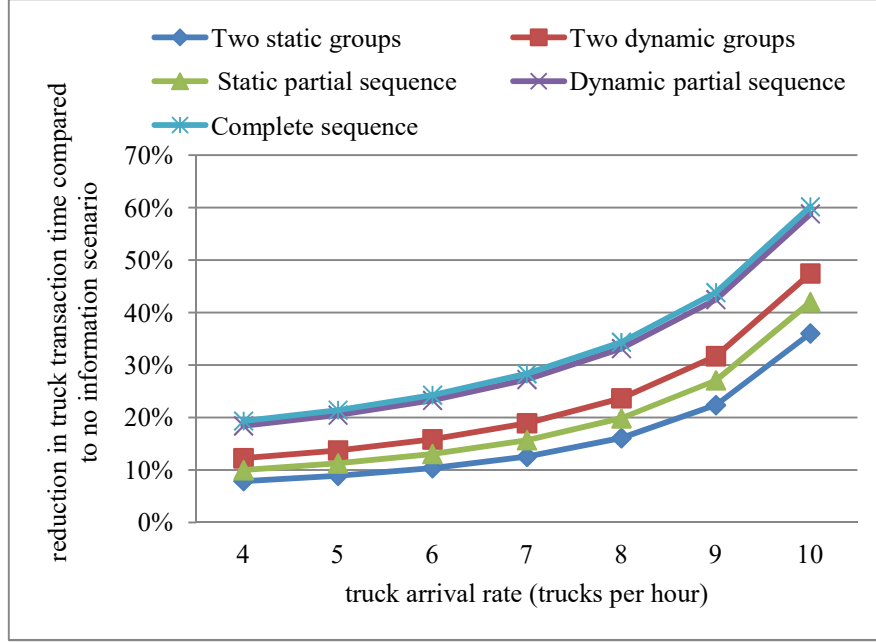


Figure 4.5 Percentage savings in truck transaction time under various arrival rates

Figure 4.5 illustrates 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 only knowing truck arrival groups. 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 4.5 also demonstrates the consistent effect of truck information quality on truck transaction time under different truck arrival rates. In general, information for two static truck groups can generate almost 1/2 of the truck time saving achieved from complete sequence; dynamic group information is more valuable than knowing 1/3 of truck arrival sequence and can result in an additional 2%-4% time saving; 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.

4.2.3 Performance analysis under different block configurations

Consider a block with 1200 containers, $\lambda = 6$ per hour, and a block with $a = 6$, $b = 5$, $c = 40$ as the base configuration. We assume that arriving trucks retrieving containers from the same bay are assigned into two groups, with the first group accounting for 1/3 of the total number of arrival trucks.

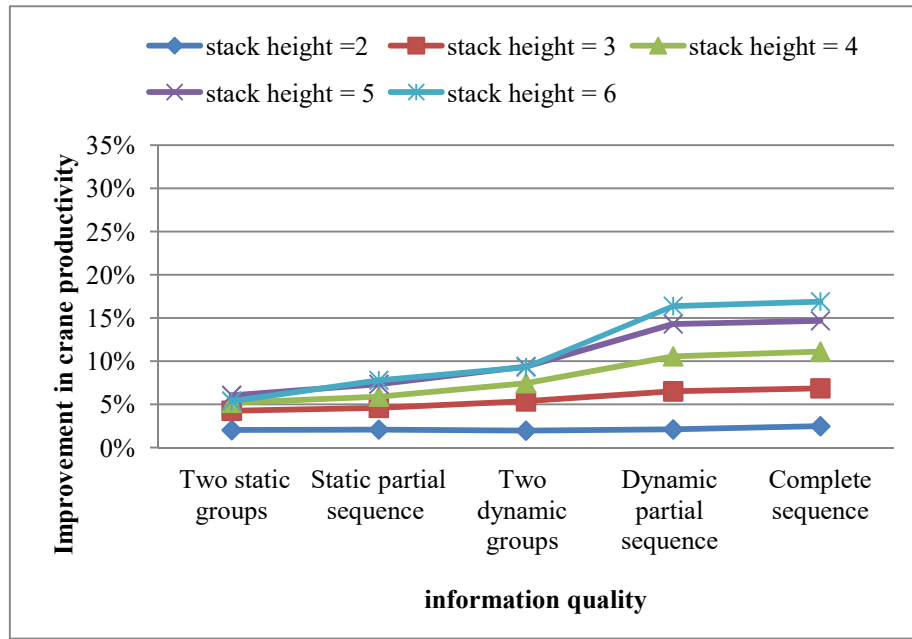


Figure 4.6 Crane productivity under various configurations of stack height and bay numbers

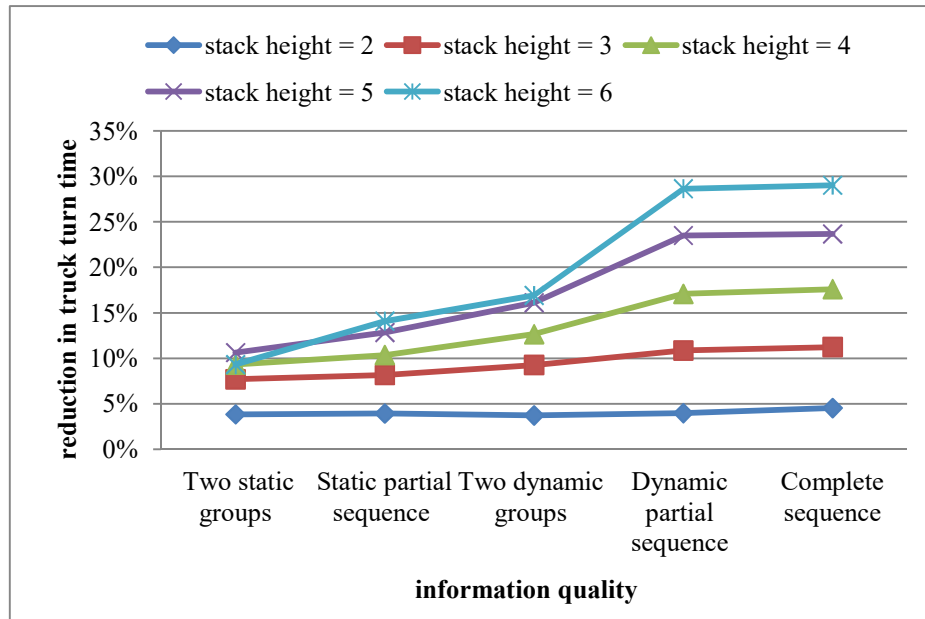


Figure 4.7 Truck transaction time under various configurations of stack height and bay numbers

Figures 4.6 and 4.7 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 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.

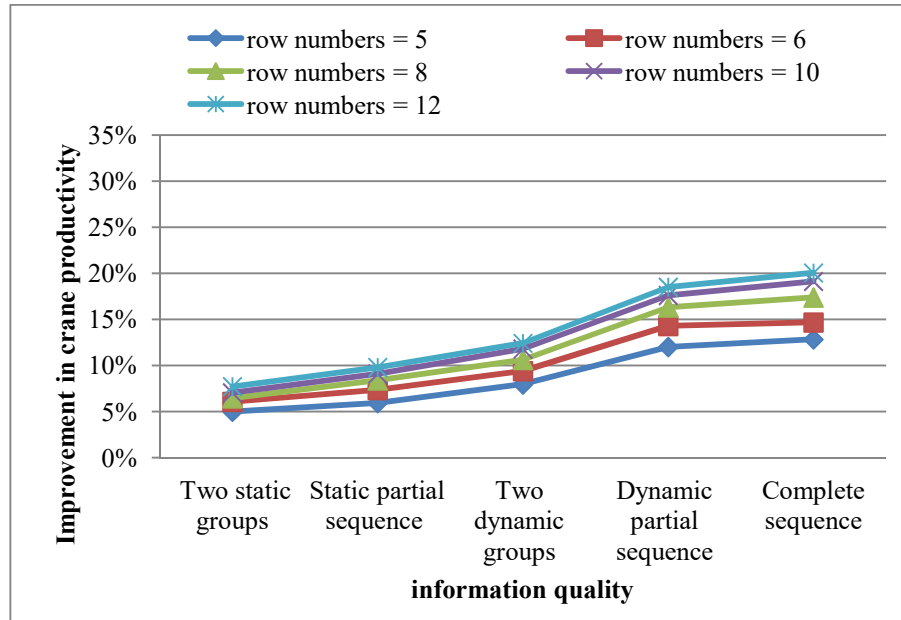


Figure 4.8 Crane productivity under various configurations of row numbers and bay numbers

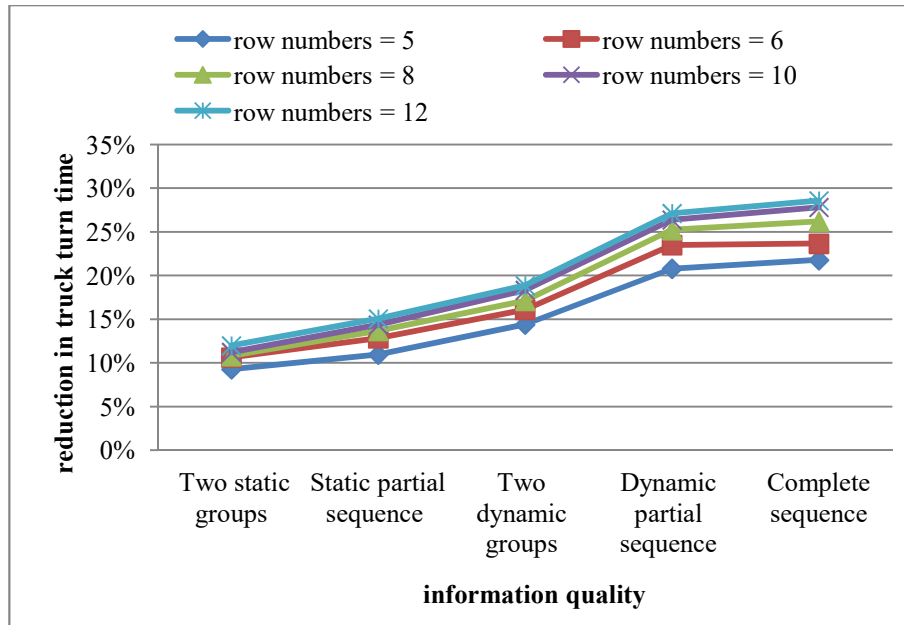


Figure 4.9 Crane productivity under various configurations of row numbers and bay numbers

Figures 4.8 and 4.9 illustrate system performance under the block configuration with initial stack height as five ($b = 5$). Again different combinations of number of rows and bays have 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. The comparison between Figures 4.6, and 4.7 and Figures 4.8, and 4.9 shows that stack height has more impact on the effectiveness of utilizing arrival information than other block configuration factors.

4.3 Summary

This chapter 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 re-handles, 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 from utilizing truck information. These results can identify terminals likely to experience significant benefits, and inform the design of a data sharing system. For very detailed estimates of improvements at a particular terminal, a micro-simulation model should be developed that captures the unique terminal configuration, flow rates, and processing times.

The 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 at 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 1/3 of total number of trucks. Complete sequence information is not required to maximize the benefit.

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.

Chapter 5 Impact of truck appointment system on the system efficiency of container terminal

Some terminal operators at the San Pedro Bay Ports are particularly interested in knowing the benefit of having the time window information for trucks arriving the next day, based on current labor staffing strategies. Container terminals at Ports of Los Angeles and Long Beach have a gate appointment system which requires that the drayage trucks make an appointment 24 hours in advance for container pickup or drop off. Their gate appointment system provides terminal operators with truck arrival information and allows exploiting such information in container handling operations. This chapter addresses the problem of whether the truck arrival information obtained from an appointment system can be used to improve the drayage truck- container terminal interface and how the accuracy of information affects the usefulness of truck information. The objective of this chapter is to identify the impact of different terminal system configurations and the accuracy of information on the effectiveness of truck information and assist terminal operators understand the potential benefit that could be realized by utilizing their current truck appointment system.

To address this problem, three analyses are presented in this chapter. In sections 5.1 and 5.2, the impact of using truck time window information on container rehandling efficiency and the performance of yard crane service system are evaluated; in section 5.3, the impact of the accuracy of information on the effectiveness of truck information is quantified. The basic assumptions introduced in chapter 3 and 4 are also applicable in this chapter.

5.1 The impact of truck time window information on the container rehandling efficiency

This section quantifies the efficiency improvement in container rehandling work by utilizing the appointment window information of trucks, and evaluates the impact of terminal system configurations on container rehandling efficiency.

With regard to terminal system configuration, there are many factors affecting the availability of truck arrival information and yard operational efficiency, such as container dwell time on the yard, the duration of truck appointment window, appointment lead time, and so on. To evaluate the impact of these factors on container handling efficiency, several parameters are defined in table 5.1 to model the terminal system configuration and listed:

Table 5.1 Modeled terminal system configurations

Description	Parameter settings
Maximum dwell time of containers	Within the range (1, 14) in days
Appointment lead time	1 day, 2 days
Duration of truck appointment window	0, 0.5 hour, 1 hour, 2 hours, 3 hours, 4 hours
Bay configuration	Number of stacks: within the range (2, 12); Stack height: within (2, min(number of stacks, 6))

The assumptions mentioned in chapter 3 are applicable here, and this section considers only a bay of containers. Four parameters are used to describe the characteristics of truck appointment system and the terminal configurations as follows: maximum dwell time of containers refers to the longest

time that an import container sits at the container yard before being picked up by a drayage truck. For its parameter value, a range within [1 day, 14 days] is considered. The second parameter, appointment lead time, refers to how early appointments are made before truck arrivals. Two cases are considered: the appointments are made 1 day in advance, and 2 days in advance. It is assumed that appointments are always made at the end of the day. These two cases respectively provide a lower bound and upper bound for the benefit realized under the actual situation, in which the truck appointments are made any time of day and 24 hours in advance. The third parameter, duration of truck appointment window, is the length of time window assigned to trucks for container pickup. Five parameter values are considered for the time window duration: 0 (an exact arrival time is assigned and its duration is zero), 0.5 hour, 1 hour, 2 hours, 3 hours, and 4 hours. Exact arrival time is not realistic but represents the best-level information that could ever be achieved and is used to provide an upper bound on the benefit achieved. Since a more realistic case is that terminal operators have the truck appointment window information, time windows with different lengths are used to model different levels of precision for truck information. The last parameter, bay configuration, refers to the number of stacks and stack height of the container bay before the container retrieval operation starts. Here it is assumed that the container bay is balanced and fully loaded.

A computer program was written in Matlab to model container retrieval operations within a bay and takes all the parameters described in table 5.1 as inputs. It is assumed in the program that the terminal is open eight hours a day, and the underlying distribution of truck arrivals is modeled as a Poisson distribution. Therefore, the total number of truck arrivals within the complete time horizon is set to the total number of containers in the bay, and the exact arrival times of trucks are generated by a homogeneous Poisson process. The arrival time window is generated for each truck by assuming that the actual arrival could occur at any time within the duration of time window. The main program first generates the bay configuration and truck arrival time windows, and then translates the time window information into arrival group information. The logic behind arrival group classification is that if the time windows for different arrival trucks overlap with each other, then they are classified into the same group; otherwise they are split into different groups. Next, the main program simulates the container pickup operation under two different strategies (Revised Difference Heuristic algorithm (RDH) and nearest relocation strategy) by calling the corresponding function when a container is required to be rehandled and updating its storage location in the bay. When the simulation time reaches the end of each day, the program obtains new information about truck arrival time windows and updates the truck group information. The program keeps track of the total number of rehandles under each strategy occurred, and output that value as well as the efficiency gain in terms of rehandled reduction from RDH compared to a nearest relocation strategy.

The benefits of utilizing truck arrival information were estimated through simulation. At least 1000 instances were tested for each combination of maximum dwell time, appointment lead time, duration of time window, and bay configurations. Results are presented in following subsections.

5.1.1 Rehandle reduction under different combinations of time window duration and dwell time

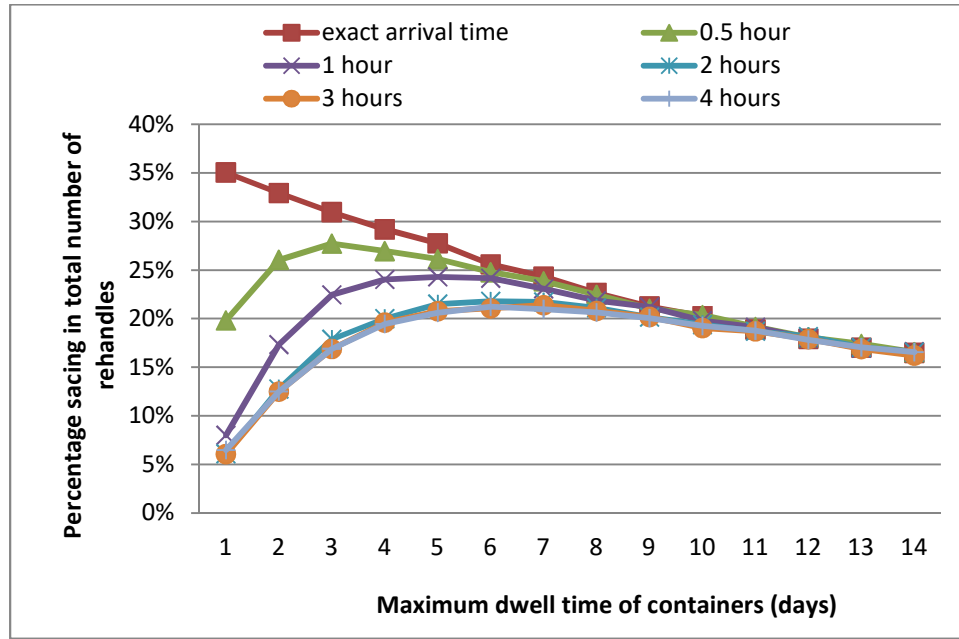


Figure 5.1 Rehandle reductions under different dwell times and durations of time windows

Assume for a container bay with six stacks and six containers in each stack and that the truck appointment lead time is one day. The impact of maximum dwell time of containers and duration of time windows on the percentage savings in total number of rehandles by using RDH over nearest relocation strategy is shown in figure 5.1. Several observations can be made from figure 5.1.

First, in the scenario with the exact truck arrival time, the percentage saving in total number of rehandles decreases linearly with the maximum dwell time of containers. This is because the amount of known truck arrival information decreases while the maximum dwell time grows. In fact, the number of trucks with a known arrival sequence equals the number of containers picked up each day. When the maximum dwell time of containers increases, the number of containers requested on each day decreases, thus the length of known truck arrival sequence also decreases.

Second, in scenarios with arrival time window information, the efficiency gain in rehandle reductions first increases with dwell time and then decreases. However, the peak benefit for various durations of time window occurs at different maximum dwell times. For a half -hour time window, the largest benefit is achieved when the dwell time is three days. For a one-hour time window, the largest benefit is achieved when the dwell time is five days. And for two, three, and four hour time windows the largest benefit is achieved when the dwell time is six days. Thus, the optimal dwell time for maximizing the benefit increases with the duration of appointment window, while the magnitude of the maximum benefit decreases as the duration of time window increases. That is because the number of arrival groups and group sizes changes with the container dwell time and the duration of time window. When the dwell time is shorter, the number of truck arrivals on each day is larger and thus the number of trucks with known arrival time windows is also larger. Their arrival time windows are more likely to overlap, which leads to fewer and larger groups. In a similar way, longer dwell

time tends to generate more arrival groups with smaller sizes. Longer dwell time also leads to smaller amount of known truck information and more frequent information updates. However, while the duration of time window increases, the truck time windows are more likely to overlap, leading to fewer and bigger groups. All of those factors affect the performance of the RDH at the same time and generate the benefit curves shown in figure 5.1.

Third, while the container dwell time increases, the difference in efficiency gain between the exact arrival time scenario and other scenarios diminishes gradually, and the difference in efficiency gain decreases even more quickly for scenarios with narrower time windows. For example, comparing the exact arrival time scenario with the half -hour time window scenario, the difference in efficiency gain is 15% if the container dwell time is one day. The difference decreases to 3% when the dwell time is three days, and is smaller than 1% if the dwell time is longer than five days. The difference in efficiency gain between exact arrival time scenario and two-hour time window scenario decreases to 1% when the dwell time reaches nine days. Such simulation result illustrates that the magnitude of efficiency improvement is more significant for scenarios with narrow time windows. However, if the containers have a long dwell time on the yard, knowing and utilizing the truck arrival time window information could generate the same magnitude of benefit as having the exact truck arrival time information, and the amount of benefit is not sensitive to the duration of time window.

5.1.2 Rehandle reductions under different combinations of appointment lead time and dwell time

Consider a container bay with six stacks and six containers in each stack. The impact of appointment lead time and maximum dwell time of containers on the rehandle reductions is evaluated in figures 5.2, 5.3 and 5.4.

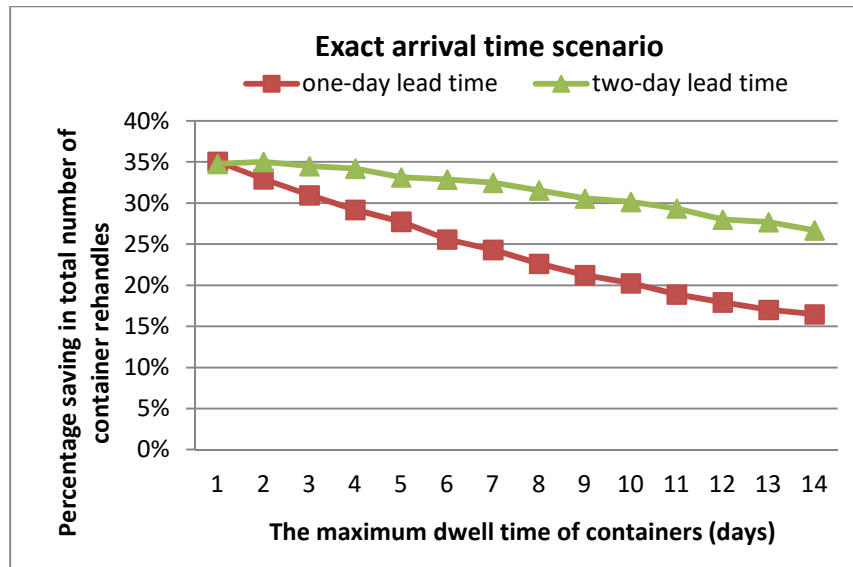


Figure 5.2 Rehandle reductions under different appointment lead times in the exact arrival time scenario

Figure 5.2 shows that percentage saving in total number of rehandles from using the RDH strategy decreases linearly with the maximum dwell time of containers, no matter how early in advance the truck arrival information is acquired. Knowing the truck arrival time two days in advance generates

more efficiency gain compared with knowing the arrival time one day in advance, and such additional benefit increases linearly with the maximum dwell time of containers.

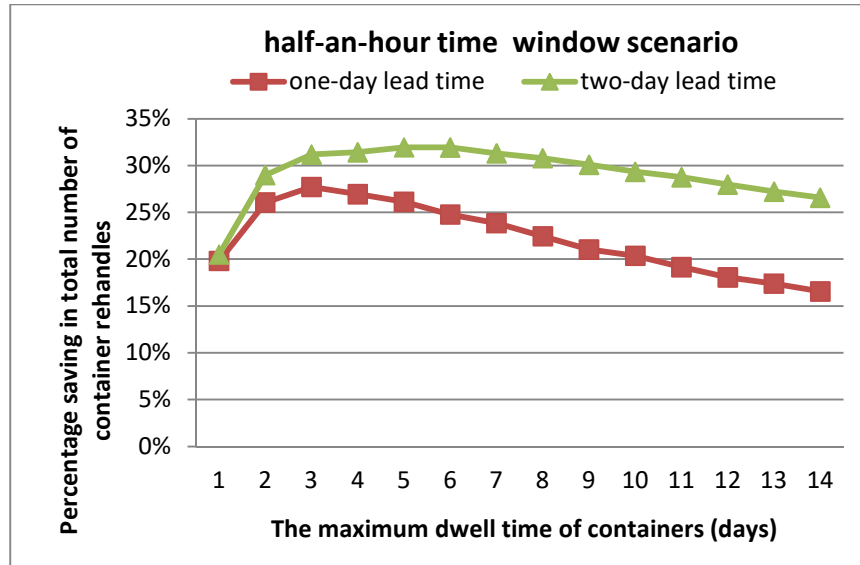


Figure 5.3 Rehandle reductions under different appointment lead times in the half -hour time window scenario

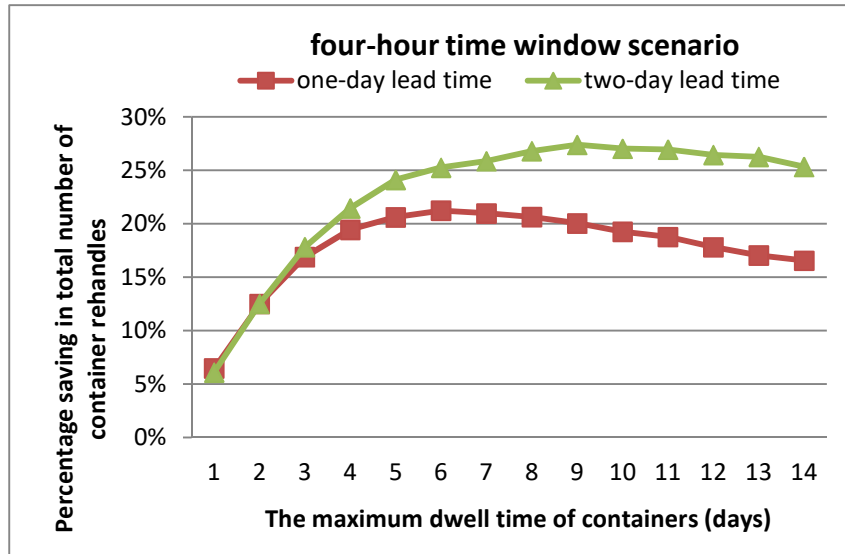


Figure 5.4 Rehandle reductions under different appointment lead times in the four-hour time window scenario

Figure 5.3 shows the rehandle reductions under different appointment lead times for the half-an-hour time window scenario. The efficiency gain first grows with the dwell time before reaching its peak value, and then decreases with the dwell time. The optimal dwell time for maximizing the benefit is three days for the one-day lead time case and is six days for the two-day lead time case. The magnitude of benefit is also greater for the scenario with a longer lead time, and such additional benefit increases gradually with the container dwell time. Similar observations could be obtained from the four-hour time window scenario (figure 5.4).

5.1.3 Rehandle reductions under different combinations of bay configuration and time window duration

Consider a container bay whose maximum dwell time of containers is five days and appointment lead time is one day. The impact of bay configuration on the efficiency of container rehandling work is evaluated in figures 5.5, 5.6, and 5.7.

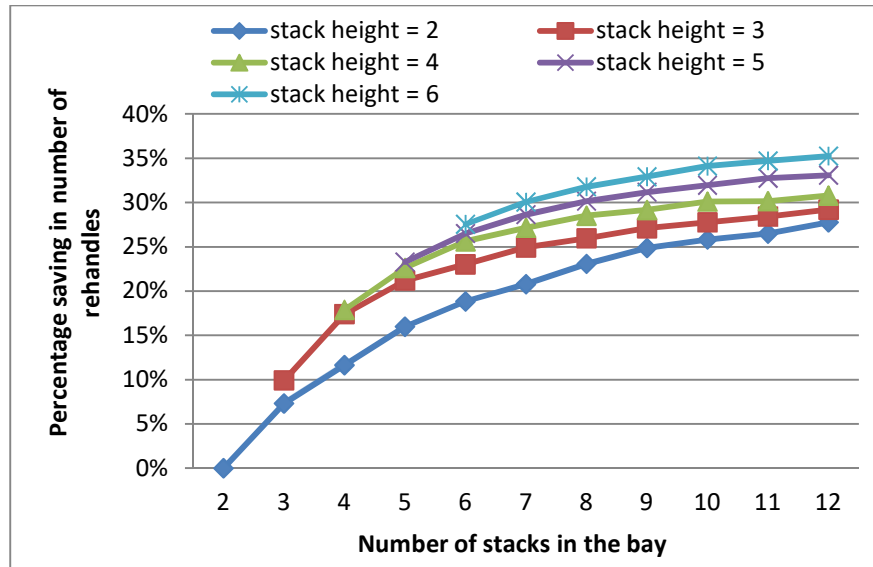


Figure 5.5 Rehandle reductions under different bay configurations in the exact truck arrival time scenario

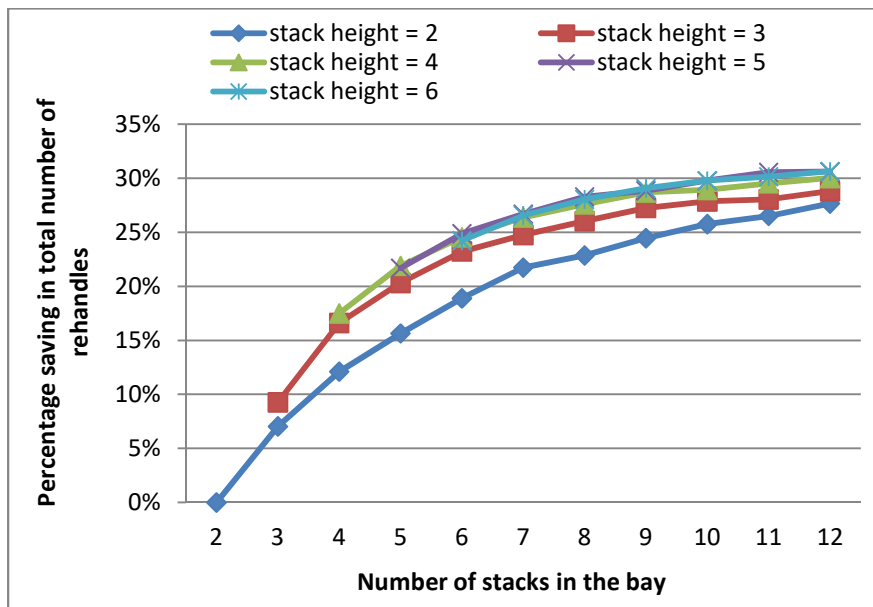


Figure 5.6 Rehandle reductions under different bay configurations in the one-hour time window scenario

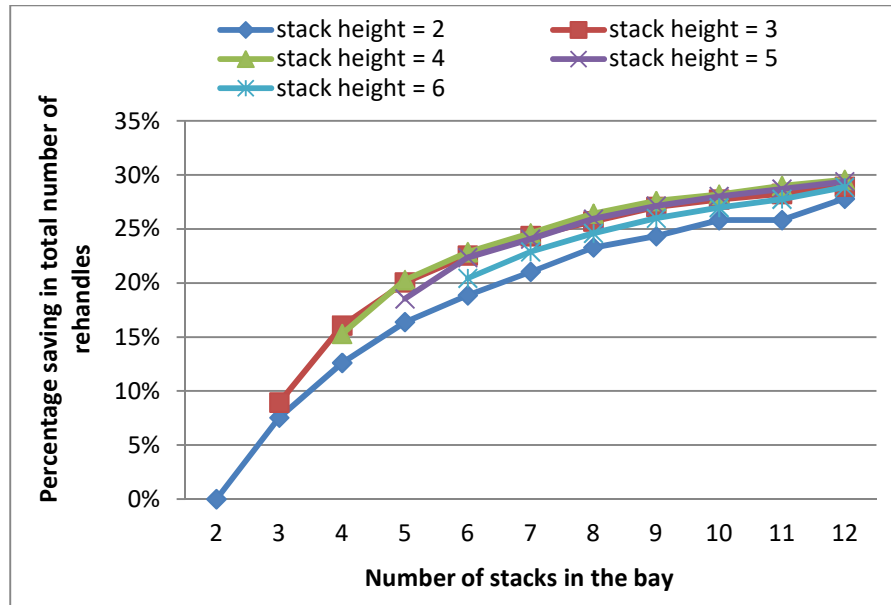


Figure 5.7 Rehandle reductions under different bay configurations in the four-hour time window scenario

Figure 5.5 indicates that the total number of rehandles can be significantly reduced under various combinations of stack height and number of stacks if the exact truck arrival time is acquired one day in advance. This efficiency gain increases with stack height and number of stacks, and reaches 35% when the bay is twelve-stacks wide and six-containers high. Figure 5.6 and 5.7 show the rehandle reductions when the time window information is acquired one day in advance, indicating that the stack height has a mixed impact on the rehandling efficiency. In the one-hour time window scenario, the efficiency gain first increases with the stack height, then levels off when the stack height reaches four. In the four-hour time window scenario, the efficiency gain first grows with the stack height and then decreases after stack height reaches four.

5.2 The impact of truck time window information on the performance of yard crane service system

This section quantifies improvements in crane productivity and truck transaction time when the terminal utilizes the arrival time window information of trucks to reduce container rehandling work. This will show how the usage of truck time window information could impact system efficiency of the container terminal, and identify the effectiveness of time window information under different system configurations. The impact of several system design factors on drayage truck-yard crane system will be evaluated, including the maximum dwell time of containers, container block configuration, truck arrival rate, and truck appointment system design such as the duration of appointment window and the appointment lead time. The methodology developed in chapter four for evaluating crane productivity and truck transaction time and the crane parameter values introduced in chapter four are applied in this analysis.

5.2.1 Performance analysis under different combinations of truck time window duration and truck arrival rate

Consider a block with $a = 6$, $b = 4$, $c = 10$ (notations are defined in subsection 4.1.1) and a truck appointment system with one day's lead time. The dwell time of containers, truck arrival rate and block configuration have the following relationship:

average truck arrival rate

$$= \frac{\text{number of stacks} * \text{number of containers in each stack} * \text{number of bays}}{\text{average container dwell time}}$$

When the block configuration and truck arrival rate is known, the length of container dwell time is determined. The impact of duration of truck time window and truck arrival rate (container dwell time) on the performance of the yard crane service system is shown in figures 5.8, 5.9, and 5.10.

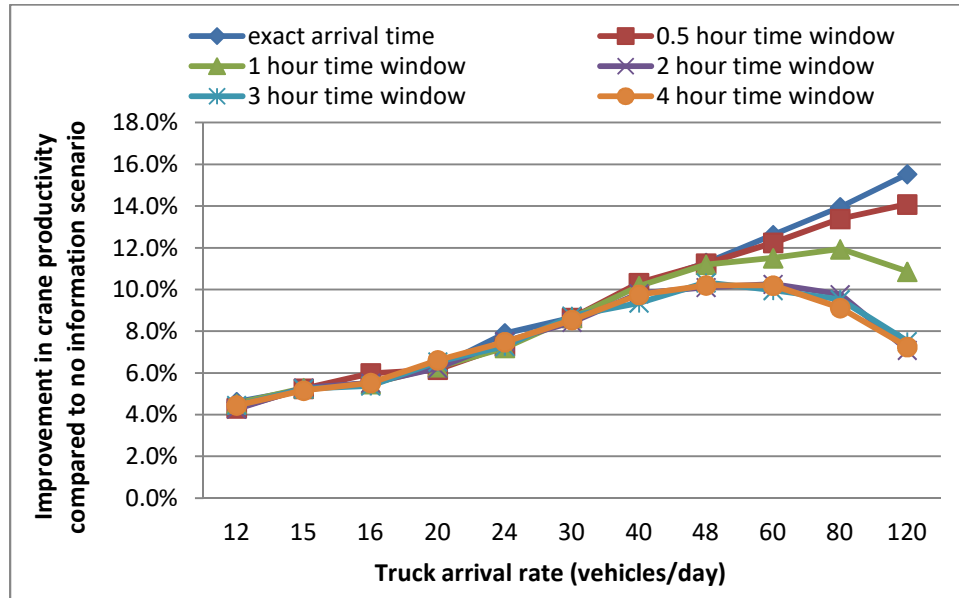


Figure 5.8 Rehandle reductions under different bay configurations in the exact truck arrival time scenario

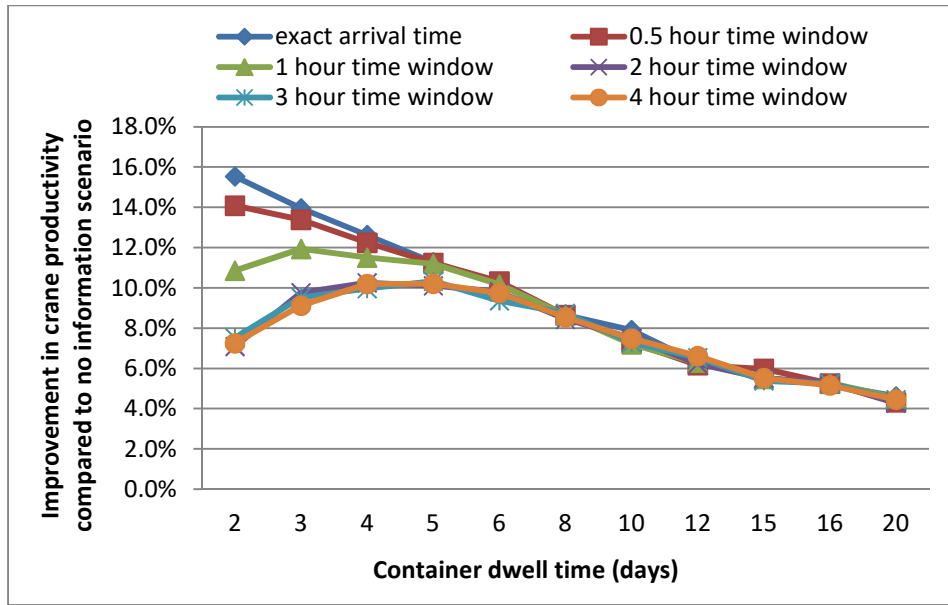


Figure 5.9 Improvements in productivity under various container dwell times and time window durations

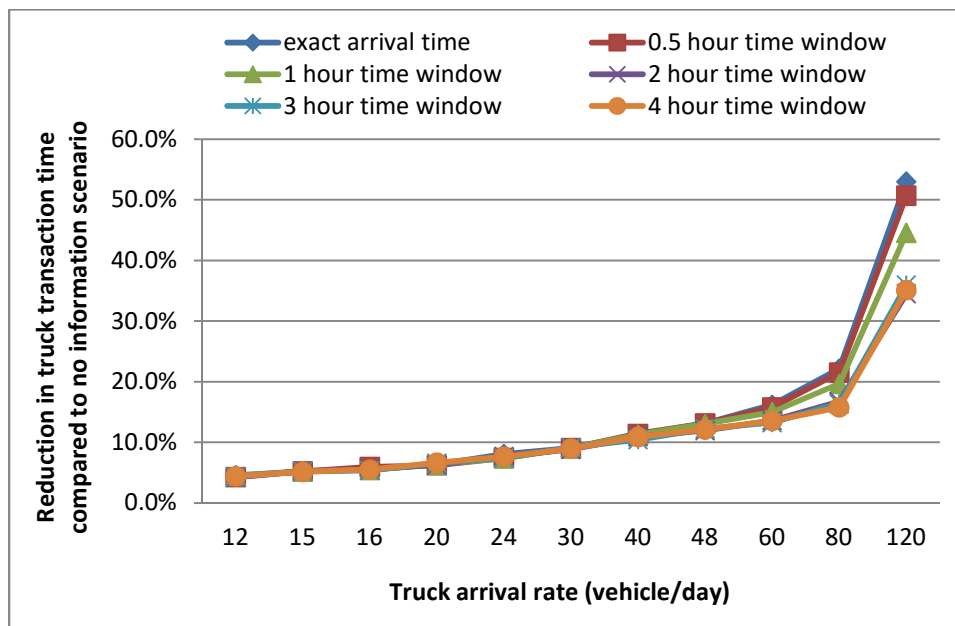


Figure 5.10 Percentage savings in truck transaction time under various truck arrival rates and time window durations

Figures 5.8, 5.9, and 5.10 demonstrate that truck time window information could generate significant benefits for the terminal and drayage trucks, and the amount of benefit is larger for trucks. Several other observations can be made from above figures.

First, figure 5.8 indicates that the improvement in crane productivity increases gradually with truck arrival rate in the exact arrival time scenario and half-hour time window scenario, while under other scenarios such improvement first increases with truck arrival rate, then decreases. This is because the number of arrival groups and group sizes change with truck arrival rate and duration of

time window. Since the truck arrival rate equals the quotient of the total number of containers in the block and the container dwell time, the benefit curve can be redrawn by replacing the x axis in figure 5.8 with container dwell time. As shown in figure 5.9, this indicates how the improvement in crane productivity is affected by container dwell time and time window duration. The similarity between figure 5.9 and figure 5.1, indicates that the change in maximum dwell time of containers and duration of time window has a similar impact on container rehandling efficiency and crane productivity.

Second, figure 5.10 indicates that the truck time saving resulting from any time window information increases exponentially with truck arrival rates. The truck time window information is therefore more valuable for a yard crane system operating near its capacity for truck delay reduction, and the truck transaction time can be further reduced by adopting a narrower appointment window. This observation is similar to the results of section 4.2.2, which indicate that truck information is more valuable for a system operating near capacity.

Third, when the truck arrival rate is low, any kind of truck time window information can generate as much improvement in system efficiency as the exact arrival time information. Figure 5.8 shows that the amount of crane productivity improvement resulting from any time window information is the same when the truck arrival rate is no higher than 40 vehicles per day (or when the container dwell time is no less than six days), and figure 5.10 indicates that the same percentage saving in truck turn time reduction can be achieved from any time window information, if the truck arrival rate is no higher than 48 vehicles per day (or if the container dwell time is no less than five days). For a container terminal with a low truck arrival rate or long container dwell times, significant improvement in crane productivity and truck transaction time can be achieved by utilizing the arrival time window information while the amount of efficiency gain is not sensitive to the duration of time windows, and the exact arrival time information of trucks is not required.

5.2.2 Performance analysis under different combinations of appointment lead times and truck arrival rates

Consider a container block with $a = 6$, $b = 4$, and $c = 10$. The impacts of appointment lead time and truck arrival rate on the performance of yard crane service system are presented in figures 5.11, 5.12, 5.13, and 5.14.

Figures 5.11 and 5.12 demonstrate that benefit curves of crane productivity show similar patterns under different appointment lead times. In the exact arrival time scenario, the efficiency gain in crane productivity increases linearly with truck arrival rate under different appointment lead times. In the two-hour time window scenario, the efficiency gain in crane productivity first increases with truck arrival rate, then decreased. Two-day lead time also generates more improvements in crane productivity compared with one-day lead time, and this incremental benefit gradually diminishes as the truck arrival rate increases.

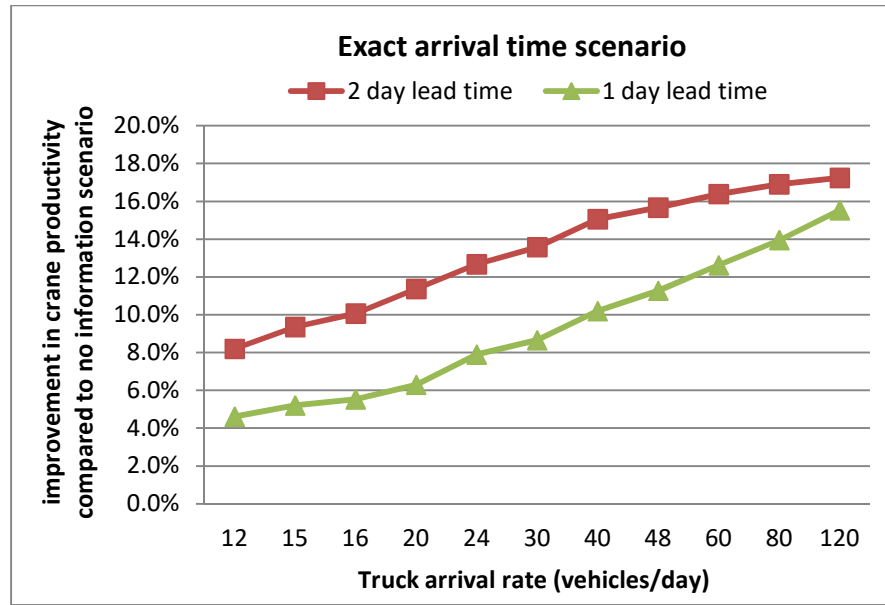


Figure 5.11 Improvements in crane productivity under different appointment lead times in the exact arrival time scenario

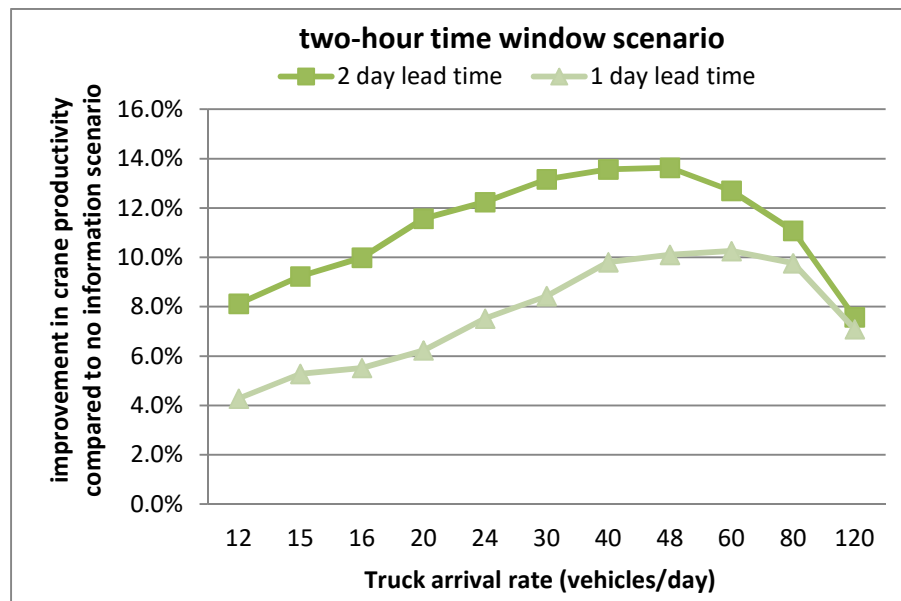


Figure 5.12 Improvements in crane productivity under different appointment lead times in the two-hour time window scenario

Figure 5.13 and 5.14 illustrate that truck time savings increase steadily with truck arrival rate under different appointment lead times. Knowing the truck arrival information two days in advance generates more reductions in truck transaction time compared with knowing the truck arrival information one day in advance; however, this incremental benefit decreases gradually as the truck arrival rate increases.

Increasing the lead time of the truck appointment system can thus further enhance the performance of yard crane service system. The additional benefit of a longer lead time gradually diminishes when the system approaches its capacity.

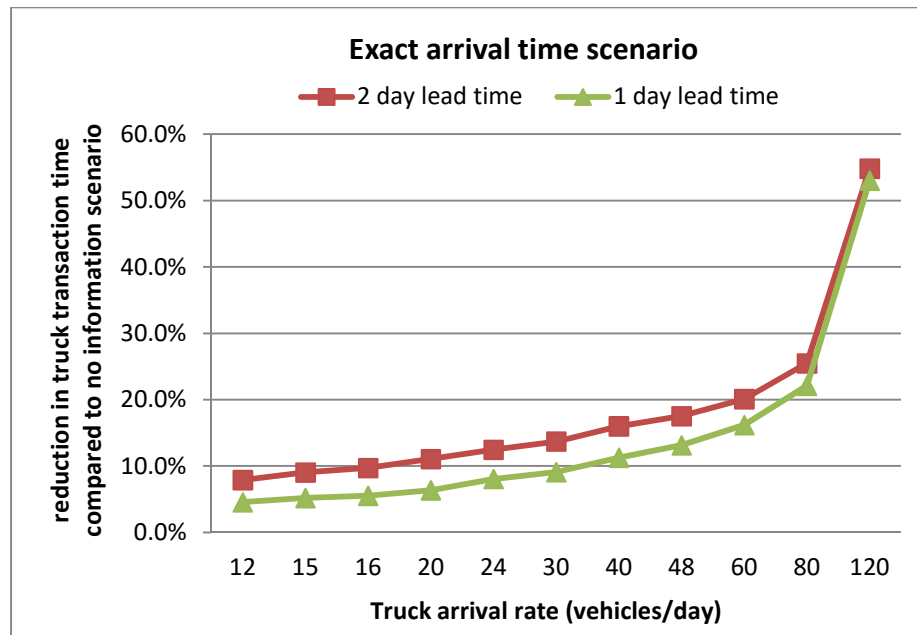


Figure 5.13 Percentage savings in truck transaction time under different appointment lead times in the exact arrival time scenario

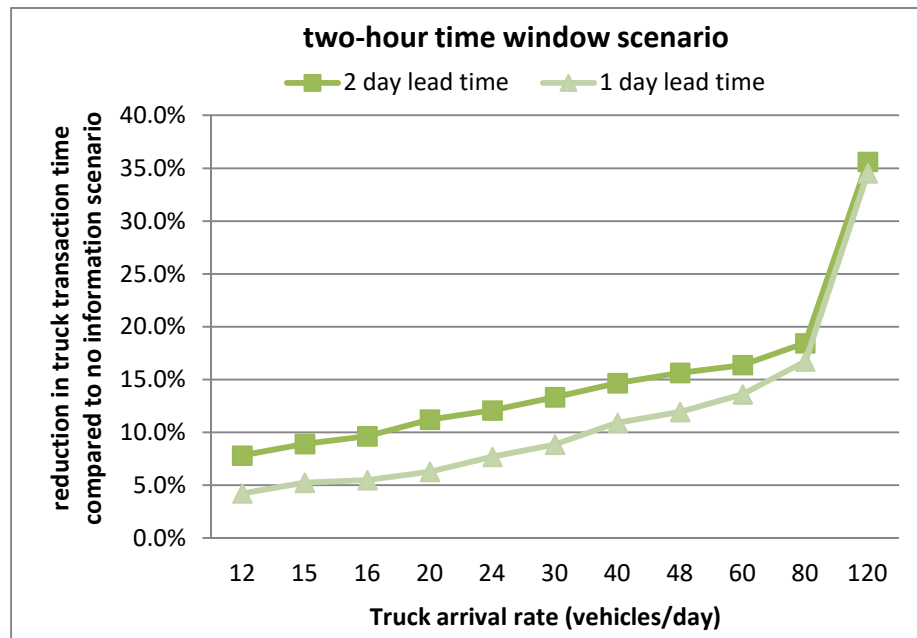


Figure 5.14 Percentage savings in truck transaction time under different appointment lead times in the two-hour time window scenario

5.2.3 Performance analysis under different block configurations

Consider a block with a base configuration of $a = 6$, $b = 6$, and $c = 10$, $\lambda = 72$ vehicles/day, and a maximum container dwell time of five days. The impacts of various block configurations on crane productivity and truck transaction time have been evaluated and presented in figures 5.15, 5.16, 5.17, and 5.18.

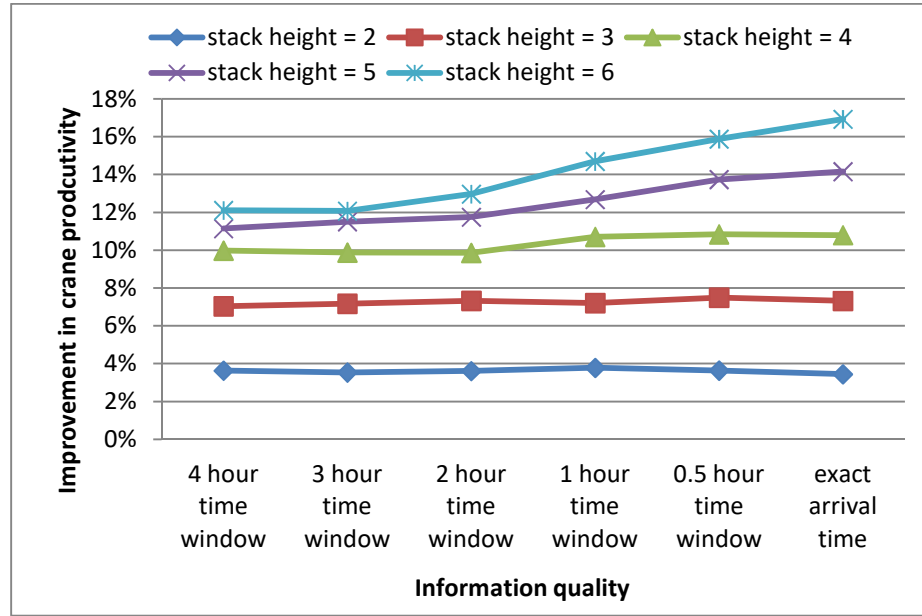


Figure 5.15 Crane productivity under various configurations of stack height and bay numbers

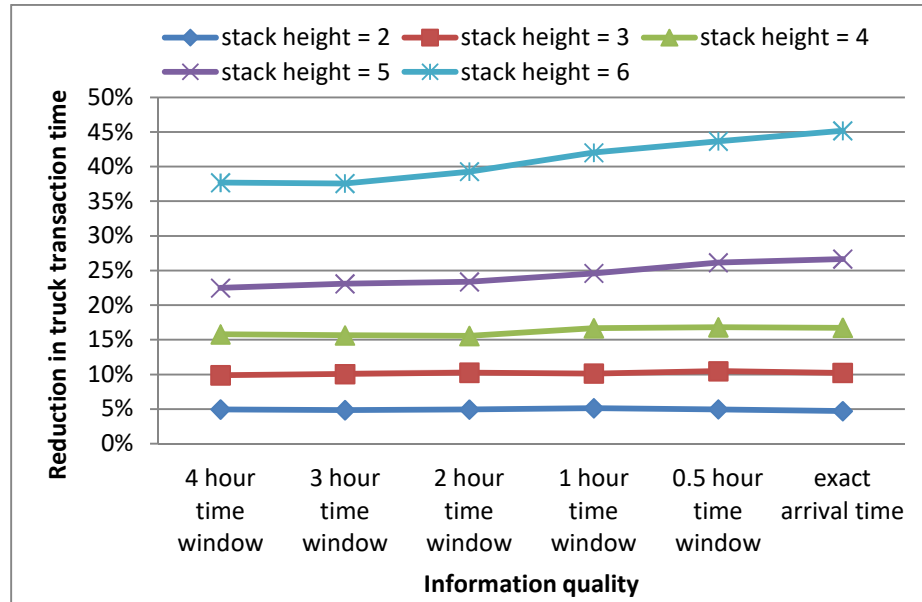


Figure 5.16 Percentage saving in truck transaction time under various configurations of stack height and bay numbers

Figures 5.15 and 5.16 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, but the magnitude of benefit is bigger for trucks. Two observations from figures 5.15 and 5.16 are as follows: first, given the same level of information quality, the truck time window information brings a greater benefit for the block configuration with higher stacks and fewer bays. Second, when the initial stack height is no less than four, adopting a narrower time window can generate incremental benefit. But the value of information quality decreases with stack height, and the four-hour time window information is as effective as the exact arrival time information for improvement when the stack height is less than four

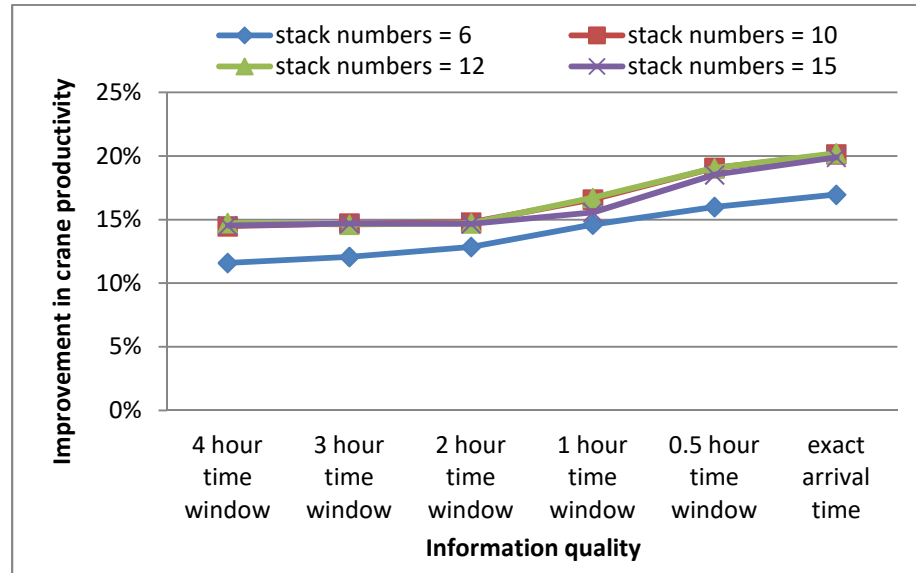


Figure 5.17 Crane productivity under various configurations of stack numbers and bay numbers

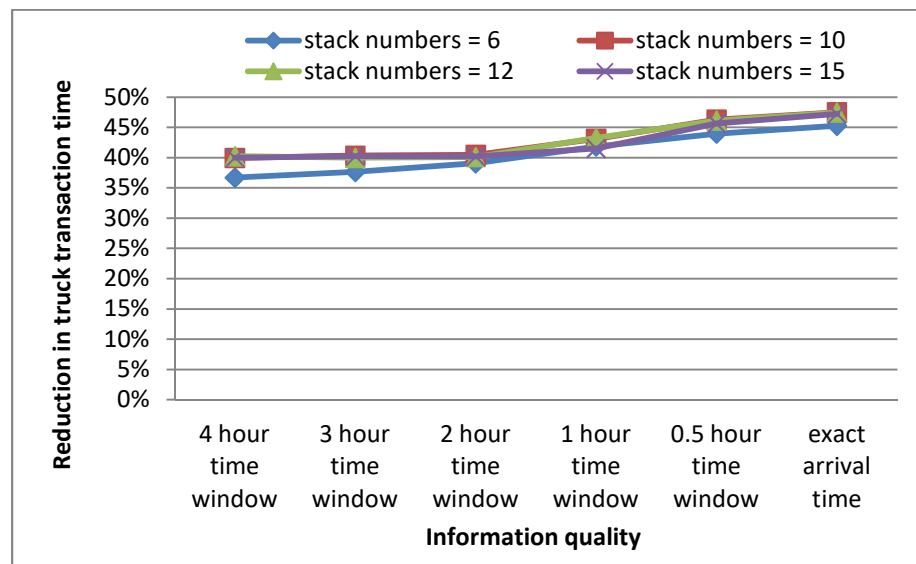


Figure 5.18 Percentage saving in truck transaction time under various configurations of stack numbers and bay numbers

Figure 5.17 and 5.18 illustrate system performance under block configuration with an initial stack height of six ($b = 6$). Different combinations of stack numbers and bay numbers have a similar effect on crane productivity and truck transaction time. Two observations are as follows: first, the magnitude of benefit increases gradually as the duration of time window decreases. Second, given the same level of information quality, the magnitude of benefit first increases with stack numbers, then levels off after the number of stacks reaches ten. Comparing figures 5.15, 5.16, 5.17, and 5.18, it is indicated that stack height has more impact on the effectiveness of utilizing truck time window information than other block configuration factors.

5.3 Impact of information accuracy on the effectiveness of truck information

In practice, container terminals need deal with inaccurate information about truck arrivals, since drayage trucks may miss their appointments. This section investigates the impact of inaccurate truck arrival information on the system efficiency of a container terminal.

Information accuracy can be defined as the degree of closeness exhibited by the information to the actual occurrence. Information accuracy is used to reflect how near the actual arrival time of trucks is to their appointment window or expected arrival time. The prior truck arrival information is considered as accurate if the trucks arrive within their appointment time window or at their expected arrival time. Otherwise the information is considered inaccurate. Two measures proposed to define the accuracy of arrival information are: deviation from appointment time and missed appointment rate.

Deviation from appointment time refers to the absolute difference between the actual arrival time of a truck and the lower limit or upper limit of its appointment window. This measure is used to capture the degree of deviation of the actual arrival time from the appointment window. Missed appointment rate refers to the probability of trucks missing their appointments. It is assumed that all the trucks will arrive within the complete time horizon. This measure reflects how frequently drayage trucks miss their appointments. In this section, the truck arrival information with different levels of accuracy is modeled by considering various combinations of deviation from appointment time and missed appointment rate (table 5.2).

Table 5.2 Information accuracy measurements

Measures	values
Deviation from appointment time	(0, 0.5 hour], (0, 1 hour], (0, 2 hours], (0, 4 hours], (0, 8 hours], (0, 16 hours], (0, 24 hours], (0, 32 hours], (0, 48 hours]
Missed appointment rate	5%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%

This section estimates the improvement in crane productivity and truck transaction time if a terminal utilizes inaccurate truck arrival information to reduce rehandling work. The impact of missed appointment rate and deviation from appointment time on the performance of yard crane service system is evaluated to identify the effectiveness of truck time window information under different levels of information accuracy. In these experiments a terminal system with a fixed container block configuration is considered, for which the number of container bays is ten, the number of stacks is six, and each stack has six containers. The maximum container dwell time is assumed to be three days, the average arrival rate of trucks is assumed to be nine vehicles per hour, and the appointment lead time of trucks is assumed to be one day. The methodology developed in section 4.1 as well as the crane

parameter values introduced in section 4.2 is used to evaluate crane productivity and truck transaction time evaluation.

5.3.1 Performance analysis under various missed appointment rates

Consider a terminal gate appointment system for which the deviation of truck's actual arrival time from appointment time is within four hours. The impacts of missed appointment rates on the performance of yard crane service system are shown in figures 5.19 and 5.20.

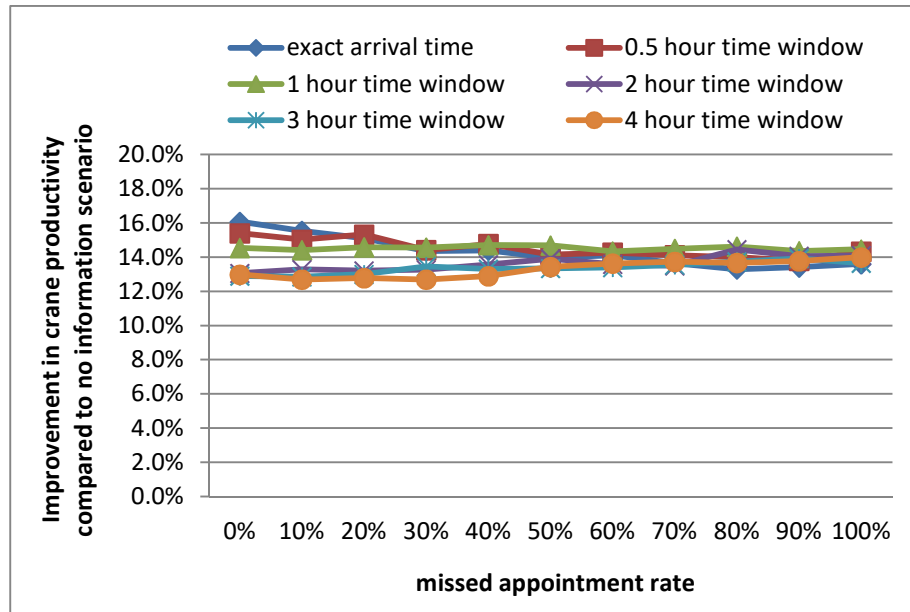


Figure 5.19 Improvements in crane productivity under various missed appointment rates and durations of time window

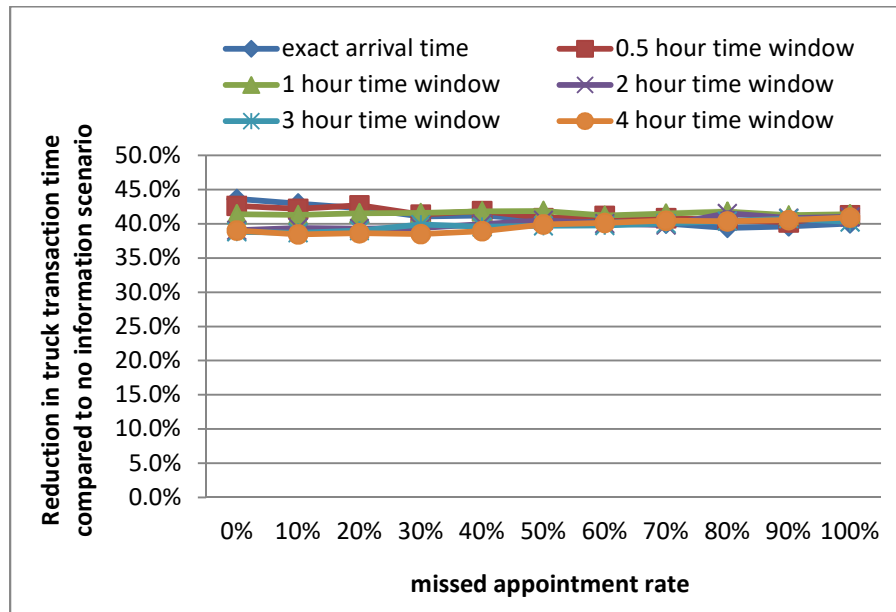


Figure 5.20 Reductions in truck transaction time under various missed appointment rates and durations of time window

Note the similarity between figure 5.19 and 5.20, indicating that the change in missed appointment rates has similar impacts on crane productivity and truck turn time. The amount of benefit is much greater for drayage trucks than the yard crane, given the same level of information quality and accuracy. Two other observations from figures 5.19 and 5.20 are as follows:

First, when the deviation of truck's actual arrival time from appointment time is within four hours, the missed appointment rate has little impact on crane productivity and truck transaction time. As the missed appointment rate increases from 0% (all the trucks keep their appointments) to 100% (no truck arrives at the terminal gate within its appointment window), the reduction in crane productivity improvement resulting from using such inaccurate information is no more than 3% for any time window scenario, and the reduction in truck transaction time savings is less than 4% for any scenario. Second, as the missed appointment rate increases, the difference in system improvement between various scenarios gradually decreases. When the missed appointment rate reaches 70%, the same amount of efficiency improvement is achieved for the yard crane service system regardless of time window information. Therefore, a high appointment-keeping rate is not required to significantly improve the performance of yard crane service system.

5.3.2 Performance analysis under various deviations from appointment time

Assume a gate appointment system for which the missed appointment rate of trucks is 50%. That is, half of the trucks kept their appointments while the other half did not. The impacts of deviation from appointment time on the performance of yard crane service system are shown in figures 5.21 and 5.22.

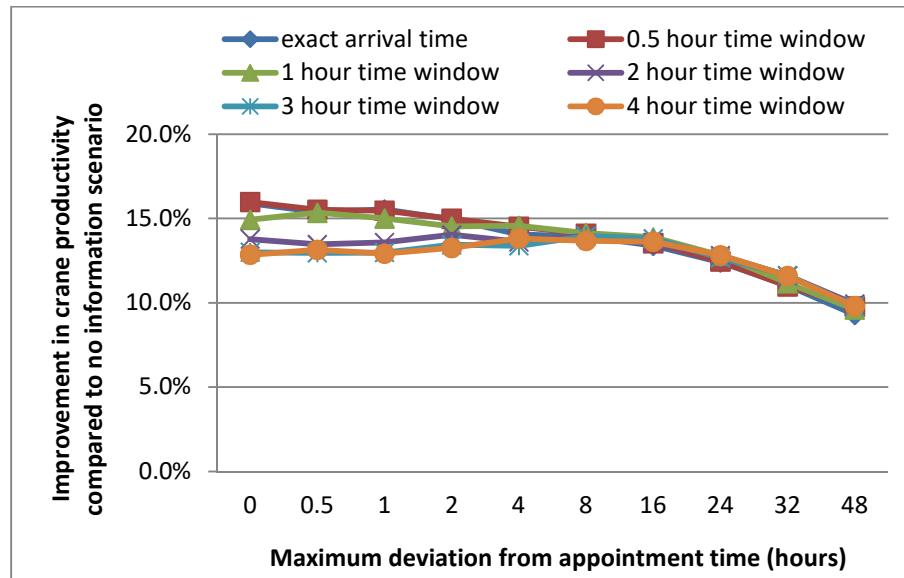


Figure 5.21 Improvements in crane productivity under various maximum deviations from appointment time

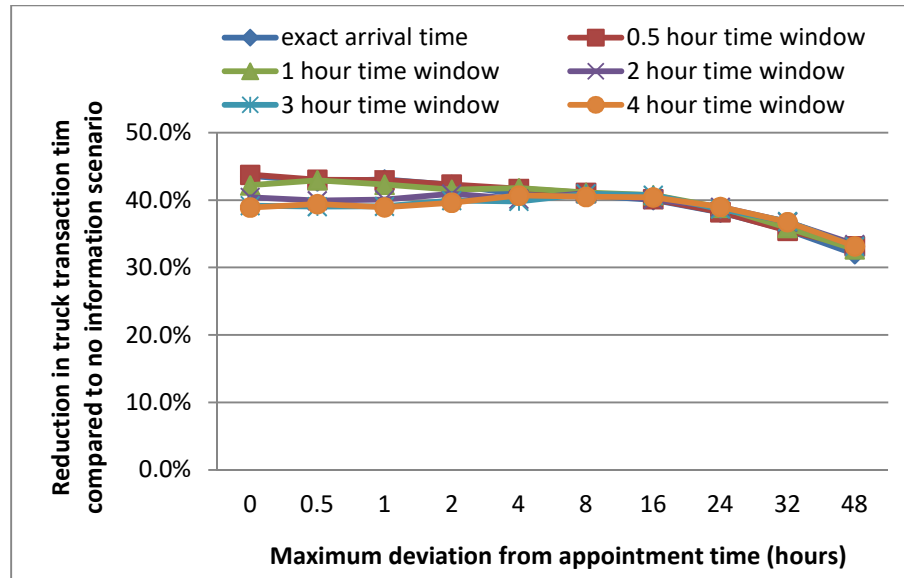


Figure 5.22 Reductions in truck transaction time under various maximum deviations from appointment time

Figures 5.21 and 5.22 indicate that change in maximum deviation from appointment time has a similar effect on crane productivity and truck transaction time. Two other observations from figure 5.21 and 5.22 are as follows:

First, in the scenario with expected arrival time information or half -hour time window information, the crane productivity improvement and truck time saving decrease gradually as the deviation from appointment time increases. In other scenarios with time window information, the efficiency improvement is constant before the deviation from appointment time reaches eight hours, then decreases as the time deviation continually increases. Thus, the magnitude of benefit obtained from a system with wider appointment time windows is less sensitive to inaccurate information if the deviation of truck's actual arrival time from appointment time is within eight hours.

Second, the benefit curves of scenarios with various levels of information quality gradually overlap as the deviation from appointment time increases to eight hours. This illustrates that if the deviation of truck's actual arrival time from the appointment time is large, knowing and utilizing the expected truck arrival time doesn't add benefit compared with having the appointment window information.

5.3.3 Performance analysis under various combinations of missed appointment rate and deviation from appointment time

Figures 5.23 and 5.24 illustrate the performance of yard crane service system under various combinations of missed appointment rate and deviation from appointment time in the exact arrival time scenario. System efficiency decreases as missed appointment rate and deviation from appointment time increase. The effect of information inaccuracy on system performance is almost negligible if the maximum deviation from appointment time does not exceed eight hours. When such deviation is within eight hours, the reduction in crane productivity improvement is less than 3% and

the reduction in truck time saving is less than 4% as the missed appointment rate increases from 0% to 100%.

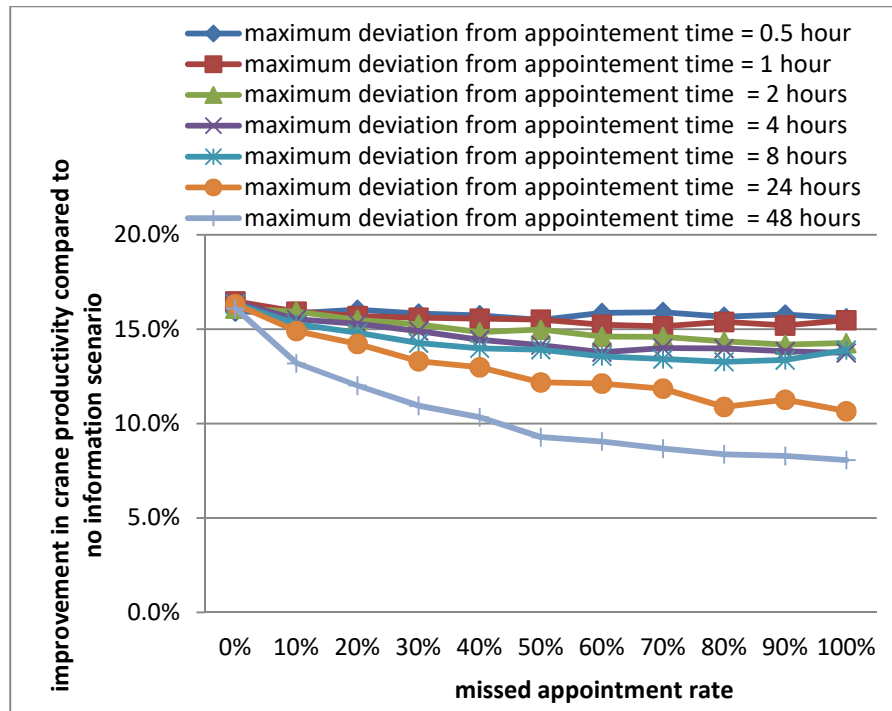


Figure 5.23 Improvements in crane productivity under different combinations of missed appointment rate and deviation from appointment time in the exact arrival time scenario

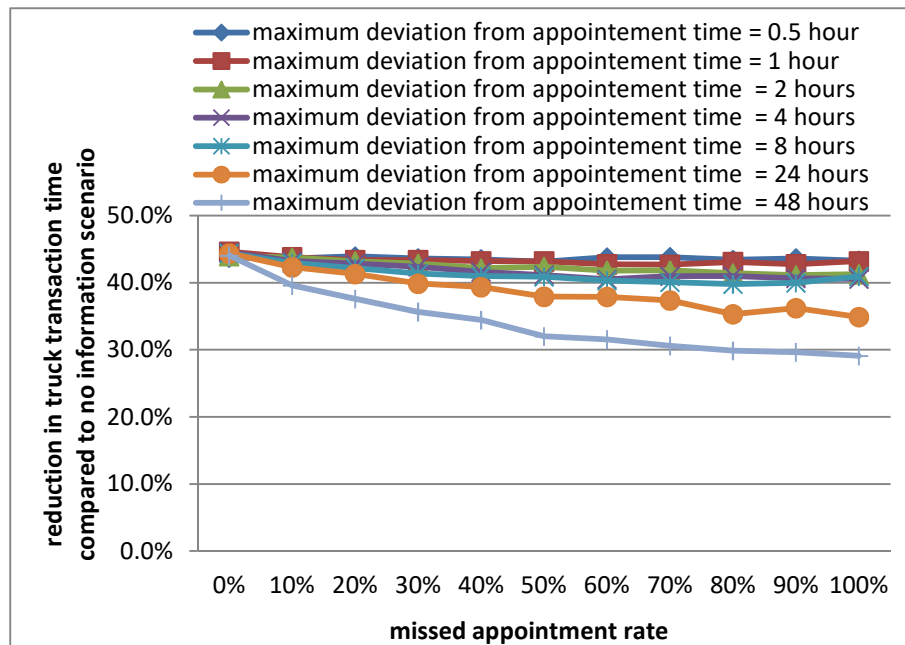


Figure 5.24 Reductions in truck transaction time under different combinations of missed appointment rate and deviation from appointment time in the exact arrival time scenario

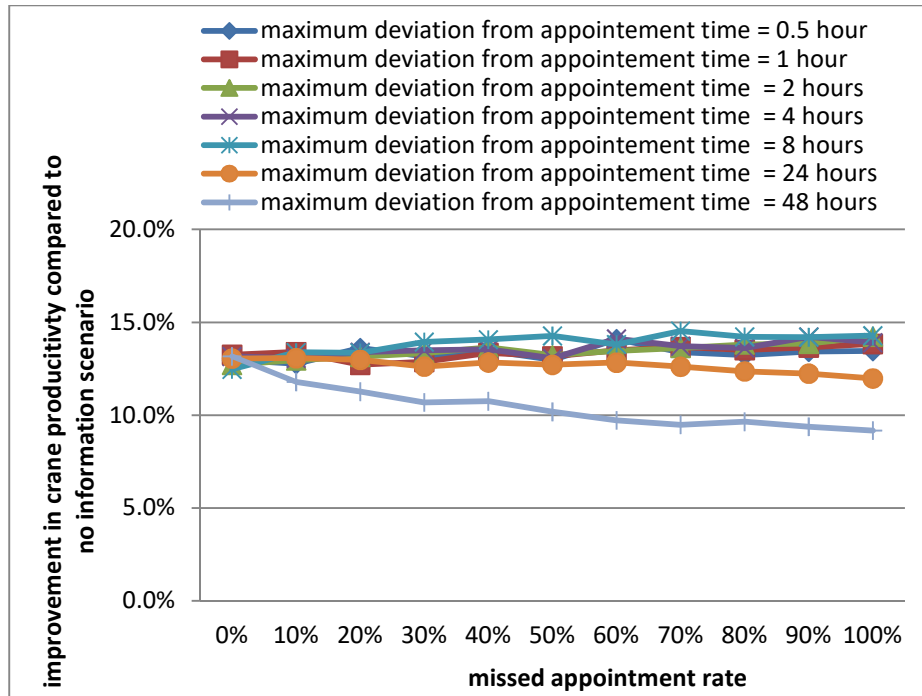


Figure 5.25 Improvements in crane productivity under different combinations of missed appointment rate and deviation from appointment time in the four-hour time window scenario

Figure 5.25 and 5.26 illustrate the performance of yard crane service system under various combinations of missed appointment rate and deviation from appointment time in the four-hour time window scenario. When the maximum deviation from appointment time is within eight hours, the use of inaccurate information has no impact on system performance. When the maximum deviation is greater than eight hours, system efficiency decreases as level of information inaccuracy increases.

A comparison among figure 5.23, 5.24, 5.25 and 5.26 shows that the level of information accuracy has a greater impact on the effectiveness of exact time information than on the effectiveness of time window information. As the level of information inaccuracy increases, the efficiency improvement obtained from utilizing exact arrival time information decreases faster than the magnitude of efficiency gain achieved from utilizing time window information.

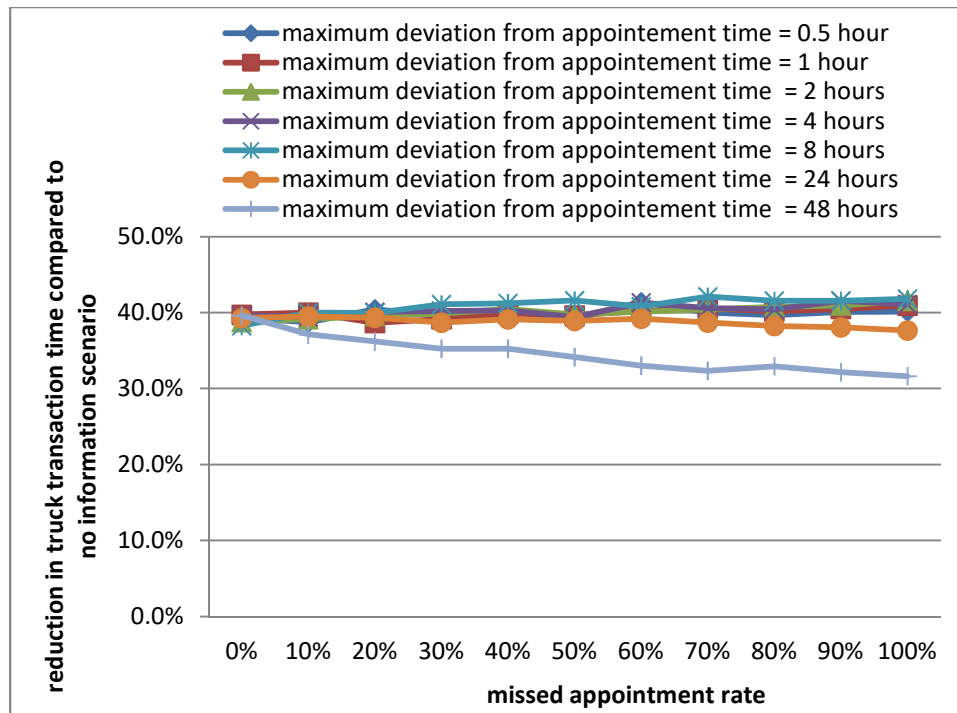


Figure 5.26 Reductions in truck transaction time under different combinations of missed appointment rate and deviation from appointment time in the four-hour time window scenario

5.4 Summary

These results demonstrate that having and utilizing a truck appointment system could effectively improve container rehandling efficiency and yard crane service system performance. The impacts of terminal system configurations on the effectiveness of truck time window information are summarized as follows:

- 1) Truck arrival rate and container dwell time have mixed impacts on the container rehandling efficiency and crane productivity -- the improvement in container rehandling efficiency and crane productivity initially increases as truck arrival rate increases (or as container dwell time decreases) and then decreases for a system utilizing time window information. The truck time saving increases steadily with the truck arrival rate.
- 2) Reducing the duration of appointment time window could further enhance the system performance if the yard crane service system approaches its operating capacity. If the crane service system has a relatively high idling time, any time window information can generate the same benefit as the exact arrival time information, and the duration of time window has no impact on the magnitude of benefit.
- 3) Increasing the appointment lead time of trucks can further improve the performance of yard crane service system, while the incremental benefit brought by a longer lead time diminishes gradually as the yard crane service system approaches its capacity.
- 4) Stack height is the most important block design factor affecting the effectiveness of truck time window information. For terminals with limited yard space and high stacking, truck time window information is more effective for system improvement, and choosing narrower time

windows is useful for further enhancing the amount of benefit. For terminals with low stacking, truck arrival information with wide time windows is as effective as exact arrival time information for improving system performance.

These results also demonstrate that the performance of yard crane service system is robust to the use of inaccurate truck information. As long as the maximum deviation of truck's actual arrival time from its appointment time does not exceed eight hours, whether or not the trucks keep their appointments has no effect on the performance of yard crane service system. When the maximum deviation from appointment time is greater than eight hours, the system efficiency of yard crane service system decreases with the level of information accuracy. However, using inaccurate truck information is still effective for improving crane productivity and reducing truck transaction time. Truck information accuracy has a greater impact on the effectiveness of exact arrival time information than on the effectiveness of time window information.

Chapter 6 Truck travel time reliability and prediction in a port drayage network

Port drayage can be defined as truck pickup from or delivery to a seaport, transferring goods between marine terminals and rail yards, local distribution centers or warehouses, with the trip origin and destination in the same region (Harrison et al, 2008; Monaco et al, 2004). According to a survey of drayage drivers serving San Pedro Bay Ports, the distance of port drayage trips is typically less than 200 miles (CGR, 2007). In the United States, the drayage trucks are not typically under the control of terminal operators or the shippers, but are operated by independent owners and contracted by brokers. Port drayage is an important component of the marine intermodal system and affects the overall efficiency of the intermodal supply chain (Harrison et al, 2008).

Previous chapters demonstrated that port efficiency and drayage can be improved by sharing and utilizing truck arrival information. If terminal operators have access to drayage truck information such as truck arrival groups or the complete truck arrival sequence and container IDs, they can utilize such information by adopting an advanced container rehandling strategy to effectively reduce container rehandling work during the import container retrieval operation. Such an operational strategy is designed to identify the optimal container storage location of rehandled containers to avoid future rehandles, and could enhance the operational efficiencies of the terminal, as well as reducing truck delays within the terminal. The goal of this chapter is to determine whether the landside network performance and simple prediction methods, are sufficient to support such practices. A case study at the Ports of Los Angeles and Long Beach is considered in this chapter, which is well known for existing in a dense, congested, urban network.

This chapter uses historical truck GPS data obtained from the NCRST project (National Consortia on Remote Sensing in Transportation). The NCRST project has developed geospatial tracking and modeling technologies to smooth the flow of freight through the San Pedro Bay Ports and the Los Angeles basin. On board data loggers were instrumented on a fleet of 150 drayage trucks serving the San Pedro Bay Ports to collect real time traffic data. Their units sampled truck locations at intervals of approximately 12 seconds, creating detailed traces of routes, stops, and speeds. The main origins and destinations of the drayage trips are the Ports of Los Angeles and Long Beach, and regional warehouses and distribution centers.

Given the quality of the available truck GPS data, this chapter addresses the question with what confidence we can predict the truck arrival time at terminal gates. This chapter is not intended to provide real-time travel time prediction or routing guidance for truck drivers; instead this chapter explores how reliable the port drayage network is and how predictable the truck arrival times at the terminal are. To address those questions two analyses are conducted:

- 1) Travel time reliability of the port drayage network. Two reliability measures are applied to examine how the travel time reliability varies across roadway links, between major OD pairs, and throughout different times of day.
- 2) Routing choice analysis and travel time prediction. First the relationship between routing choice and route attributes is examined. Then a simple method is proposed to predict the

confidence interval of truck travel time between the given OD pair. This method is further validated and applied to the entire drayage network to evaluate how the truck travel time varies across temporal and spatial extent of the drayage network.

This chapter is organized as follows. The first section introduces data acquisition and processing procedure. The travel time reliability of the drayage network is discussed in the second section. Next the factors affecting routing choices are examined, and a travel time prediction method is proposed and validated in the third section. Conclusions are then presented.

6.1 Data Acquisition and Processing

Three months of tracking data (January 21st to March 31st, 2010) for approximately 150 trucks serving San Pedro Bay Ports are used as a case study for this analysis. The acquired truck data has been pre-processed to protect the privacy of the businesses. First, the trip origins were approximated to the closest roadway intersections to prevent disclosure of business locations. Second, the truck tracking data was aggregated to major intersections, that is, data record was only provided at major intersections instead of the final location. The locations of those intersections where truck data record was provided in Los Angeles basin are shown in figure 6.1. Figure 6.2 is an example of the data format obtained. Figure 6.2(a) is the truck trip data with timestamp and location information, and figure 6.2(b) is the latitude and longitude information for the major intersections where data were collected. The Ports of Los Angeles and Long Beach combine to form the largest port complex in U.S.. In addition, the regional road network represents a particularly unreliable network, and provides an extreme case for examining whether the landside network performance could support the container rehandling strategy proposed in chapter three.

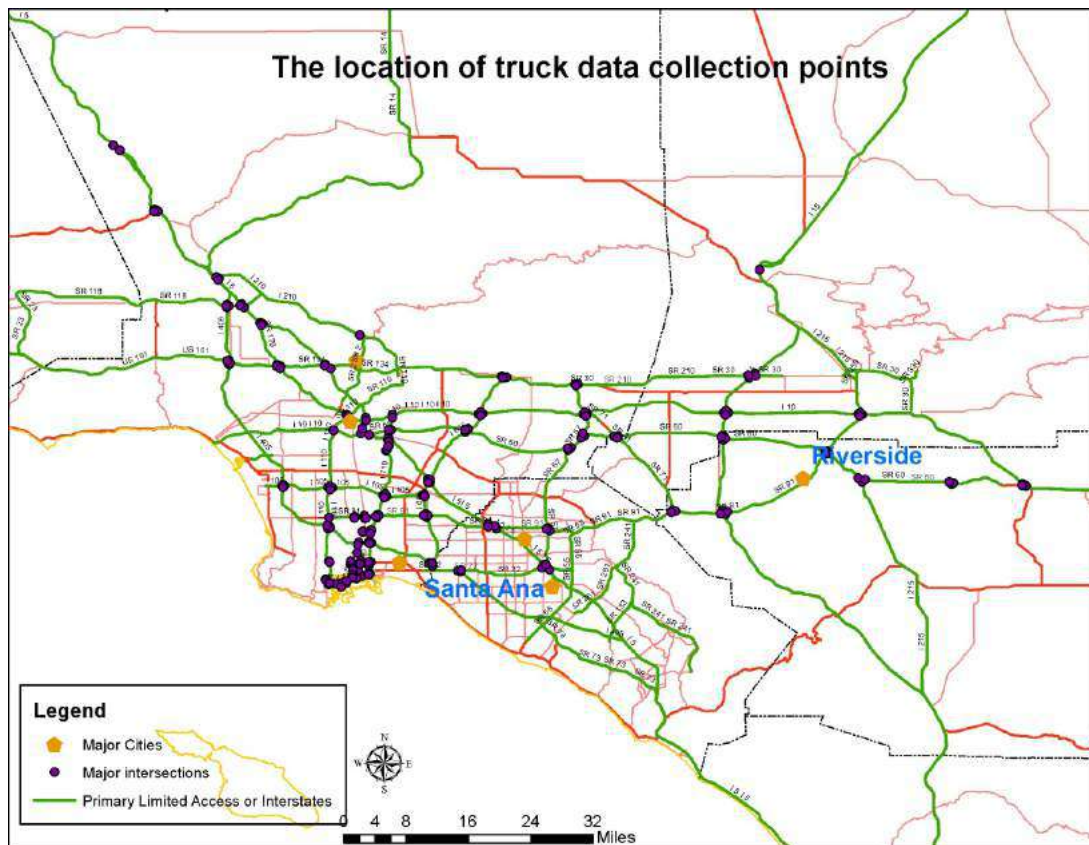


Figure 6.1 The locations of major intersections where truck data were collected

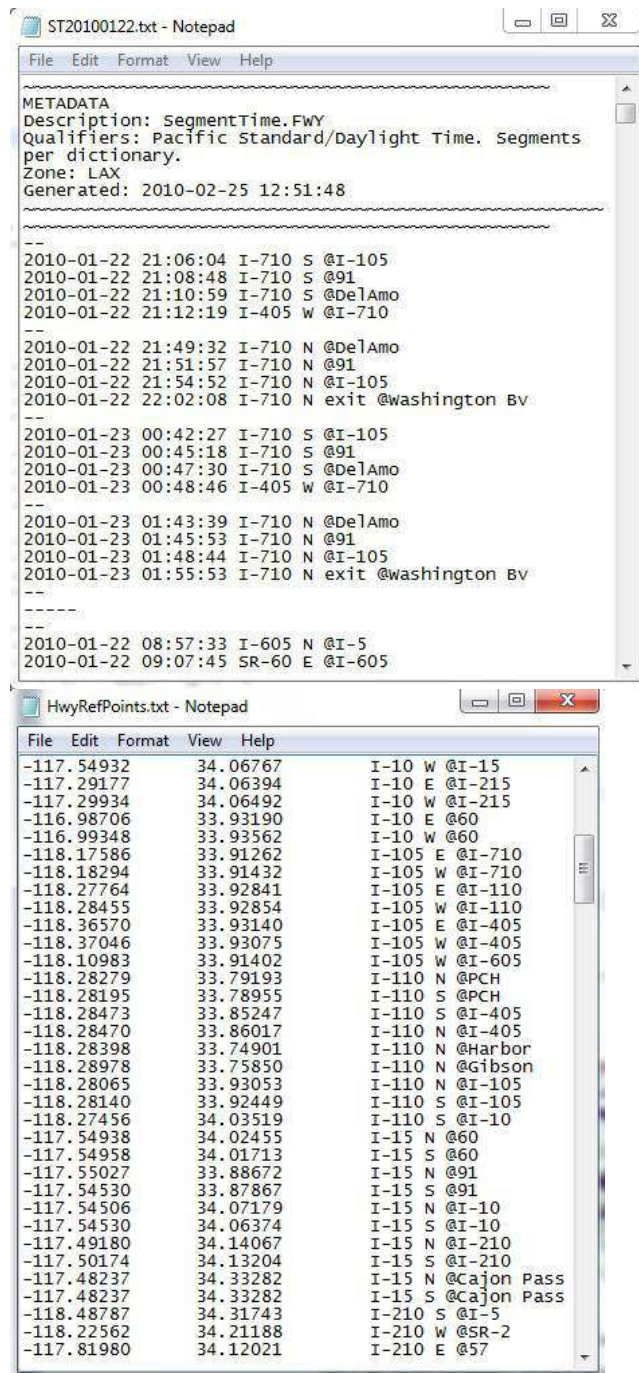


Figure 6.2 Format of data obtained for this study: (a) truck trip records; (b) location record of major intersections

Table 6.1 truck GPS data archived in SQL database

ID	TruckID	TripID	OD	Date	Timestamp	Location	Longitude	Latitude	NodeID
1100	1	1	O	1/21/2010	19:31:58	I-605 S @I-5	-118.099	33.93858	110
1101	1	1	M	1/21/2010	19:33:55	I-605 S @I-105	-118.106	33.91204	108
1102	1	1	M	1/21/2010	19:36:39	I-605 S @91	-118.102	33.87343	107
1103	1	1	M	1/21/2010	19:43:27	I-405 S @I-605	-118.091	33.7822	73
1104	1	1	D	1/21/2010	19:46:54	I-405 S @SR-22	-118.038	33.77207	75
1105	1	2	O	1/21/2010	20:16:22	I-405 N @SR-22	-118.044	33.7746	69
1106	1	2	M	1/21/2010	20:19:53	I-605 N @I-405	-118.09	33.78813	104
1107	1	2	M	1/21/2010	20:26:59	I-605 N @91	-118.104	33.8804	101
1108	1	2	M	1/21/2010	20:29:37	I-605 N @I-105	-118.106	33.916	103
1109	1	2	D	1/21/2010	20:32:17	I-5 N @I-605	-118.099	33.94422	83
1110	1	3	O	1/21/2010	21:45:00	I-710 S @I-105	-118.181	33.91024	125
1111	1	3	M	1/21/2010	21:47:54	I-710 S @91	-118.194	33.8726	122
1112	1	3	M	1/21/2010	21:50:01	I-710 S @DelAmo	-118.206	33.84379	123
1113	1	3	D	1/21/2010	21:51:31	I-405 W @I-710	-118.21	33.82723	78
1114	1	4	O	1/21/2010	22:16:55	I-710 N @DelAmo	-118.205	33.84964	114
1115	1	4	M	1/21/2010	22:30:16	I-710 N @91	-118.193	33.87813	113
1116	1	4	M	1/21/2010	22:34:16	I-710 N @I-105	-118.179	33.91656	116
1117	1	4	D	1/21/2010	22:41:40	I-710 N exit @ Washington Bv	-118.172	34.00497	121
1118	1	5	O	1/21/2010	0:54:22	I-710 S @I-105	-118.181	33.91024	125
1119	1	5	D	1/21/2010	0:57:08	I-710 S @91	-118.194	33.8726	122
1120	1	6	O	1/21/2010	1:27:11	I-710 N @91	-118.193	33.87813	113
1121	1	6	M	1/21/2010	1:30:18	I-710 N @I-105	-118.179	33.91656	116
1122	1	6	D	1/21/2010	1:37:27	I-710 N exit @ Washington Bv	-118.172	34.00497	121
1123	1	7	O	1/21/2010	3:09:03	I-710 S @I-105	-118.181	33.91024	125
1124	1	7	D	1/21/2010	3:11:53	I-710 S @91	-118.194	33.8726	122

A port drayage network is built by taking the observed intersections as the nodes and the roadway segments connecting these intersections as network links. The truck travel time on each link can be queried by specifying the node IDs of its two ends, and the trip information can be obtained in a similar way. Table 6.1 shows an example of the archived truck GPS data in the SQL database.

The GPS data has some outliers and has been filtered before being used for any analysis. For some links, the collected truck travel time on the link is extremely long (for example several hours) while the link is only a few miles in length. Since the link length is not recorded in the GPS data, we used Euclidean distance between the two ends of the link as an approximation of the link length for data filtering. Any collected link data satisfies the following rule is considered as an outlier:

$$\frac{\text{Euclidean distance between two ends of the link}}{\text{recorded travel time on the link}} \leq 5 \text{ mph}$$

About 1.0% of the collected truck trip data are outliers and removed from the database.

6.2 Travel Time Reliability Analysis

This section first examines the port drayage network in the LA basin by identifying the most frequently used corridors, the major origins and destinations of port trips. Then two reliability measures are used to evaluate the travel time reliability of truck trips and the drayage network.

6.2.1 Attributes of port drayage network

A simplified drayage network was built in ArcGIS by importing the intersection location data as the network nodes, and drawing straight lines between those nodes as the network links. The network attributes were analyzed by identifying the most frequently used truck corridors, major origins of port trips and destinations within the port complex. Since the objective of this research is to evaluate the predictability of the truck arrival time at the terminals, only those truck drayage trips whose destination is within San Pedro Bay Ports are considered for the origin and destination analysis.

By examining the sample size on the network links, the frequently used truck corridors are identified and illustrated in figure 6.3. Those corridors are denoted by purple lines in the figure, and the width of the line indicates its usage frequency. It can be observed that major truck corridors are important freeways which connect San Pedro Bay Ports with inland areas. I 710, SR 91, SR 57, SR 60, I 110, and I 605 are the corridors most frequently used for port drayage operations. The travel time reliability of those corridors will be discussed in next subsection.

By examining the sample size at different locations, the major origins and destinations of port drayage trips are identified and presented in figure 6.4 and 6.5. Figure 6.4 shows the distribution of the major origins of truck drayage trips terminating within the San Pedro Bay Ports. The green circle in the figure indicates the total number of port drayage trips collected from different origins. It is found that a majority of origins are concentrated along I-710 and I-110. There are also some major origins along SR 60 and SR 91. It could also be observed that the density of origins changes over

space. Many origins are located close to the port complex; further away from the port complex, fewer origins are identified and fewer truck trips collected.

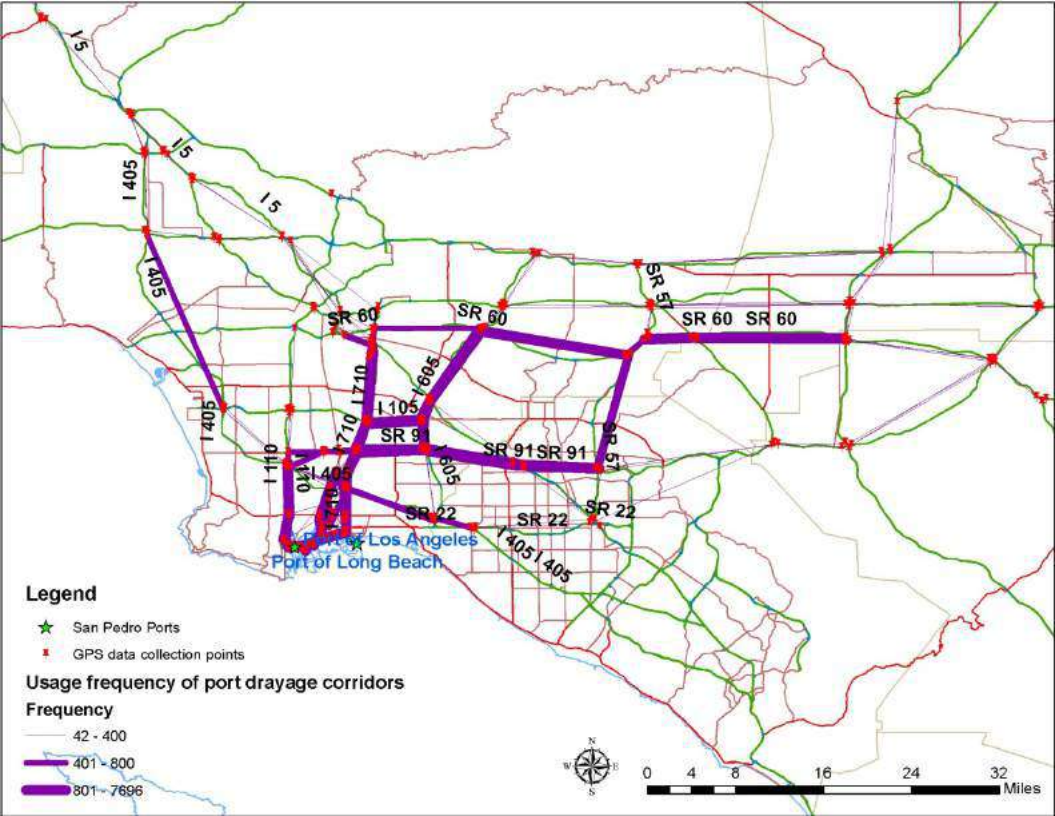


Figure 6.3 The usage frequency of port drayage corridors in greater LA area

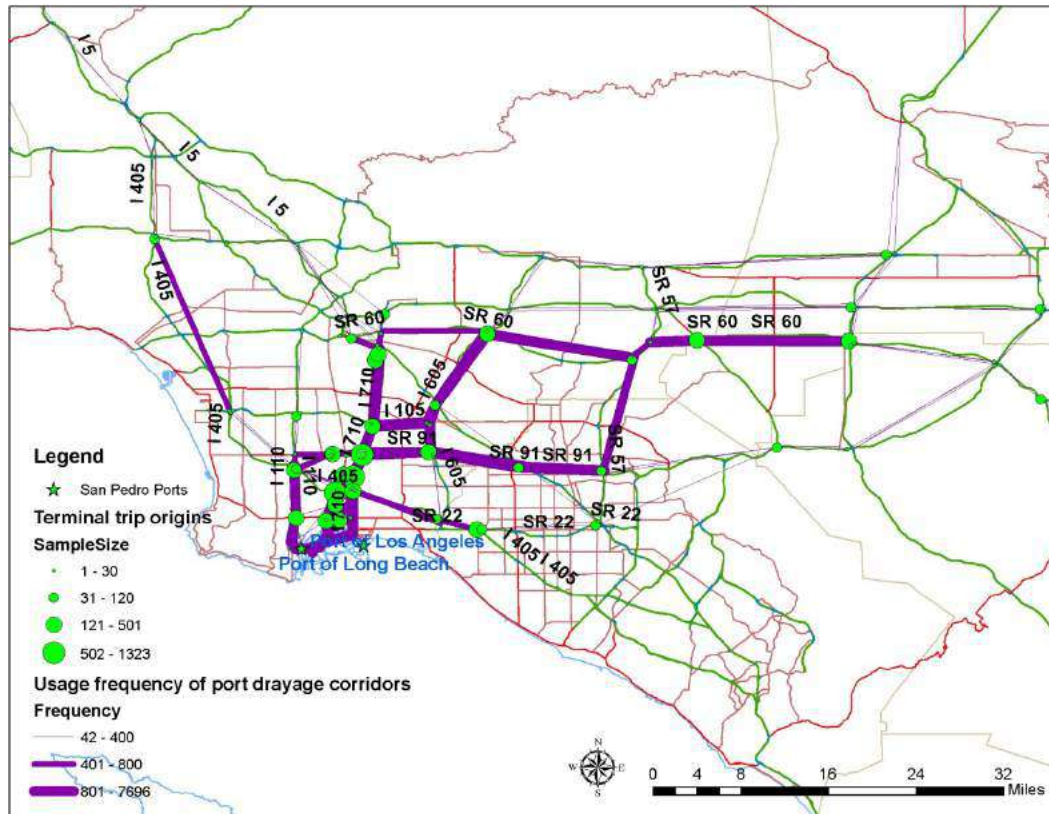


Figure 6.5 shows the major destinations of port drayage trips within San Pedro Bay Ports. The blue circle indicates the total number of trips collected at different destinations. It is found that most major destinations are concentrated along SR 47 and Ocean Blvd. Those identified major origins and destinations will be further studied in the travel time prediction section.

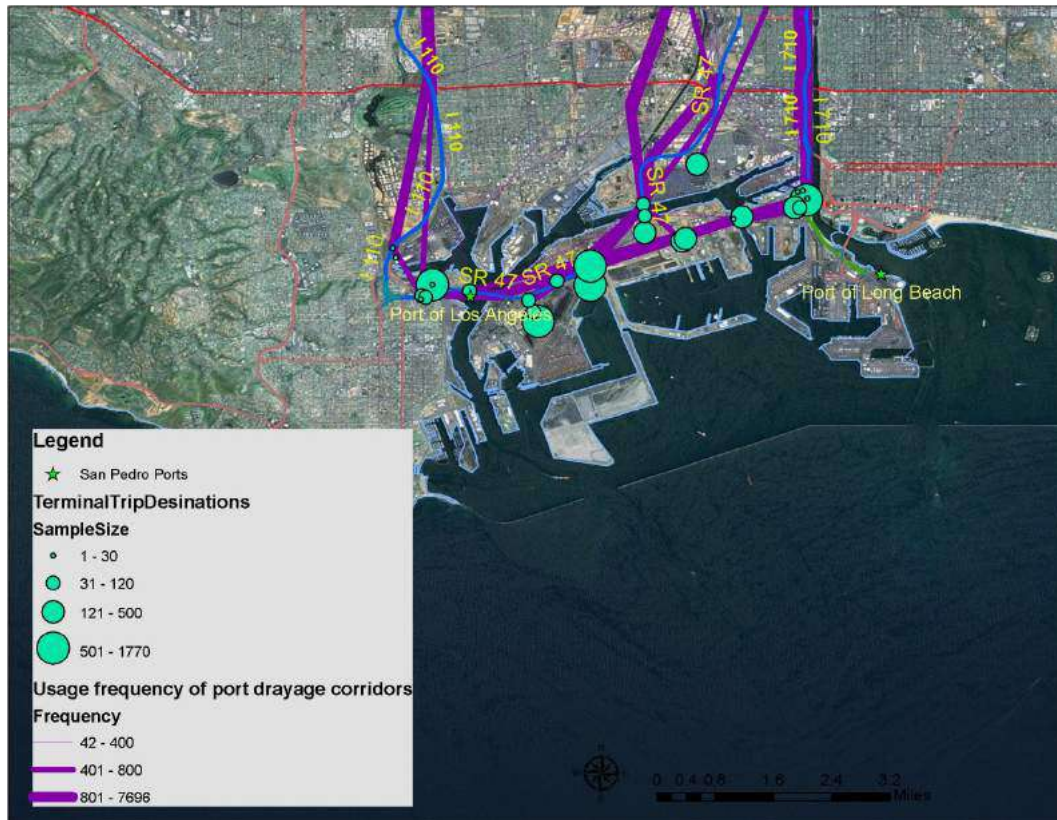


Figure 6.5 Major Destinations within the port complex

6.2.2 Travel time reliability analysis

To evaluate the travel time reliability of trucks on the drayage network, two measures are used for reliability analysis: the standard deviation and the coefficient of variation. The standard deviation shows the variability of truck travel times from the mean travel time, and gives a good idea of the amount of uncertainty. The coefficient of variation is calculated by following formula to measure the travel time reliability:

$$\text{Coefficient of Variation} = \frac{\text{Standard deviation of travel time}}{\text{Mean travel time}}$$

Coefficient of variation (CV) combines the average and standard deviation values, and is therefore a relative value. This measure has been widely used in the literature for travel time reliability analysis. Unlike the standard deviation, the coefficient of variation allows for comparison of the travel conditions across a variety of trip lengths. This measure can be applied to individual segments, corridors, or trips as well as a combination of modes (Lomax and Schrank, 2002). In this subsection, first the travel time reliability of truck trips is evaluated, and then the drayage network reliability is explored by examining the major freeway links and corridors.

6.2.2.1 Trip Reliability analysis

Figure 6.6 shows the coefficient of variation for different drayage trips. Each dot in figure 6.6 corresponds to an OD pair for which the destination is within the port complex and at least 30 truck

trips were observed. The x axis represents the Euclidean distance of the trip origin from the port (or the Euclidean distance between trip origin and destination). It can be observed from figure 6.6 that the coefficient of variation for most drayage trips is within the range of 0.1 to 0.3. To consider how the coefficient of variation changes with trip distance, the coefficient of variation is averaged by distance and the results are shown in table 6.2. Table 6.2 shows that the mean coefficient of variation fluctuates around 0.15 and does not increase with the Euclidean distance between the trip origin and the San Pedro ports. That means, the length of the truck drayage trips has little impact on this measure of reliability performance. Table 6.2 also indicates that the value of mean standard deviation increases with distance between the trip origin and the port. That is because the trip travel time increases with the trip length and thus the absolute value of trip uncertainty also increases with distance.

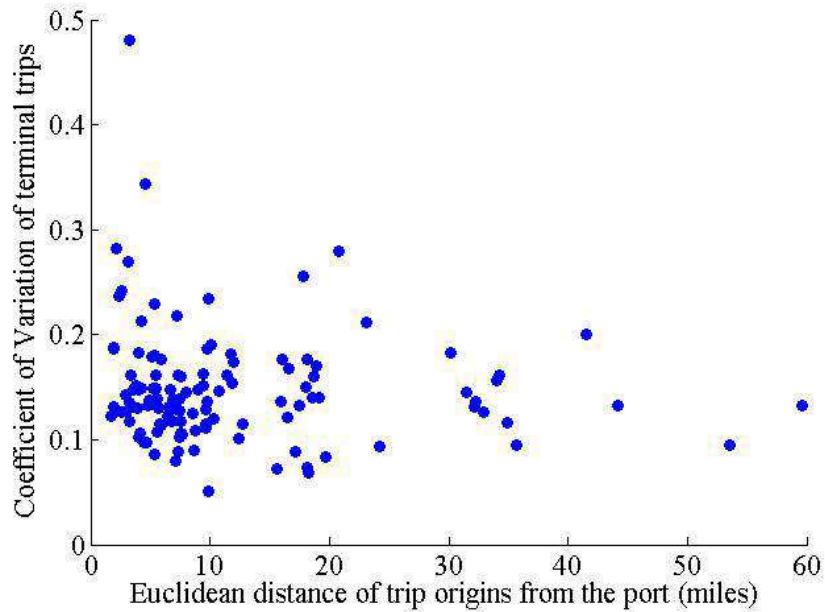


Figure 6.6 Scatter plot of Coefficient of Variation of port drayage trips

Table 6.2 Mean coefficient of variation for terminal trips classified by Euclidean distance from the port

Euclidean distance from port	0-10 mile	10 - 20 mile	20 - 30 mile	30 - 40 mile	40 - 50 mile	50 - 60 mile
Mean Coefficient of Variation	0.151	0.141	0.195	0.139	0.167	0.114
Mean Standard Deviation (Minute)	1.5	3.3	6.5	7.4	11.2	10.5

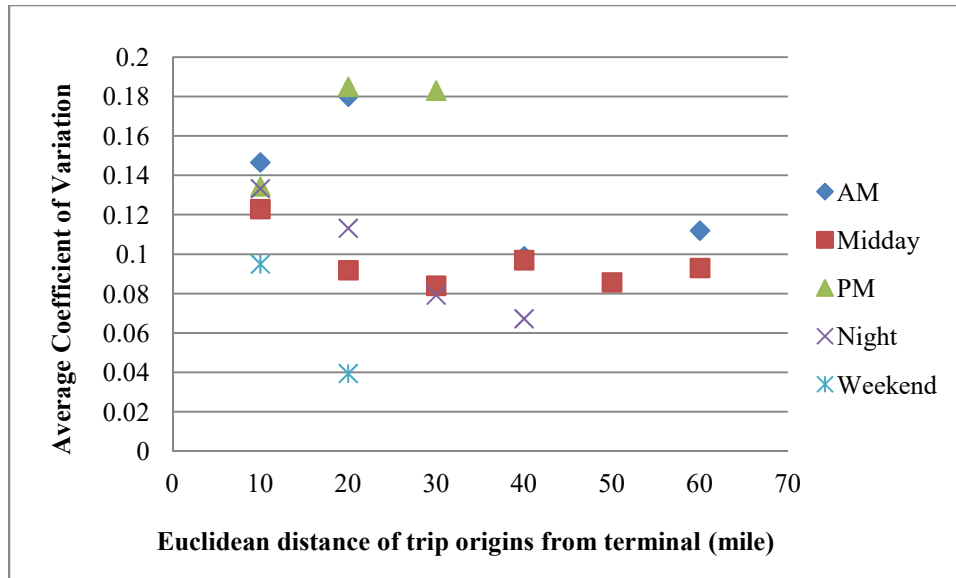


Figure 6.7 Mean Coefficient of variation for different time periods

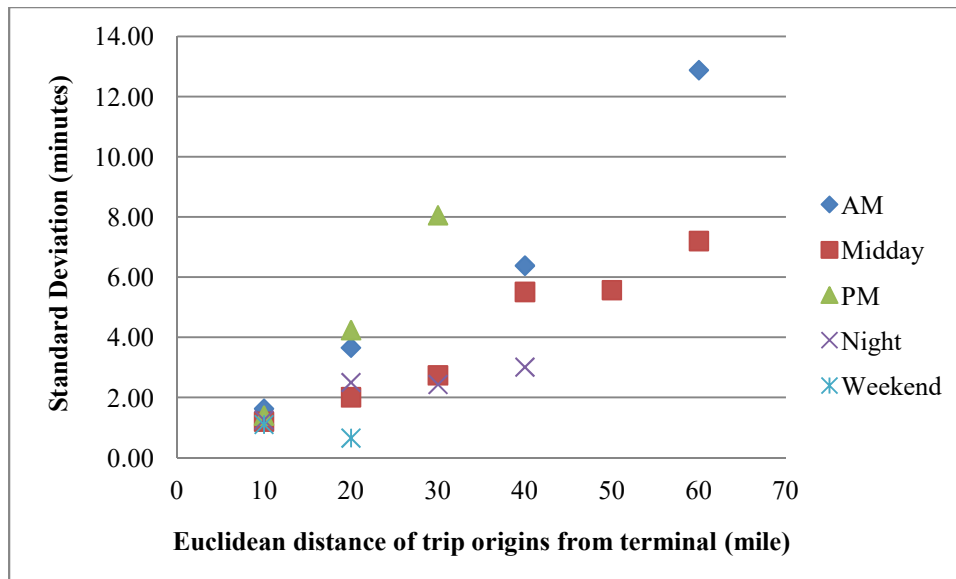


Figure 6.8 Mean Standard deviation for different time periods

How does the travel time reliability change with time of day? The port drayage trips are first classified into four categories according to their departure times: AM (6am – 9am), Midday (9am – 3pm), PM (3pm – 7pm), and Night (7pm – 12am and 0am – 6am) trips, and then the coefficient of variation of drayage trips from the same category is averaged over Euclidean distance between the trip origin and the port and plotted in figure 6.7. There are some missing data points in figure 6.7 because no truck trip data was collected within certain time periods and certain distance interval. Figure 6.7 shows that the mean coefficient of variation value of drayage trips is larger during AM and PM time periods, and smaller during other times of the day. However, how the coefficient of variation changes over distance is not consistent for different times of the day. For example, the CV value for midday trips stays constant over distance while the CV value for night decreases over distance.

The standard deviation of trip travel time averaged over Euclidean distance from terminal is shown in figure 6.8. It can be observed that the standard deviation increases over distance, which indicates that the absolute value of trip uncertainty increases with the trip length. It could also be observed that the standard deviation of travel time is larger during AM and PM hours, and smaller during other time periods. And such difference increases with the Euclidean distance from terminal.

It can be concluded from this analysis that time of day has a significant impact on travel time reliability while trip length has less impact on the reliability. The port drayage trip is much more reliable during midday, night and weekend than AM and PM hours.

6.2.2.2 Network reliability analysis

Network reliability is further evaluated by analyzing the truck GPS data collected on freeway links. The coefficient of variation is used as the reliability metric to measure how the travel time reliability changes over time and space, and the results are presented in figures 6.9, 6.10, 6.11 and 6.12.

In these figures, the coefficient of variation is classified into three categories to represent three different levels of reliability: most reliable, moderately reliable, and least reliable. First, it can be observed from those figures that the network is most reliable during night time and the CV for most freeway links is below 0.17; and that the drayage network is least reliable during PM hours and the CV value for most freeway links is above 0.17. Second, the unreliable freeway links can be identified from those figures. SR 60 section between I 710 and SR 57 is unreliable during most of the time periods, with the CV above 0.34. Some other freeway links are found unreliable during peak hours, which include I 105 section between I 710 and I 605, SR 91 section between SR 57 and I 605, I 405 section between I 710 and SR 22, I 405 section between I 105 and I 110, I 710 section between I 105 and SR 91, SR 57 section between SR 60 and I 210, and I 605 section between I 105 and SR 91. The CV for those links is above 0.34 during AM or PM peak hours.

The network reliability is also evaluated by examining the travel time reliability on major corridors. The most frequently used corridors identified in subsection 6.2.1 are used for analysis, and the CV is calculated for each corridor by averaging the CV values of all the links constituting that corridor. The results are presented in table 6.3. It can be observed that most corridors are more reliable during midday and night than peak hours. By comparing the performances of different corridors, it is found that I 605 is the least reliable corridor, while I 110 is the most reliable corridor.

It can be concluded that time of day has a significant impact on travel time reliability. The network links as well as corridors are more reliable during night than peak hours. While the corridor reliability indicates the overall performance of the entire corridor, the link reliability could be used to identify bottlenecks on the corridor.

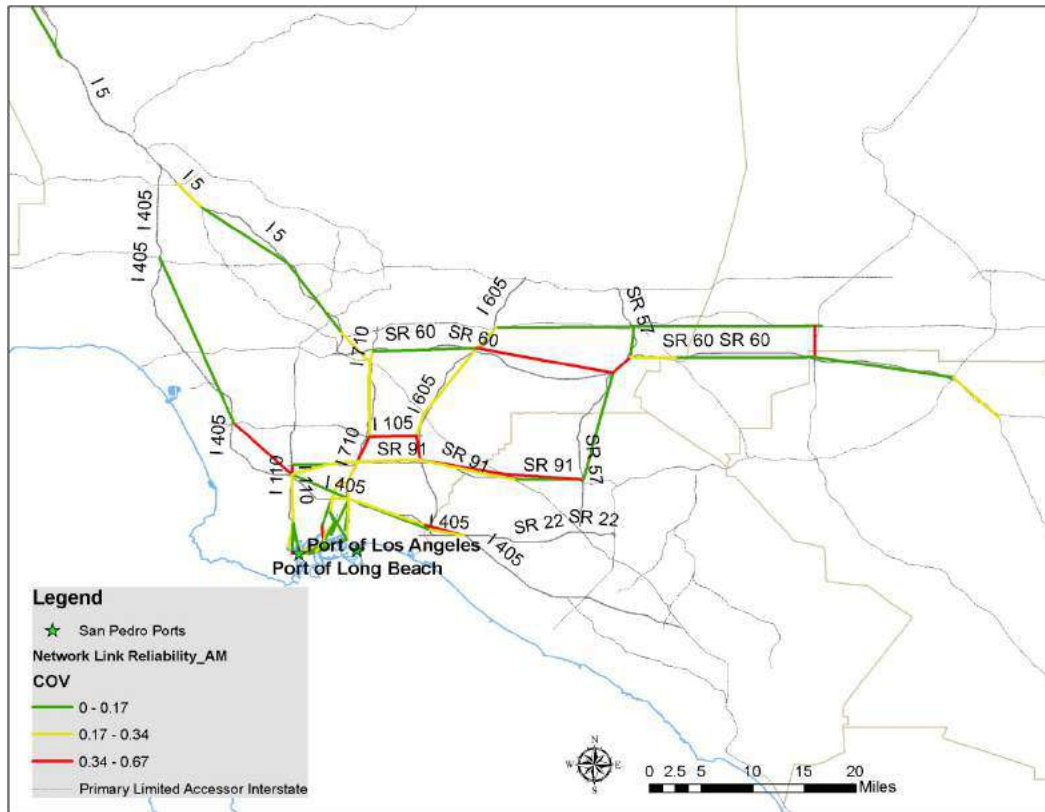


Figure 6.9 Network link reliability during AM time period

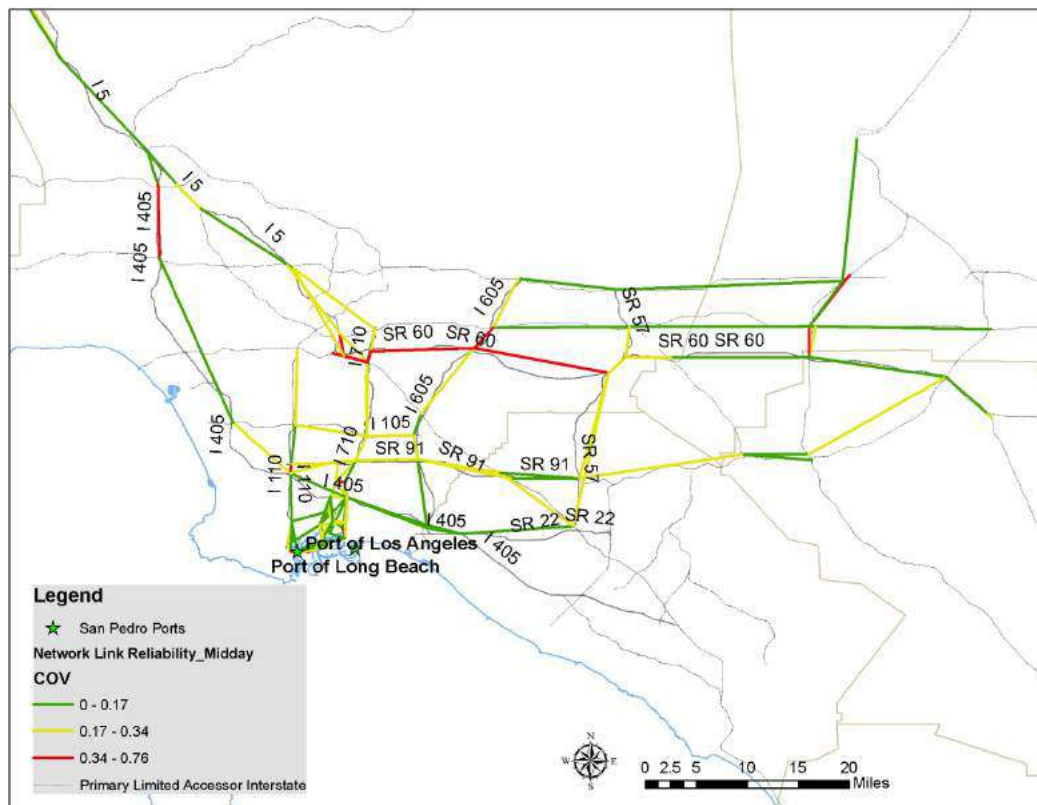


Figure 6.10 Network link reliability during Midday

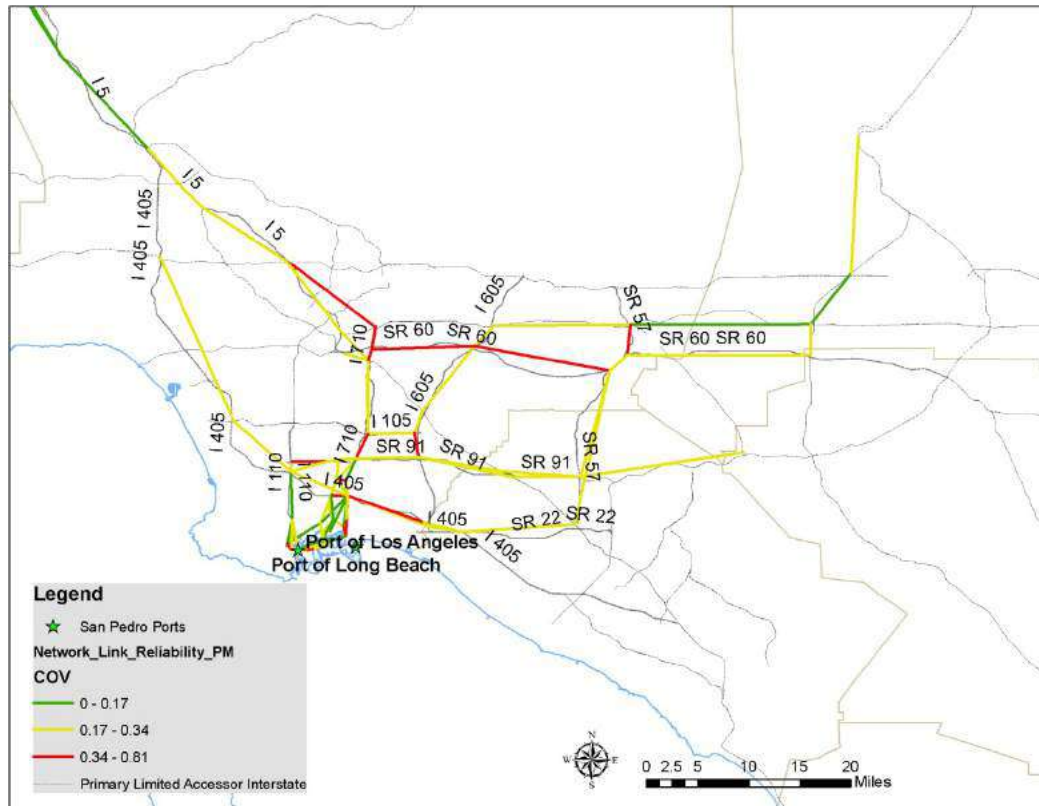


Figure 6.11 Network link reliability during PM time period

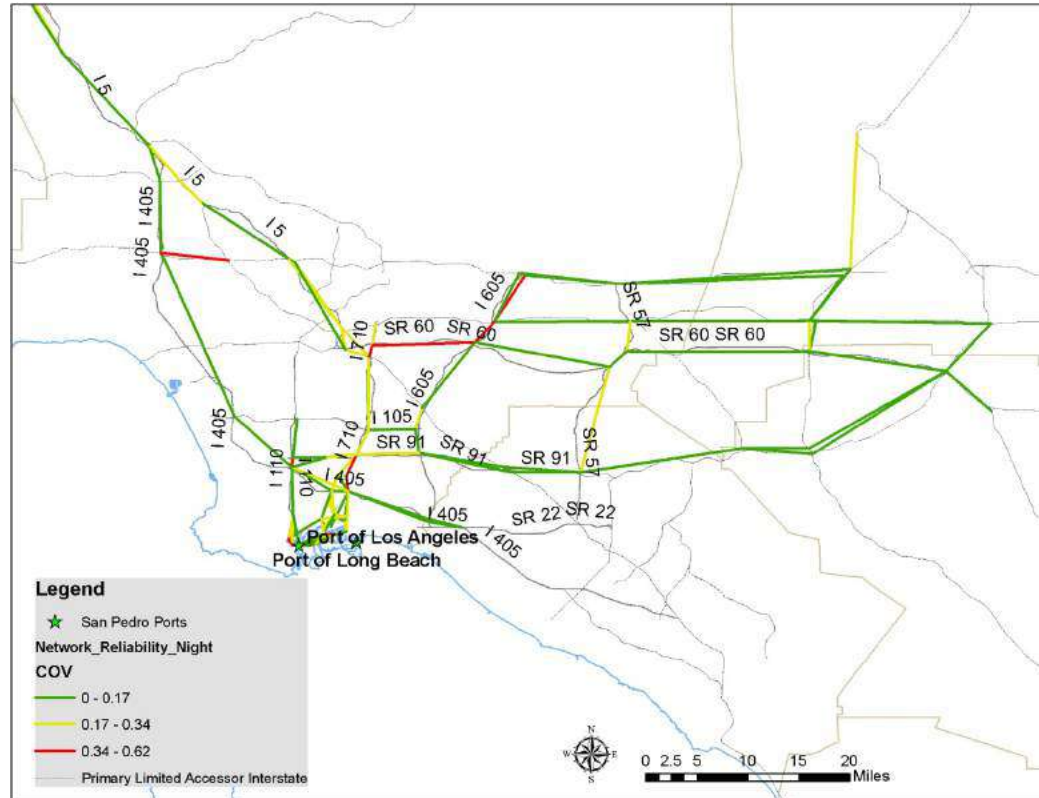


Figure 6.12 Network link reliability during Night

Table 6.3 Coefficient of variation on major truck corridors during different times of day

Name	Freeway Section	AM	Midday	PM	Night	Average
I 710	from SR 60 to SR 47	0.161	0.211	0.265	0.212	0.212
SR 91	from I 110 to SR 57	0.277	0.190	0.236	0.145	0.212
SR 57	from SR 91 to I 10	0.183	0.228	0.263	0.161	0.209
SR 60	from I 710 to I 215	0.206	0.187	0.249	0.173	0.204
I 110	from SR 91 to SR 47	0.260	0.144	0.178	0.107	0.172
I 605	from I 210 to SR 91	0.241	0.283	0.299	0.197	0.255
Average	-----	0.221	0.207	0.248	0.166	0.211

6.3 Routing Choice Analysis and Travel Time Prediction

This section will first analyze the routing choices between certain OD pairs to better understand what factors might affect the routing decisions and how the routing choice is related to the route attributes. Then a simple method is proposed to predict the confidence interval of truck travel times. This method is validated with the collected truck trip data and then applied to the entire drayage network for travel time prediction. The prediction results are also evaluated to explore how such results could be translated into truck arrival information and used by terminal operators for improving container handling operation on the yard.

6.3.1 Routing choice analysis

To identify the routing choices between any OD pair and evaluate route attributes, a computer program was written in Matlab to process the truck trip data. One function of the program is to identify all the routing choices between any given OD pair and the frequency of each route being taken. Another function of this program is to evaluate the major attributes of each route based on collected trip data, such as the mean and the standard deviation of the travel time.

Here an OD pair is chosen as a case study, for which the origin is at the intersection of SR 60 and SR 71, and the destination is at the intersection of I 710 and Ocean Blvd. This OD pair is selected because both the origin and destination have been identified as one of the major origins and destinations in subsection 6.2.1, and several alternative paths are available between this OD pair which allows for multiple route choices. After analyzing the routing decisions made by drivers between this OD pair based on GPS data, a total of ten routes have been identified. Four major routes along with their usage frequency are illustrated in figure 6.13. To explore the relationship between routing decisions and the route attributes, data collected during midday and night is examined and the results are shown in figure 6.14 and 6.15.

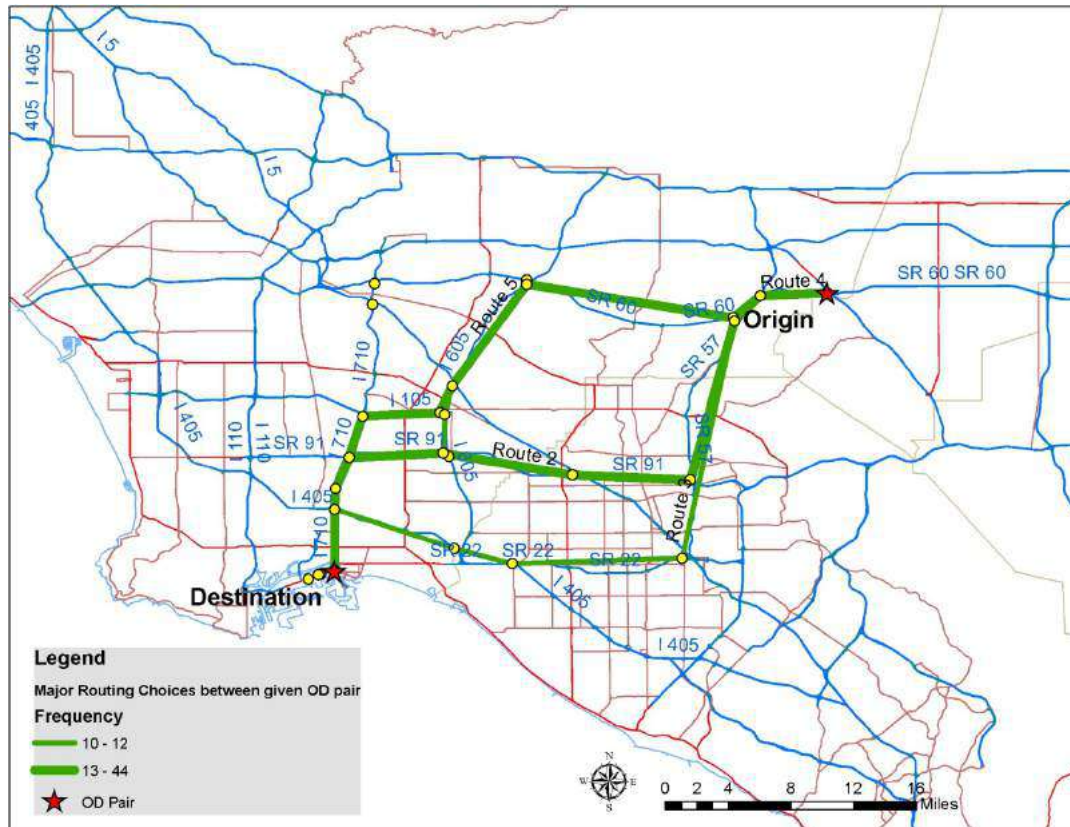


Figure 6.13 Major Routing choices between a given OD pair

Figures 6.14 and 6.15 show the mean and standard deviation of travel time, and the route choice percentage for midday and night trips on major routes. The 95% confidence interval of travel time is also shown in the figures as black bars. A total of 57 midday trips and 33 night trips were collected for this OD pair. It can be observed from figure 6.14 that route 2, which has the shortest mean travel time and smallest standard deviation, is selected more than other routes. It illustrates that truck drivers tend to choose the route with shortest travel time. However, for routes 3, 4, and 5, the travel time attributes of these routes cannot explain the truck drivers' preference. Route 4 has a longer mean travel time and larger standard deviation, but is selected more often than route 3 and 5. That could be because there are some other factors affecting the truck drivers' decisions but not collected by GPS dataset, such as the geometric attributes of the routes, and also the lack of perfect information held by the drivers.

Figure 6.15 shows a good correlation between route attributes and route choice percentage. The mean travel time on routes 4, 2, and 5 increases gradually while their usage frequency decreases gradually. Route with a shorter travel time has a higher probability being selected.

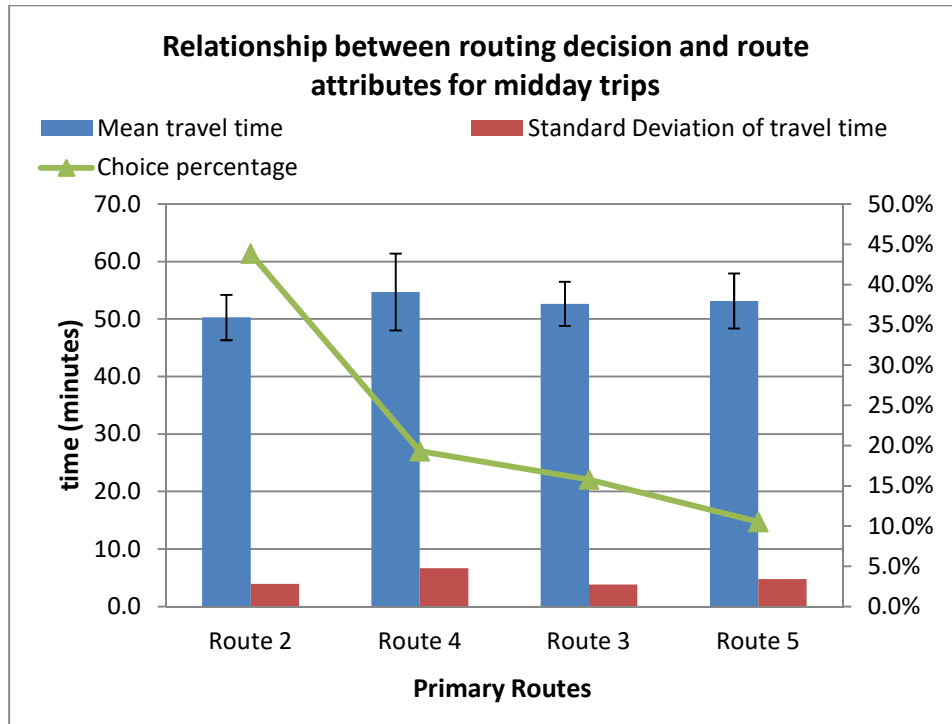


Figure 6.14 Relationship between routing decision and route attributes for midday trips

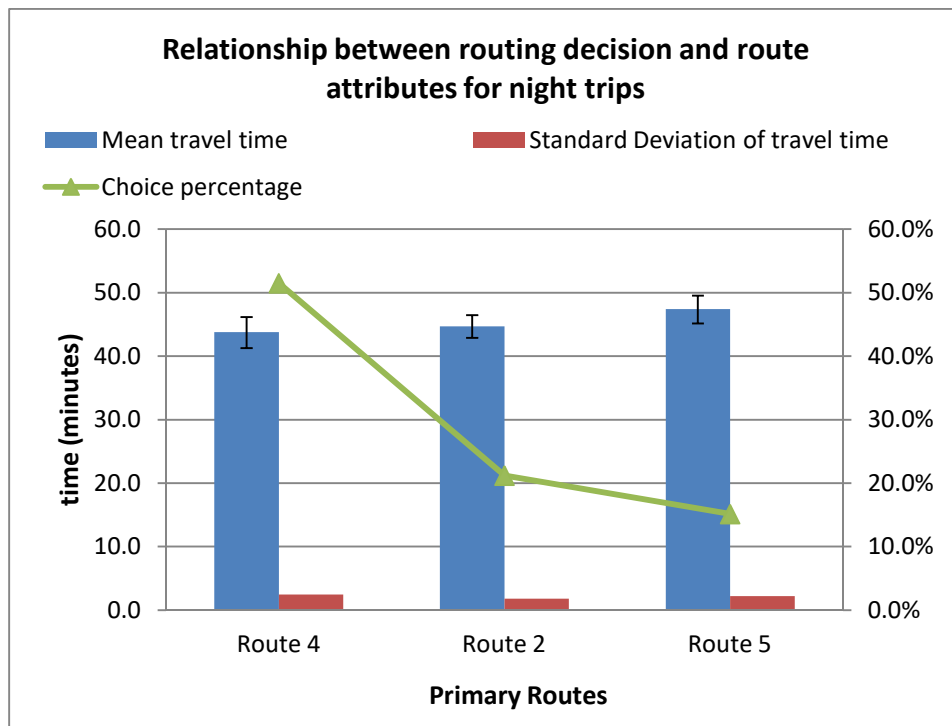


Figure 6.15 Relationship between routing decision and route attributes for night trips

6.3.2 Travel time Prediction

6.3.2.1 Travel time prediction method

In this subsection, a method for travel time prediction will be discussed and the results will be presented. The 95% confidence interval is used to estimate the truck travel time between a given OD pair. If the truck departure time is known in advance, such prediction results can be translated into truck arrival time windows and support the implementation of the container rehandling strategy proposed chapter three.

Considering the large size and high density of this port drayage network in LA basin, it is reasonable to assume that the network links are independent of each other. In addition, this chapter considers predicting travel time throughout twenty-four hours of a day, during which the traffic condition varies a lot and the travel time on each link is less likely to be dependent on each other. The validity of this assumption will be confirmed later in this subsection. Given this assumption, the mean travel time of a path between the given OD pair can be estimated by summing up the mean travel time of all the links which constitute this path. In the same way, the variance of the travel time can be estimated by summing up the variance of all the links. Then the 95% confidence interval of truck travel time can be calculated based on the estimated mean and variance. The estimated 95% confidence interval of travel time on a path can be expressed by the following equation:

$$CI = \left[\sum_{i=1}^n M_i - 1.96 \cdot \sqrt{\sum_{i=1}^n V_i}, \sum_{i=1}^n M_i + 1.96 \cdot \sqrt{\sum_{i=1}^n V_i} \right]$$

i —the i th connecting link on the path;

n —the total number of links which constitute the path;

M_i -- the mean travel time on the i th connecting link;

V_i -- the variance of travel time on the i th connecting link.

To forecast the 95% confidence interval of travel time between a given OD pair without knowing which route is taken, we first estimate the 95% confidence interval for all the routes being used before, and then compute the lower limit and upper limit of those confidence intervals. The estimated 95% confidence interval of travel time between a given OD pair can be expressed by the following equation:

$$CI = [\min(CI_1^l, \dots, CI_i^l, \dots, CI_m^l), \max(CI_1^u, \dots, CI_i^u, \dots, CI_m^u)]$$

i —the i th route that has been used by truck drivers before between the given OD pair;

m – the total number of different routes being used by truck drivers before between the given OD pair;

CI_i^l -- the lower limit of estimated 95% confidence interval of truck travel time for the i th route;

CI_i^u -- the upper limit of estimated 95% confidence interval of truck travel time for the i th route.

The proposed method is applied to the entire drayage network to predict the truck travel time between different OD pairs. The entire GPS dataset is divided into two parts, with the first part used as input data for travel time prediction (data collected from January 21st to March 8th), and the second

part used for evaluating the accuracy of the prediction results (data collected from March 9th to March 31st). For the method validation, the collected truck travel time on different routes is compared with the 95% confidence interval estimated for corresponding route to evaluate the frequency of actual travel time falling within the estimated confidence interval.

6.3.2.2 Travel time prediction result

First a specific OD pair is used as an example to illustrate the travel time prediction method and validation results. The origin of this selected OD pair is at the intersection of SR 60 and SR 71, and the destination is at the intersection of I 710 and Ocean Blvd. This is the same OD pair evaluated for routing choices in subsection 6.3.1. Table 6.4 shows the 95% confidence interval estimated for the three major routes between this OD pair during AM, Midday, PM, and Night. It can be observed from table 6.4 that under most times of the day route 2 has the narrowest travel time confidence interval. Table 6.5 shows the validation results of the predicated 95% confidence interval, in which collected trip number indicates the number of trips collected for prediction result validation, and frequency indicates the frequency of actual travel time falling within the estimated confidence interval. Although not many trips were collected for the result validation, it still can be observed from table 6.5 that in most cases the actual travel time falls within the estimated 95% confidence interval. By considering all the routes being used, the 95% confidence interval of travel time between this OD pair is estimated and presented in figure 6.16. Figure 6.16 shows that the estimated confidence interval is wider during AM and PM time period, but much narrower during midday and night. Such results can be explained by the network reliability results presented in section 6.2.2.2, in which it is found that the drayage network is more reliable during midday and night.

Table 6.4 95% confidence interval estimated for major routes between the given OD pair (minute)

Route No.	AM		Midday		PM		Night	
	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit	Lower Limit	Upper Limit
2	56	88	44	59	48	67	43	49
4	58	102	40	68	47	75	42	48
5	51	103	39	69	51	75	43	49

Table 6.5 validation results of predicted 95% confidence interval

Route No.	AM		Midday		PM		Night	
	collected trip number	frequency	collected trip number	frequency	collected trip number	frequency	collected trip number	frequency
2	2	100.0%	8	87.5%	1	100.0%	1	100.0%
4	1	100.0%	3	66.7%	0	-	3	100.0%
5	1	100.0%	1	100.0%	0	-	0	-

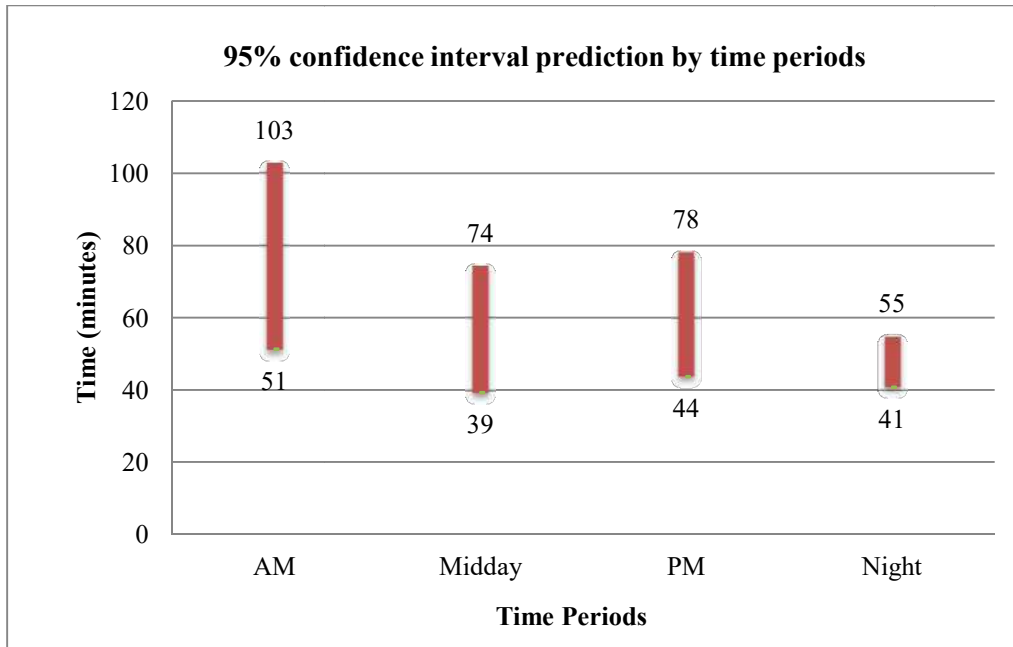


Figure 6.16 Estimated 95% confidence interval of travel time by different times of day between given OD pair

To examine how the estimated travel time confidence interval and its accuracy changes with trip origins, several major origins along I-710 and SR 60 identified in subsection 6.2.1 are selected for analysis and the trip data collected between those origins and the terminal destination at the intersection of I-710 S and Ocean Blvd is used for travel time prediction and validation. The locations of the destination and those origins are marked in figure 6.17. The proposed travel time prediction method is applied to estimate the 95% confidence interval of travel time between those OD pairs for different time periods, and the prediction accuracy is calculated by comparing the confidence interval estimated for each route with the actual trip data collected on that route. The results are presented in table 6.6.

It can be observed from table 6.6 that the predicted confidence interval is quite accurate and the basic assumption that truck travel time on each link is independent is reasonable. The accuracy of travel time prediction for any OD pair is no less than 84% and the average accuracy rate is as high as 94%. In addition, table 6.6 and figure 6.17 indicate that when the trip origin is close to the port, our proposed prediction method can provide quite a tight estimate of the truck arrival time window. For example, with regard to the trips originating from the intersection of I-710 S and I-405, the width of the predicted time interval is only 2 minutes. If the trip origin moves farther away from the port, although the width of the estimated confidence interval increases gradually with the trip length, this prediction method is still able to provide a tight estimation of arrival time window for midday and night trips. Take the trip origin at the intersection of SR 60 and SR 71 for example, the width of the estimated confidence interval for night trips is only 14 minutes and much narrower than the width of confidence interval for AM trips, which is 52 minutes. Again this can be explained by the network reliability characteristics. As discussed before, the drayage network is more reliable during midday

and night; therefore, the travel time variability is also smaller during midday and night, resulting in a narrower confidence interval of travel time.

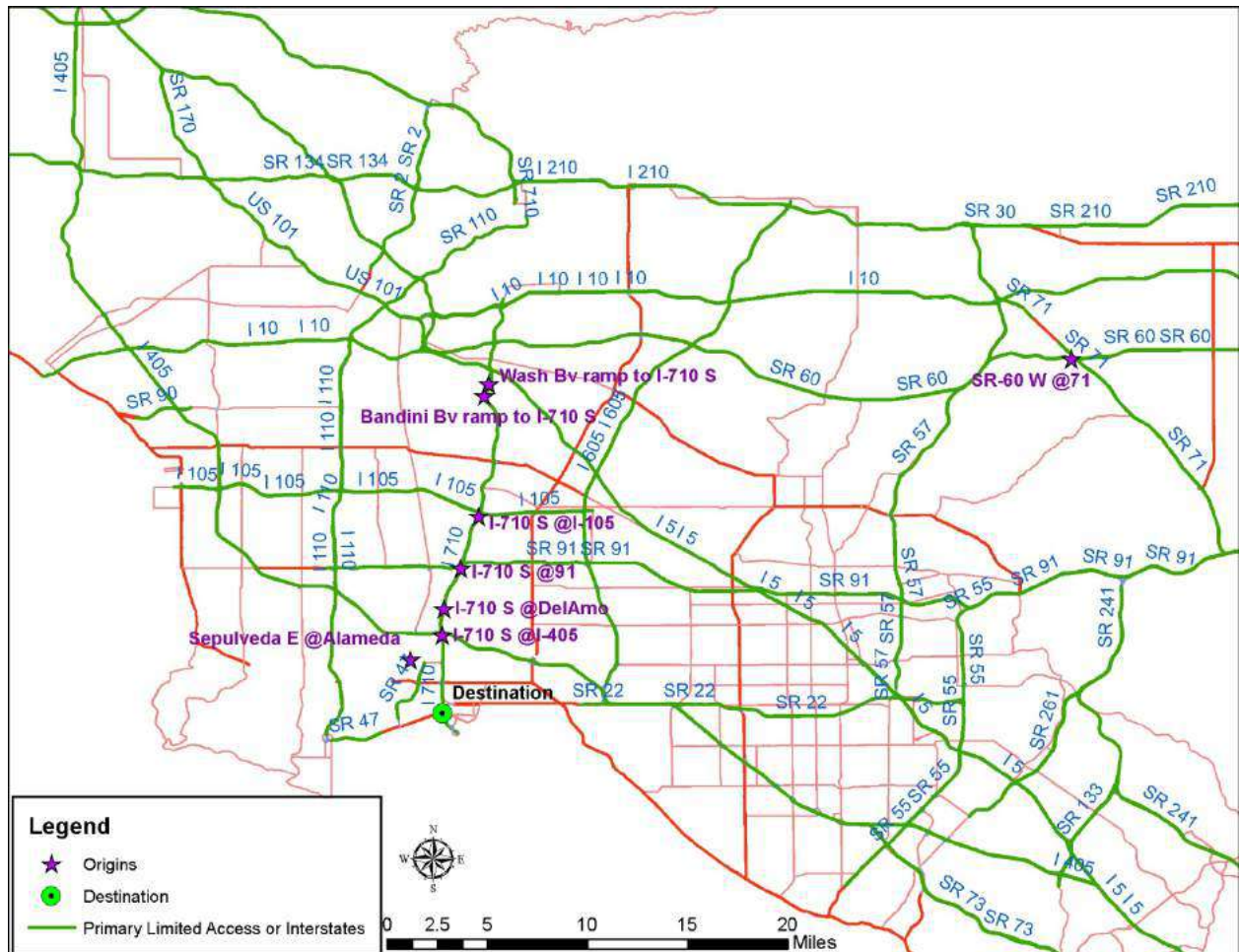


Figure 6.17 The distribution of estimated travel time interval across network

Table 6.6 Estimated confidence interval of travel time for major trips terminating at I-710 and Ocean Blvd

Origin Location	AM	Midday	PM	Night	Prediction Accuracy
Sepulveda E @Alameda	[7, 11]	[7, 11]	[8, 12]	[6, 10]	92.6%
I-710 S @I-405	[4, 6]	[4, 6]	[4, 6]	[4, 6]	100.0%
I-710 S @DelAmo	[5, 9]	[5, 9]	[5, 9]	[5, 9]	90.8%
I-710 S @91	[7, 13]	[7, 11]	[7, 11]	[7, 10]	100.0%
I-710 S @I-105	[10, 17]	[10, 14]	[10, 15]	[9, 13]	92.9%
Bandini Bv ramp to I-710 S	[17, 27]	[15, 27]	[19, 27]	[14, 27]	97.9%
Wash Bv ramp to I-710 S	[18, 34]	[16, 34]	[18, 34]	[15, 34]	92.7%
SR-60 W @71	[51, 103]	[39, 74]	[44, 78]	[41, 55]	84.0%

These results demonstrate that the methodology proposed in this chapter can be used to estimate the truck arrival time window, even on a congested and dense network such as that in the Los Angeles basin. In addition, a narrower confidence interval of travel time will be achieved if the terminal operator knows the truck routing choice. The confidence interval estimation is more useful for terminal operators if the truck departs from its origin during midday or night because a narrower arrival time window will be achieved, which could translate into truck arrival information with higher quality, such as more arrival groups and smaller group sizes.

6.3.2.3 Potential implementation of travel time prediction method for improving truck arrival information

As demonstrated in chapter three and four, the truck arrival group information is effective for improving the crane productivity and reducing truck transaction time; updating this group information in real time lowers the information requirement and provides significant benefit even with a small amount of information.

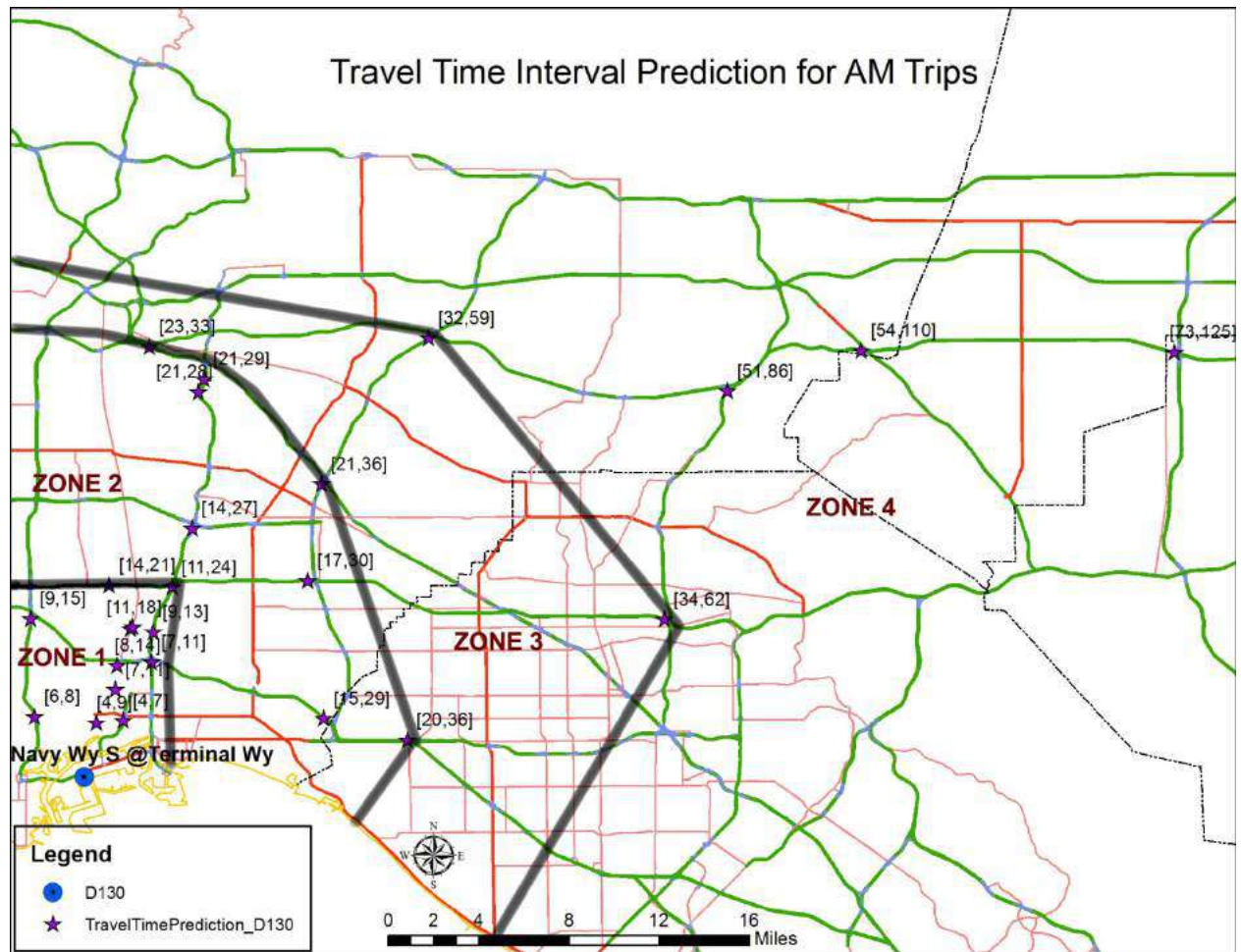


Figure 6.18 The prediction interval of travel time for morning trips

Figure 6.18 shows the travel time prediction interval for morning trips from various origins. By considering the geographical locations of those origins and the travel time prediction interval, this drayage network can be easily divided into several zones to show the boundaries of travel time changes. Zone 1 is the area from where the drayage truck will arrive at the terminal within 11 minutes, zone 2 is the area from where the drayage truck will arrive at the terminal within 8-36 minutes, zone 3 is the area from where the drayage truck will arrive at the terminal within 20 – 62 minutes, and zone 4 is the area from where the drayage truck will take more than 50 minutes to drive to the terminal. If the current locations of all the drayage trucks heading towards the terminal are known, then these trucks can be classified into several arrival time groups according to which zone they are located within, and used for implementing the container rehandling strategy proposed in chapter three. For example, trucks arriving in 30 minutes can be classified into the first group, trucks arriving in 30 – 60 minutes can be classified into the second group, and those trucks arriving after 1 hour can be classified into the third group. Such group information can be directly used by terminal operators to improve the container handling operation on the yard and have proved effective in enhancing the system performance of drayage truck/ terminal interface. In addition, if there is some mechanism for truck drivers to update their current location and share such information with the terminal operators, then

their arrival time window can be recalculated based on their new location and the truck grouping can be updated. Such dynamically updated group information will further enhance the system efficiency if being utilized by terminal operators.

6.4 Summary

This chapter explores the travel time reliability of the port drayage network and evaluates the predictability of drayage truck travel time. First the coefficient of variation and standard deviation are used as reliability measures to calculate travel time reliability between major OD pairs, across network links and major corridors, and throughout different times of day. Then the truck routing choices are analyzed by examining the relationship between the routing choice and route attributes such as the mean and standard deviation of travel time. In the end, a simple method is proposed to predict the 95% confidence interval of travel time between any OD pair. This method is applied to the entire drayage network and validated by comparing the prediction results with the collected truck trip data. Its implementation is also discussed. This research is not intended to provide real-time travel time prediction or routing guidance for truck drivers, but to provide terminal operators with more knowledge about truck arrivals and support the implementation of container rehandling strategy proposed in chapter three.

The travel time prediction and validation results demonstrate that the proposed travel time prediction method is quite accurate in estimating the arrival time window of trucks at the terminals, with the average accuracy rate as high as 94%. Besides, the proposed method could provide a tight estimation of truck arrival time window when the trip origin is close to the port. Even if the trip origin is far away from the port, this method is still able to provide a tight estimation of arrival time window for midday and night trips. This method can be implemented by terminal operators to estimate the truck arrival time window at the terminal gates and obtain truck arrival group information. Such information has proved very useful for improving the system efficiency of drayage truck/ terminal interface. If there is some mechanism for truck drivers to update their current location and share such information with the terminal operators, then the prediction result of truck arrival time window can be updated in real time to provide dynamically updated truck arrival information, which could further enhance the system efficiency if utilized by terminal operators.

Although the proposed method of travel time prediction is very simple and our collected GPS dataset is aggregated, it is good enough for providing the terminal operators with truck arrival time window information and can be used for implementing our proposed container rehandling strategy, enabling significant improvements in the drayage truck/mariner terminal interface.

Chapter 7 Conclusion

This dissertation explored using truck arrival information to integrate drayage truck and container terminal operations and improve the system efficiency. The first part of this dissertation focused on the import container retrieval operations on the container yard and proposed an advanced container rehandling strategy (Revised Difference Heuristic), for using truck arrival information to reduce

container rehandling work. That strategy is designed to identify the optimal storage location for rehandled containers to avoid future rehandles, and thus enhance the operational efficiencies of the terminal and reduce truck delays within the terminal. To assist terminal operators in understanding the benefits of using truck arrival information, a computer simulation model was developed. This model evaluates the impact of truck arrival information on container handling efficiency by adopting proposed container rehandling strategy during the import container retrieval operation. In addition, an M/G/1 queuing model was employed to assess the impact of truck information on crane productivity and truck transaction time. A variety of information quality scenarios as well as different terminal system configurations were modeled to evaluate how the information quality and terminal design impact the effectiveness of the proposed strategy. The second part of this dissertation investigated the travel time reliability of the port drayage network and evaluated the predictability of drayage truck travel time. A simple but effective method was developed for predicting the confidence interval of truck travel time between given OD pairs based on historical GPS data. This method provides a useful tool for terminal operators to estimate the truck arrival time window at the terminal gates and supports the implementation of the proposed container rehandling strategy for improving yard operations.

The research results demonstrate that any amount of information about arrival trucks is effective for improving crane productivity and reducing truck transaction time. For example, given a container block with a single yard crane assigned for retrieval operations and with forty bays, six stacks and five containers in each stack, knowing the complete arrival sequence of trucks could improve the crane productivity by 15% and reduce the truck transaction time by 24% if the truck arrival rate is six per hour. Splitting the truck arrivals into two groups can generate almost one-half of the truck time savings achieved from having the complete arrival sequence. In addition, 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. In addition, the truck information is more valuable for terminal systems with high stacking or operating near their capacity.

The research results also illustrate that having and utilizing a truck appointment system could generate significant improvements in system performance. For example, utilizing the arrival information obtained from a truck appointment system with one day's lead time and four-hour appointment window for a container block with a single yard crane assigned for retrieval operations and with ten bays, six stacks, and four containers in each stack could improve the crane productivity by 10% and reduce the truck transaction time by 15% if the average dwell time of containers is four days. Reducing the duration of appointment window could further enhance the system efficiency if the yard crane service system approaches its operating capacity. Also, increasing the appointment lead time of trucks could improve the system performance but such an additional benefit gradually diminishes as the yard crane service system approaches its capacity. In addition, the performance of yard crane service system is robust to the usage of inaccurate truck information. As long as the deviation of truck's actual arrival time from its appointment window does not exceed eight hours, whether or not the trucks keep their appointments has no effect on the system performance.

This dissertation demonstrated that the proposed travel time prediction method is quite accurate in estimating the arrival time window of trucks at the terminals, with the average accuracy rate as high

as 94%. The proposed method can provide a tight estimation of the truck arrival time window when the trip origin is close to the port, or when the truck departs from its origin during midday or night. This method can be utilized by terminal operators to estimate the truck arrival time window at the terminal gates if they know the trip origin and the departure time, and support the implementation of the proposed container rehandling strategy. In addition, a mechanism for truck drivers to update their current location and share such information with the terminal operators would provide dynamically-updated truck arrival information, which could further enhance the system efficiency if utilized by terminal operators.

In summary, this research provides terminal operators with insights as to the impact of truck arrival information on system efficiency of drayage truck/terminal operations, tools for them to obtain better information without technology improvements, and operational strategies to effectively utilize such information. To implement the proposed container rehandling strategy, container terminals could incorporate the proposed algorithm into their current operating systems to determine the storage location for each rehandled container on yard. The required truck arrival information can be obtained from an existing truck appointment system, or phone calls from approaching trucks. To further improve the information quality, the drayage trucks could be equipped with GPS units to share their location information with the container terminals so the terminals could estimate truck arrival times using the travel time prediction method proposed in this dissertation. The implementation requires some modifications to current terminal operations and cooperation between container terminals and drayage trucking industry, which may raise privacy and other concerns. For example, equipping trucks with GPS units and sharing their location with the terminal operators may disclose the shipping and logistics information of businesses and be rejected by shippers. Truck drivers might be unwilling to use the gate appointment system since making and keeping gate appointments could cause additional costs. Those concerns in part explain why the container terminals have not investigated utilizing truck arrival information to improve terminal operations even if they have a truck appointment system in place. Those concerns need to be addressed to encourage the implementation of the proposed container rehandling strategy and truck travel time prediction method.

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