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# High-Throughput Intermodal Container Terminals: Technical and Economic Analysis of a New Direct-Transfer System

**Bernardo de Castilho**

High-Throughput Intermodal Container Terminals:
Technical and Economic Analysis of a New Direct-Transfer System

By

Bernardo Jose De Castilho

Engineer  (Federal University of Rio Grande do Sul)  1984
M.A.Sc.  (University of British Columbia)  1987


DISSERTATION

Submitted in partial satisfaction of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

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of the

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## Abstract

The volume of containerized cargo traffic has increased steadily over the last three decades.
Because of significant cost advantages on long-haul trips and growing concern for the environment,
large portions of this traffic are now transported by trains rather than trucks. The main stumbling
block that has prevented rail transportation from playing an even more prominent role in the
movement of containerized cargo has been the cost of transferring containers between vessels and
trains. This research explores innovative systems capable of performing such transfer operations
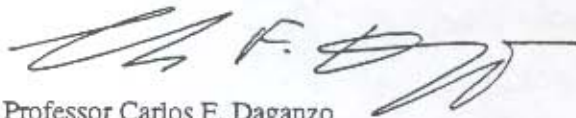efficiently.

Terminals with rail tracks along the docks -- allowing for trains to be loaded directly from ships --
are common for bulk cargo, but have not to date been implemented successfully for containerized
cargo. The main reasons for this are: (i) the need to classify trains by container destination, and
(ii) the reduced dock crane throughput resulting from interference among multiple cranes unloading
containers onto a single rail track.

The main thrust of this research is the development of a direct-transfer terminal design that allows
trains to be loaded and simultaneously classified by destination, largely eliminating the need for
further train processing at downstream rail yards.

Analytical methods are developed to evaluate the performance of the proposed design, including
train classification levels attainable during the loading process and the productivity of the dock
system. The methods are validated against a computer simulation.

A comprehensive economic model is developed to measure the costs incurred while moving containers through the proposed terminal and through conventional facilities. The model includes factors that are often neglected in the literature, such as container inventory costs.

Several operating scenarios are used to identify the conditions under which each type of terminal design is most effective. The results show that direct-transfer terminals can be more cost-effective than conventional approaches, especially in cases where a significant portion of the traffic is intermodal. The savings are mainly due to reduced handling and inventory costs, but the approach also has environmental advantages and lends itself very well to automation.

Professor Carlos F. Daganzo
Committee Chair

Dedication:

This work is dedicated to my family:

Marlene, Maria Elisa, Elysio and Rodrigo de Castilho.

For always being the best friends anyone could have.

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# Acknowledgements

# 1. Introduction

This chapter introduces the subject of this research: the analysis of high-throughput intermodal container terminals. Section 1.1 presents a brief description of the problem. Section 1.2 explains the objectives and relevance of the research. Section 1.3 reviews the literature available on the subject and summarizes the methods that have been used to analyze the problem. Finally, Section 1.4 describes the research approach adopted and the structure of this document.

## 1.1 Problem Description

The essence of intermodalism is to use the most efficient and economical transportation mode (e.g., ships, trains, or trucks) to cover each part of the journey. The intermodal problem is not so much a challenge along the steady-state components of the trip (that is, aboard the ship or train), but rather in designing and executing the interface points. The ship-to-train transfer point, in particular, is presenting the industry with a formidable challenge.

It is well recognized by major U. S. ports that the issue of ship-to-rail intermodal exchange is a critical competitive factor. The nature of this linkage system, however, has been the center of much debate, especially whether ports should establish intermodal yards within terminals or, instead, share off-terminal, central intermodal facilities.

Almost without exception, the current procedure for handling the movement of containers between a ship and a train involves the following steps:

- Discharge the box to a set of wheels or via yard equipment to a storage buffer on the terminal.

- Classify the box with regard to destination, size, weight, and intended mode of transport.

- Transport the box via truck to an off-dock rail yard.

- Transfer the box from the truck to the train or to a buffer within the rail facility and then to the train.

Terminals capable of providing more direct ship-to-rail transfers could eliminate most or all of the intermediate handling and buffering steps, achieving the following benefits:

- Reduced handling costs: direct transfers saves drayage (truck transport) costs, extra lifts, gate movements, and paperwork.

- Reduced transportation time: reducing the number of handling moves and time spent in storage might save 12 to 24 hours of transportation time (Ashar, 1991). This would reduce inventory costs and increase container utilization.

- Reduced terminal area requirements: coordinated operation of ship and rail creates a continuous flow of containers in and out of the terminal, eliminating the accumulation of boxes in storage areas. The reduction of yard space requirements is extremely important because waterfront property is expensive and frequently unavailable.

- Environmental merits: utilizing rail instead of road transportation relieves road congestion, increases safety, and saves energy.

Despite all these potential benefits, few ports in the U. S. are equipped to provide direct intermodal transfers, and skepticism about their viability is fairly widespread throughout the maritime and railroad industries. Some of the common objections to direct transfers include:

- The perception that providing on-dock rail terminals would be a waste of scarce waterfront property.

- The necessity to handle trains with both international and domestic containers on a single rail yard. Locating such a facility within a marine terminal would require even more land and could be disruptive to normal port operations.

- The significant public investment required to realign regional road and rail transportation systems.

- Operational difficulties arising from the need to sort trains without intermediate storage buffers. This is especially true of double-stack rail cars, which face a series of restrictions with respect to their loading patterns (Smith, 1990). Also, direct transfers may require train and vessel schedules to be coordinated.

All these objections are at least questionable. Terminals with significant intermodal throughput could actually require less land if their on-dock rail facilities reduced the need for in-transit container storage areas. The need to consolidate domestic and international traffic at the rail facility could be addressed by providing the terminal with rail access only, and not necessarily with a full-blown rail terminal.

Operational difficulties can be addressed in a number of ways, including the use of automation and state-of-the-art communications, and taking advantage of special characteristics of certain services, such as pre-sorted vessels or single-customer, single-destination trains.

Perhaps more serious than the technological and operational objections, however, are the organizational ones. In order to offer innovative intermodal services, ports and railroads must often re-negotiate existing institutional and regulatory arrangements as well as change deeply ingrained work practices. This concern is well expressed by Mr. Bernard Sain, vice president of R&D for Trailer Marine Transport (American Shipper, Nov. 1985):

> "'Pure thought' has to divorce itself completely from labor and artificial constraints to consider new concepts. All secondary issues need to be swept away and attention focused on optimum container flow patterns and equipment."

Our research follows this recommendation. The impacts of direct intermodal linkage between vessels and trains are explored from a systems analysis perspective.

## 1.2. Research Objectives and Relevance

The main goal of the research is to determine efficient ways for container terminals to provide direct vessel-to-rail transfer operations and to identify situations where this alternative can be economically attractive compared to more conventional approaches.

To achieve this, we introduce a classification system for container terminals based on the type of intermodal transfer they provide (direct, semi-direct, or indirect transfer), and then develop a simple economic model for evaluating the performance of each type of terminal.

The analytical framework for the model makes the best possible use of the limited data typically available in the preliminary design stages of a terminal. Examples of such data include target port throughput, main types of services to be provided, land availability, and equipment performance characteristics.

Because there is currently no standard method for providing direct vessel-to-rail service, a significant portion of this study is devoted to the development of a design for a direct-transfer terminal, including its layout and operating strategy. This part of the research focuses on the problem of sorting containers as they are unloaded from the ship. The economic model is used to compare the performance of this innovative design to more conventional ones under a variety of scenarios. The conditions under which each type of terminal is most appropriate are identified, and the benefits that can be attained by providing on-dock rail are discussed and quantified.

A number of current developments in the container industry have increased the potential pay-off and feasibility of more efficient intermodal operations. These include:

- Exceptional increases in container traffic, especially through a few strategic terminals (Rijsenbrij, 1986). It is generally accepted that this trend will continue and a handful of mega-terminals (or "load-centers") will handle the bulk of all international container traffic by the end of the decade, and high-throughput container corridors between load-centers will

become even more important than they are today. To avoid congestion of the roadways along these links, rail traffic will be intense, making it easier to justify the capital investment required to provide on-dock rail facilities.

- Technological advances such as automatic equipment identification (AEI) and electronic data interchange (EDI) have enabled shippers and terminal operators to change their operations substantially. Today, ship manifests can be transmitted quickly and accurately to terminals operators and to the shipper's clients, enabling more efficient retrieval of containers from the terminals. Vessel loading and unloading plans can be generated based on reliable information transmitted from the previous port of call, with the aid of sophisticated software. The availability of detailed information in real-time will facilitate the task of creating loading/unloading plans suitable for direct vessel-to-rail transfers.

- Highway congestion and the strong concern with the environment have made rail transportation increasingly attractive as compared to trucks. In Europe, for example, EEC transport ministers have recently passed measures designed to boost the growth of intermodal transport (Container News, March 1991). These measures include tax rebates designed to encourage carriers to shift from pure road transport to a combination of road, rail, and ship.

Current methods used by terminal planners and designers are usually based on the extrapolation of previous experience or on detailed simulations of proposed designs. The former approach is obviously inappropriate in the design of innovative facilities, for which current experience is limited or non-existent. The latter usually requires detailed information, often unavailable during the planning process, and extensive analysis to calibrate the models and to determine the relative importance of each parameter. Also, simulations are generally application-specific and therefore incapable of providing analysts with the type of insight and flexibility yielded by simple mathematical models.

Furthermore, current planning methods tend to focus on localized aspects of terminal operations, often making it very difficult for the analyst to consider the port as a single system. The situation described by Imakita in 1978 still persists to a large extent:

> "Existing studies of port operations have tended to follow a piece-meal approach to systems analyses. This has not let to a generally satisfactory treatment of the problems of port development, in spite of the large quantities of data available. Two of the key difficulties seem to be the hesitancy of most investigators to make full use of mathematical modeling, and the tendency to regard port operations in terms of a few independent activities rather than in terms of a highly complex entity of subsystems."

To quantify the benefits of direct-transfer operations in the context of a port, we will develop a simple analytical framework to analyze not only the ship-to-rail interface, but the whole terminal as a component of the transportation chain. We will consider often neglected factors such as container transit times (and associated inventory costs) and the quality of the interfaces between vessel, rail and road transportation.

## 1.3. Literature Review

There is a significant amount of port literature available, but only a small fraction of it deals with relatively new services such as intermodal containerized cargo. This section reviews the work that has been done in the area and puts in context the contributions made by the present research.

For many years, port planners and operators relied on trial-and-error or extrapolation of previous experience for strategic and managerial decisions. The limitations of these methods became evident when new technologies were introduced and ports grew in complexity and importance, spurring new interest in port and rail research.

Computer simulations have been used extensively as planning, managerial, and marketing tools for equipment manufacturers. They require the creation of computer programs that mimic the operation of specific facilities and enable the analyst to examine the performance of the target system under a variety of assumptions.

Simulation programs have been successfully applied to a number of specific problems, including:

- Stowage planning of container vessels and microscopic models for vessel traffic control (Fee, 1980),

- Analysis of container yard layouts, container handling equipment fleet sizing, and traffic flow patterns within marine container terminals (Jordan 1988),

- Prediction of the performance of innovative handling systems (Watanabe, 1981), and

- Railroad capacity and operations analysis (Leachman, 1991)

Advances in computer technology have increased the quality and reduced the cost of creating simulations, making them effective for testing proposed solutions under specific conditions. However, they do not yield the type of general understanding associated with analytical solutions, and are therefore inadequate in generating designs and strategies.

The analytical approach has qualities that complement simulations. It unveils the basic relationships between components of the port system, helping the analyst identify the important aspects of the problem at hand and develop good (if not optimal) solutions.

A number of authors have developed analytical models for the analysis of port-related problems. One of the most comprehensive contributions from a systems analysis viewpoint was by Imakita (1978), who developed several models covering navigation, handling, storage, and inland cargo transport systems. Edmond and Grundey (1975, 1982) examined the rigid schedules imposed on container routes and their effect on the economics of container ports. Taleb-Ibrahimi, Castilho and Daganzo (1989, 1991) examined trade-offs between container storage requirements and handling effort for different operating strategies.

In the railroad field, comprehensive analytical work has been done by Beckman et al (1956). More recently, Petersen (1977) and Daganzo (1985) developed methods for evaluating the delays, handling effort, and track requirements for performing train classification using different

strategies. Harris and Keeler (1980) performed econometric studies to determine factors that influence railroad profitability, and Keaton (1991) investigated the effects of crew size and train frequency on railroad economics.

A number of authors have addressed the issue of intermodal container operations from a qualitative viewpoint, stressing its importance, current trends affecting the industry, and the need for future research in the area (see, for example, McKenzie et al, 1989, Hochstein, 1988, and Gilman, 1988). Ashar (1991) developed a classification system for terminals based on the type of intermodal transfer they provide and presented a brief cost-benefit analysis for the intermodal container facility serving the Port of Long Beach, CA.

The operations of modern container terminals are described by many authors (see, for example, Atkins, 1983 and Rijsenbrij, 1986). A variety of data on virtually all aspects of containerized cargo is available from national and international government agencies and transportation institutes.

The proposed research addresses the growing importance of intermodal container transport by developing innovative solutions for vessel-to-rail transfer and general analytical methods for assessing the technical and economical feasibility of these solutions.

## 1.4. Research Approach

The analysis of intermodal operations is inherently complex because it involves many parties -- shippers, terminal operators, railroads, road haulers, and consignees -- who often pursue conflicting objectives. Also, there are numerous institutional constraints dictated by government regulations, strong labor unions, and deeply ingrained operating practices.

Attempting to address every detail of the intermodal transportation process would inevitably lead to models of such complexity that their usefulness would be restricted to a handful of cases. To prevent this, the scope of the research is restricted to the planning and design aspects of container

terminals. Detailed operational issues are deliberately avoided, as well as macroscopic factors such as trade patterns and the configuration of the rail networks serving the terminals. It is our hope that the generic nature of the results obtained will yield useful insights into the intermodal transportation process and make them easy to modify, if necessary, to model particular applications more accurately.

The research is organized as follows:

Chapter 2 defines the scope of the system under study and introduces a terminal classification procedure based on the number and type of handling moves required to process an intermodal container through the terminal.

Chapter 3 describes the layout and operation of a terminal that allows for the direct transfer of containers between vessels and trains. The most important feature of the design proposed is that it allows for trains to be loaded taking into account the final destination of each container, largely eliminating the need for train classification at intermediate rail yards. Analytical methods to evaluate the performance of the terminal are developed and validated against a detailed computer simulation.

Chapter 4 presents a simple but comprehensive economic model for measuring the costs of processing containers through each major terminal type. Because of its simplicity, the model can be easily extended and modified, and could thus be used as a framework for more detailed studies. It includes important cost factors that are often neglected in the literature, such as inventory costs incurred when transporting loaded containers. Chapter 4 also presents results obtained by applying the model to each of the major terminal types described in Chapter 2, and identifies scenarios where each terminal type would be most appropriate.

Finally, Chapter 5 summarizes all findings, presents conclusions, and suggests areas that deserve further research.

# 2. Intermodal Operations and Terminal Classification

The ship-to-rail intermodal transfer can be performed in a variety of ways, and a basic understanding of its intricacies is a prerequisite for the analysis that follows in later chapters. To this end, Section 2.1 helps define the scope of this study by describing the nature of intermodal container traffic in the United States. Section 2.2 describes ways in which vessel-to-rail intermodal transfers can be performed at container terminals and introduces a terminal classification system that serves as a basis for the discussion and analysis that follow in subsequent chapters.

## 2.1. Intermodal Traffic in the U. S.

The importance of developing efficient intermodal terminals is directly related to the demand for intermodal services. This demand has been increasing steadily over the last few years, especially since the introduction of double-stack rail cars. As an example of this trend, the table below contains forecasts of intermodal container moves for the ports of Los Angeles and Long Beach until the year 2020 (source: Ashar, 1991).

|  | Weekly Train Departures | | | |
|  | 1986 | 1990 | 2000 | 2020 |
|---|---|---|---|---|
| Long Beach | 17.1 | 17.8 | 36.1 | 77.3 |
| Los Angeles | 16.0 | 19.1 | 34.9 | 69.0 |
| Total | 33.1 | 36.9 | 71.0 | 146.3 |

As the above table shows, intermodal containers moves from the two ports are expected to increase fourfold between now and the year 2020[1]. The predicted increases in volume handled by these two ports is a product of three factors: (i) net increases in international trade volume, (ii) a predicted expansion of the market share for rail over other modes, and (iii) the diversion of traffic from other ports.

The expansion of the rail market share over other modes is in turn a result of several factors. The deregulation of the industry after the 1980 Staggars Act and the 1984 Shipping Act, for example, have allowed shippers to form alliances with railroads and offer more competitive intermodal services.

Also, the growth in vessel capacity that culminated with the introduction of the C-10 post-Panamax vessel class represents a vote of confidence in the U. S. rail system, since such ships cannot use the Panama Canal and must thus rely on intermodal land bridge services to move cargo between the Far East and the Continental U. S..

Finally, the introduction of innovative railcar technologies has made rail transportation more flexible and competitive. Double-stack railcars, for example, have increased the capacity of trains (to up to 560 twenty-foot equivalent units, or TEU) and thus reduced rail transportation costs. Other technologies, such as bi-modal trains, have been used to reduce capital costs and increase the flexibility of short-haul, low-volume (up to 150 to 200 TEU) trains. (Some of these advances in rail technology will be discussed in later chapters.)

The growth in ship and train capacity is also the major factor behind the concentration of container flows through a few strategic ports.

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[1]    This estimate reflect the use of current rail technology. Other authors, proposing improved rail systems, have suggested that intermodal volumes could experience a tenfold increase in the next ten to twenty years (Stevens and Engle, 1991).

Another important characteristic of intermodal container traffic in the U. S. is that it is highly unbalanced, because Far East imports to mid-American destinations have traditionally been far greater than exports. This is illustrated in Figure 2.1, discussed below.
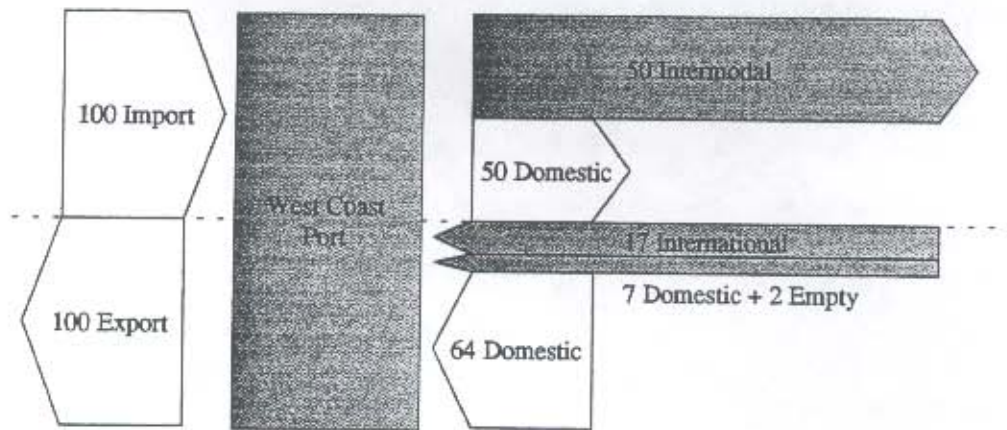


*Figure 2.1: Typical Container Flows for a U. S. West Coast Port*
*(source: Ashar, 1991)*

The rectangle at the center of the figure depicts a typical West Coast port. The white arrows represent vessel and truck container moves, and dark arrows are used for rail moves. The direction of the arrows corresponds to the direction of the container flows. The figure shows that only 17 out of every 50 intermodal containers shipped through West Coast ports return with international cargo.

Because import operations represent the predominant flows at typical West Coast ports, the analysis that follows in subsequent chapters focuses on vessel-to-rail, rather than on rail-to-vessel transfers.

## 2.2. Terminal Classification

The purpose of this subsection is to provide a terminal classification system based on the type of vessel-to-rail intermodal transfer they provide. This classification will serve as a basis for the operation and economic analysis developed in later chapters.

In the literature, terminals are often described as having "on-dock" rail access even if the tracks are located at the periphery of the terminal, away from the actual berths. It is also customary to describe a terminal as having rail facilities even if they are not located within or adjacent to the terminal, as long as the terminal authority owns or operates the rail yard.

In this research, we do not make distinctions based on who owns or operates each part of the terminal system. Intermodal operations are viewed as a unified service provided by a single entity. This type of service is increasingly popular in the U. S., as a result of deregulation and subsequent agreements between major shipping lines and railroads (Smith, 1990).

For our purposes, terminals are classified based on how many handling moves are required to transfer a container between a vessel and a railcar. Based on this criterion, we identify the following three basic terminal types:

- **Indirect-Transfer Terminals: (three or more moves required)**

  Indirect transfer terminals provide no rail access within their facilities. Vessel-to-rail transfers require dock cranes to remove the containers from the ship and terminal trucks (hostlers) or other types of wheeled equipment to take containers to temporary storage areas. Later, trucks retrieve the containers from storage and take them to rail yards located outside the terminal.

  This is currently the most common arrangement in the U. S., including terminals found at the ports of New York, Houston, New Orleans, Long Beach, and Oakland.

- **Semi-Direct Transfer Terminals: (two moves required)**

  These terminals feature tracks at the periphery of their facility but not at the berths, enabling containers to be transferred from ship to rail using a crane move and a single additional move by a piece of handling equipment (such as a straddle-carrier or a side-loader). In these terminals, the drayage operation is absorbed by the terminal, and substantial savings may result from eliminating the road haulage and reducing the time containers spend in storage.

This type of terminal has been gaining popularity in the U. S., where examples can be found at the ports of Seattle, Tacoma, Portland, San Francisco, Norfolk, Savannah, and Baltimore.

- **Direct-Transfer Terminals: (one move required)**

  Direct-transfer operations require rail tracks at the docks, under the dock cranes. It is then possible to unload containers with the crane directly onto railcars below. This type of operation involves the minimum possible handling and is therefore -- potentially at least -- the most economical option for performing the transfer.

  Due to operational difficulties to be discussed later, no North American port has ever maintained direct ship-to-rail transfers of significant volume or duration (McKenzie, 1989).

Figure 2.2 depicts each type of terminal, with arrows depicting each handling move required to perform the transfer. It should be noted that direct-transfer terminals may also be operated as semi-direct or indirect. Likewise, semi-direct transfer terminals may also be operated as indirect.
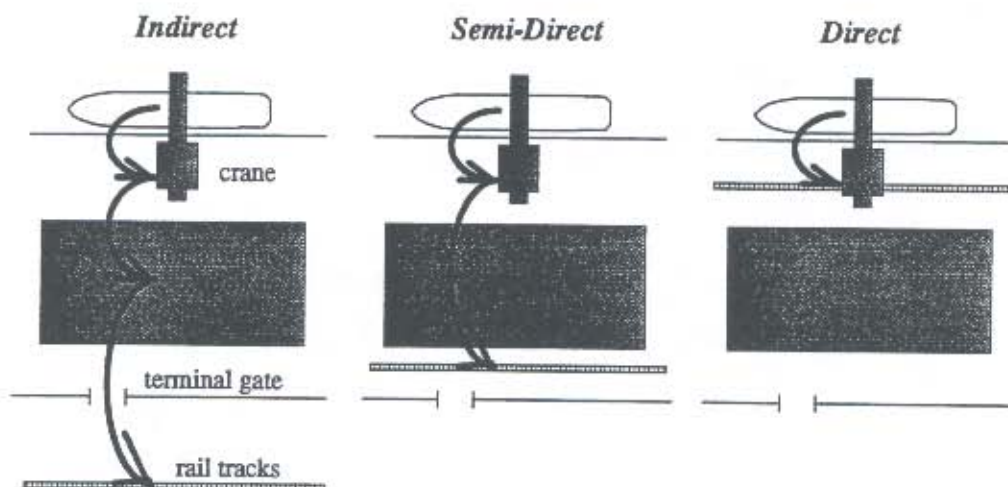


*Figure 2.2: Terminal Classification*

Because there are many indirect and semi-direct terminals currently in operation, their strengths and weaknesses are well known. Direct-transfer terminals, on the other hand, have not been implemented in the U. S., and there is no consensus as to how they should be designed and

operated. The next chapter is devoted to the development of an innovative direct-transfer design and to the analysis of its operations.

## 3. Direct Transfer Terminals

This chapter describes an innovative terminal design that allows for direct transfer operations. It focuses on the dock subsystem and on the train loading process, because these are the aspects where the proposed terminal differs from more conventional designs.

Section 3.1 describes the physical configuration of the terminal and its operation. It also identifies the main performance measures according to which the terminal can be evaluated.

Because there are no direct-transfer terminals in operation today, a computer simulation was developed to verify the analytical methods developed for measuring terminal performance. The simulation program is described in detail in Section 3.2.

Section 3.3 contains the analysis of the terminal. It develops formulas that require little data and can therefore be used by terminal designers to estimate equipment requirements and terminal productivity.

Finally, Section 3.4 presents a qualitative discussion of additional issues that should be addressed in a complete operational analysis of the terminal (as opposed to the design-level analysis presented in Section 3.3).

### 3.1.    Terminal Configuration and Operations

One of the main technical objections to the direct-transfer approach has been the difficulty in coordinating the vessel unloading and train loading plans. This coordination is necessary if trains are to be classified by destination during the loading process.

Typical intermodal trains stop at a number of destinations along their routes. If the train is sorted by destination, as is usually the case, the containers bound for the current stop can be easily separated from the rest of the train with a single cut. This process is efficient and allows the remaining containers to continue their trip with little delay. Unsorted trains, on the other hand,

may require many cuts. The delays incurred while cutting and reforming the train affects all the containers bound for all downstream destinations.

Unfortunately, the order in which containers are unloaded off the ship is to a large extent determined by other factors such as the container's port of origin and vessel balancing constraints. This does not represent a problem for indirect and semi-direct operations, because the equipment used to load the train can easily access any car regardless of its position within the train. In direct-transfer operations, however, the dock cranes themselves are used to load the trains. Using the dock cranes to classify the train is not practical for two reasons. They are mounted on rails and cannot pass each other, so multiple cranes working in parallel to unload the ship would interfere with one another. Also, these cranes are extremely large and can only move at relatively low speeds.[2]

Instead of moving the cranes, the proposed design uses pusher tractors (or similar devices) to move the railcars under the cranes. The motion is synchronized with the operation of the cranes so that, whenever the crane is ready to set a container, the railcar under the crane belongs to a "block" of cars pre-assigned to the destination of the arriving box. Note that, in order to perform the pre-assignment procedure (described in detail in the next section), the pusher operator would need access to the vessel unloading plan. This should not represent a problem given the current state of information exchange technology available.

To load a full intermodal train, empty railcars are grouped into "strings" of manageable size. Breaking up the train into strings is necessary because typical intermodal trains are too long and too heavy for the pusher-based operation to be practical. It also makes it possible to assign each string to a single dock crane thereby avoiding the possibility of cranes trying to unload containers

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[2] Typical Post-Panamax cranes weigh about 750 tons and have gantry speeds of about 3 miles per hour.

onto different parts of a string at the same time. Naturally, in this case, there should be at least one dockside track per crane.

Within each string, containers are sorted by destination. Each string thus consists of a number of "blocks," or sets of contiguous railcars bound for a common destination. Because some destinations might be represented in multiple strings, simply attaching all strings will generally not result in a perfectly sorted train. If the strings are long and contain few blocks, however, the final sorting effort can be substantially reduced if not altogether eliminated. Alternatively, it may be advantageous to perform any additional classification at one or more of the destination stations, eliminating the need for a conventional rail yard on or near the terminal.

The proposed direct transfer terminal features a number of parallel rail tracks alongside the docks. The tracks are straddled by double-hoist dock cranes, which have two independent trolleys and a small (say 2 to 4 slots) internal container buffer.

Double-hoist cranes were originally developed to increase productivity in chassis-based operations.[3] They decouple the waterside cycles, which depend mainly on the time required to pick and set containers and are therefore fairly constant, from the landside work, where the crane is often delayed because chassis are not available or properly positioned. This decoupling is also essential in our design, where containers are placed on railcars instead of chassis. Alternatively, the terminal could deploy rail-mounted gantry cranes (RMG's) operating alongside conventional dock cranes.

Figure 3.1 depicts the proposed layout, with three 100-foot gage cranes straddling six rail tracks.

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[3] Such cranes are in use today at a few terminals, including European Container Terminus' Delta Terminal in Rotterdam, Holland and Virginia Port Authorities' cranes in Norfolk, Virginia.
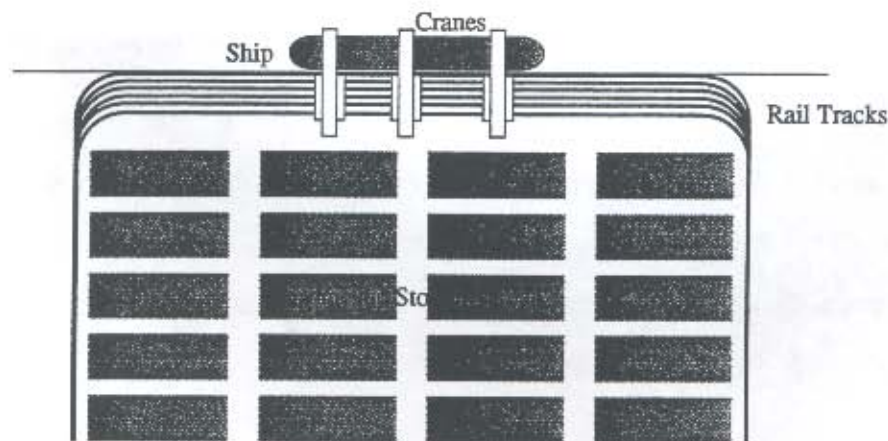
*Figure 3.1: Direct Transfer Terminal Layout (Plan View).*

The ability to load and sort strings of railcars directly is the most innovative feature of the proposed design. To accomplish this, every container is unloaded according to the following steps:

- The dock crane removes a container from the ship and sets it on its internal buffer.

- Meanwhile, the pusher adjusts the position of the string on one of the tracks so that the incoming container is placed adjacent to others going to the same destination. If the current container has the same destination as the previous one, the pusher only has to shift the string by one railcar. Otherwise, longer moves will be needed, possibly as long as the whole string.

- The second spreader of the double-hoist crane or the RMG retrieves the container from the buffer and sets it on the railcar.

- Whenever a string is fully loaded, it is dispatched (either to an on-terminal or to an off-terminal yard) and a fresh string takes its place on the loading tracks.

The importance of using double-hoist cranes or RMG's working in parallel with the dock cranes becomes evident from the description above: they provide an internal buffer between the dock

crane, which unloads containers at an approximately constant pace, and the pushers, whose service time may be highly variable from move to move.

The dock cranes should never have to wait for pushers to position the railcars, because this type of delay would reduce berth throughput and increase ship turn times. To prevent this situation from happening, the internal buffer should be carefully dimensioned and the pushers should have average cycle times significantly shorter than the dock cranes.

Once the basic terminal design has been established, we need to develop methods for evaluating its performance given a set of overall design and operating parameters. Ideally, these methods should be validated by comparing its results with data collected from an actual terminal. This is not possible in the present case, because there are no terminals similar to the one described, so a computer simulation was created for this purpose. The simulation is also useful for testing general operating strategies (such as the assignment of containers to railcars) and for analyzing particular designs in detail. The next section describes the simulation program and the assumptions underlying its operation.

## 3.2.    Simulation Program

The direct transfer simulation program was written in the C language using the MOSAIC simulation library.[4] The program simulates the operation of a single crane unloading a number of containers onto a set of rail tracks. Because the dockside cranes operate independently (as described in the previous section), the results given by the simulation can be used to analyze more realistic situations where multiple cranes work the ship in parallel.

Each simulation run requires the following parameters:

N   The number of containers to be unloaded during the run;

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[4]    The simulation program is listed in Appendix II.

S   The number of railcars on a string;

D   The total number of destinations for the intermodal containers;

K   The number of rail tracks available under the crane; and

P   A parameter used to describe the level to which containers are sorted aboard the ship.

After reading the above parameters from the command line, the simulation program proceeds to create a vessel unloading plan. This is done by creating a list of N containers represented by numbers ranging from 1 to D (the total number of destinations). Before each container is created, a pseudo-random number "r" is generated and compared with P. If r is greater than P, the previous destination is repeated. Otherwise, a new destination (possibly the same) is created at random. Therefore, if P=1, the plan contains only a single destination. If P=0, the plan is perfectly random, that is, every box is equally likely to be bound for any destination regardless of the destination for all other boxes. It is easy to show that, unless P is very close to 1 or D is large compared to N, the expected number of containers created for any destination is a constant,[5] N/D. The implications of this fact are discussed in the following section.

Note that the parameter P is used to capture the randomness across different vessel unloading plans. For any given ship, the entire sequence of containers to be unloaded is fixed and known in advance. A typical terminal, however, receives a number of ships every week, each with a different unloading plan. Rather than pre-defining several "typical" unloading plans and simulating each one, the parameter P is used to describe a family of unloading sequences representative of the vessels calling at the terminal.

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[5]   The algorithm creates batches of containers of the same type. The length of the batches, "b", is a random variable with a geometric distribution and mean $1/(1-q)$, where $q=P+(1-P)/D$. Provided that the number of batches is large compared to D (i.e. $N(1-q) \gg D$), the expected number of containers bound for any destination is simply the product of the number of batches bound for the destination times the length of each batch: $[N(1-q)/D] [1/(1-q)] = N/D$.

After the vessel unloading plan has been created, the simulation assigns each container to its destination track. The simplest way to perform this task would be to adopt a static assignment, D/K destinations to each track. For example, if intermodal containers bound for 6 different destinations were to be unloaded onto 2 tracks, one could simply assign to track 1 all containers bound for destinations 1, 2, and 3; and to track 2 all containers bound for destinations 4, 5, and 6. This type of strategy should work well when the number of containers bound for each destination is approximately constant and when the vessel unloading plan is fairly random. Otherwise, a track might be assigned to one or more "rare" destinations, being underutilized most of the time.

To avoid this type of situation, the simulation program uses a heuristic algorithm to assign destinations to tracks dynamically. To apply the algorithm, the program creates a list of valid destinations for each track. All lists start empty, indicating that no destinations have been assigned to any tracks yet. The vessel unloading plan is then scanned, and for each container the following steps are taken:

- If the current destination appears on any track's valid destination list, then that track will receive the current container.

- Otherwise, the program scans the tracks for the one with the fewest destinations in its destination list and adds the current destination to the corresponding list. The current container will be assigned to that track.

  By choosing the track with the fewest destinations, the procedure tends to keep the number of destinations per track approximately constant. This in turn tends to distribute the workload evenly among the tracks. The strategy would not work well if a track happened to receive several "rare" destinations, but this is unlikely, and could be easily avoided in practice through use of more sophisticated algorithms.

- Whenever a track has been assigned a multiple of S containers, its valid destination list is emptied (because the corresponding string of railcars is dispatched and replaced by a new empty one).

At this point, the simulation program is ready to calculate the total number of homogeneous blocks that will result from the operation, or, equivalently, the number of cuts that will be required to send each container to its destination. This number corresponds to the sum of the sizes of each "destination list" generated by the procedure described above. To make this result independent of N, the simulation reports the expected number of cuts required per container, $E[C]$. $E[C]$ is a number between 0 and 1, where values close to 0 indicate a good sorting level (very few cuts required per car) and 1 indicates poor sorting. Note that we use the expected value of cuts per railcar because two simulation runs with the same parameters would create distinct vessel unloading plans and thus yield different values of C.

There is no clear-cut value for what would be an acceptable $E[C]$. This threshold would depend on many factors including the type of rail yard available to perform the sorting. A rough estimate can be obtained, however, if we consider that many current intermodal double-stack cars are built in groups of five platforms, each capable of carrying 2 forty-foot-equivalent units (FEU's). These five platforms cannot be separated, so the maximum number of cuts per container on fully loaded railcars would be 0.1. This value could be lower if twenty-foot boxes were used, or higher if the railcars were not fully loaded, but it seems to be a useful figure for comparison purposes.

While the calculation of $E[C]$ is sufficient to determine whether the sorting level that can be attained is acceptable, it is also necessary to evaluate the pusher cycle times and crane buffer requirements to establish whether the operation is feasible. For this purpose, the simulation proceeds to analyze the entire operation, move by move. This is done with three main simulated

entities: a waterside spreader (or dock crane), a landside spreader (or train crane), and the railcar positioning mechanism (the pushers). These main components interact in the following manner:

- **Waterside Spreader Entity**

  The waterside spreader scans the vessel unloading plan, reading each instruction one by one.

  For each instruction, it creates a container bound for the appropriate destination, places it in a buffer queue, then undergoes a delay corresponding to its cycle time. This operation is repeated until the vessel unloading plan is exhausted.

  A constant value is used for the crane cycle time, because its variability should be fairly small compared to the variability of the landside cycle times.[6]

  The simulated crane buffer has infinite capacity and the boxes in it are processed according to a first-in, first-out (FIFO) discipline. The implications of this will be discussed in later sections.

- **Landside Spreader Entity**

  When idle, the landside spreader monitors the crane buffer. As soon as a container becomes available, the spreader removes it from the buffer and takes it to the appropriate (pre-assigned) rail track. The time required to move the container to the track depends on how far the track is located relative to the buffer.

  Upon arrival at the track, the spreader communicates with the appropriate pusher to determine whether the string has been properly positioned and is ready to receive the container. If necessary, the spreader waits for the pusher.

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[6] As we mentioned earlier, crane cycles are largely determined by the time the crane spends picking and setting containers. These times are fairly constant compared to the variability in the performance of the landside portion of the system.

The spreader then transfers the box to the railcar, signals the pusher that it may start positioning the next car, returns to its initial position next to the buffer, and resumes monitoring the crane buffer for the next container.

- **Pusher Entities (one per track)**

  Each pusher starts with a string of empty railcars. It scans the vessel unloading plan until it finds the next S containers to be unloaded onto its track and pre-assigns each box to a specific railcar within the current string.

  The pusher uses this information to calculate the time it would take to move the string so that the rail car assigned to the next incoming container is located under the crane, and undergoes a corresponding delay.

  Once the string has been positioned, the pusher communicates with the landside spreader to determine whether the container is ready to be set on the railcar. If necessary, the pusher waits for the arrival of the landside spreader.

  After "meeting" the spreader, the pusher undergoes an additional delay corresponding to the time required to actually set the box on the railcar.

  The pusher continues positioning the string and interfacing with the spreader as long as there are empty railcars in the string.

  When the string becomes full, it is immediately replaced by a fresh one (with S empty railcars), and the whole cycle is repeated from the first step.

These entities act simultaneously, and statistics are gathered throughout program execution. Upon completion of the vessel unloading plan (N moves), the program generates a report

including the number of cuts required per container as well as the average, standard deviation, and extreme values of all equipment cycle times and crane buffer population.[7]

The following sections develop simple formulas for estimating some of these values. To validate the analytical methods, the simulation was used to measure the performance of the terminal under 192 different combinations of the parameters described above.[8] The ranges of parameters used are indicated below:

| | | |
|---|---|---|
| N | Containers unloaded at each run | 5000. |
| S | Number of railcars on a string | from 15 to 35 in increments of 5. |
| D | Total number of destinations for the intermodal containers | 2, 4, 8, and 12. |
| K | Number of rail tracks available under the crane | 2, 4, and 6, provided that $K \leq D$. |
| P | Probability that the next container to be unloaded off the ship belongs to the same batch (and thus has the same destination) as its predecessor | 5%, 25%, 50%, 75%, and 95%. |

Other constants adopted for the simulation are listed below:

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[7] Appendix III contains a typical simulation output file.

[8] Appendix IV lists all the parameter combinations used (data set #1).

| | | |
|---|---|---|
| | Inter-track spacing | 15 ft |
| | Railcar length | 60 ft |
| | Pusher speed | 4 ft/s |
| | Landside spreader speed | 3 ft/s |
| $t_w$ | Cycle time for the waterside crane spreader (assumed constant). | 90 s |
| $t_s$ | Time to set or pick a container on the crane buffer or on a railcar. | 5 s |
| $t_l$ | Time to lift or lower the landside crane spreader. | 15 s |
| $t_k$ | Time to move the landside crane spreader over one rail track. | 5 s (15 ft at 3 ft/s) |
| $t_p$ | Time it takes the pusher to move the train segment by one railcar. | 15 s (60 ft at 4 ft/s) |

Most of these constants were obtained from databases at Liftech Consultants Inc.[9] The actual values are not particularly important, because the main purpose of these runs was to generate a batch of results for comparison with the analytical methods, but some comments are in order:

- The times required to pick or set containers are rather short, reflecting the use of automated positioning mechanisms.

- The railcars assumed are single-stack 60 ft long, which corresponds to the length of a standard intermodal platform. Other types of railcars (including double-stack) could also be used with the proposed scheme; this is discussed in later sections.

- The speed of the pushers is a conservative estimate based on the speed of conventional switch engines. The engines used at the Terminal Island Container Transfer Facility (TICTF) move train segments at over 6.5 ft/s.

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[9] Liftech (Oakland, CA) designs container cranes and provides terminal planning and analysis services.

- Pusher speeds are assumed constant: acceleration and deceleration times are not considered. This simplifying assumption reflects the fact that the nature of the pusher mechanism has not been defined. Pushers could be rubber-tired tractors, similar to conventional switch-engines. They could be also be implemented with cables or chains running under the dockside rail tracks or with friction devices similar to the ones used in roller-coasters. In any case, the effects of acceleration and deceleration are more significant for short distances, where the landside cycles are not determined by the pusher anyway, but by the landside spreader.

## 3.3. Performance Analysis

This section develops analytical methods for evaluating the performance of the proposed rail system, including the expected number of cuts required per railcar, the duration and variability of the landside cycles, and the crane buffer requirements. These methods are used in Chapter 6 to evaluate the performance of the entire terminal.

The analysis is based on the following parameters (similar to the input parameters for the simulation):

D  The total number of destinations for all containers to be unloaded from the ship.

N  The total number of containers to be unloaded.

$N_i$  The number of containers bound for destination i (i = 1, 2,..., D).

K  The number of rail tracks to be used for discharge by each dock crane.

S  The length (in railcars) of each "string," and

P  A parameter that accounts for the level of sorting of the containers on the vessel. Ships may be pre-sorted to a certain level either specifically to improve the unloading process or simply because containers tend to be processed in homogeneous batches. P represents the probability that the next container to be unloaded off the ship belongs to the same batch as

the previous one.[10] It is important to understand that the loading of each ship is deterministic; the parameter P allows us to group many ships with similar loading patterns into a "family" that can be analyzed with a single set of parameters.

### 3.3.1. Train Sorting Level

As was mentioned before, a key factor that has prevented terminals from performing direct-transfer operations is the need to sort containers as they are discharged from the ship. This section develops a simple method for estimating the sorting level attainable with the transfer process described above. For now, we will assume that the landside part of the operation will be able to keep up with the waterside.

Each destination present in a sorted string will require the train to be cut at least once, either at a conventional rail yard or at intermediate destinations. Thus, the sorting level can be measured as the expected number of cuts required per railcar (or, equivalently, as the expected ratio of "blocks" to railcars in a string). Long strings result in fewer cuts per car, but they also require longer tracks, more pusher motion, and possibly larger crane buffers. If the strings are too long, it may be impossible to perform the operation without delaying the crane.

To obtain an expression for $E[C]$, the expected number of cuts per container, let us start by considering a simplified case where a single track is used to unload a completely unsorted ship (i.e., $K=1$ and $P=0$). The analysis will be extended later to deal with more general situations.

### 3.3.1.1. Single Track, Unsorted Ship

The expected number of cuts per container can be calculated as the ratio between the expected number of destinations represented on a typical string of railcars and the number of boxes on a

---

[10] If the next container to be unloaded does not belong to the same batch as its predecessor, there is still a possibility that the next batch will be bound for the same destiantion as the current one. Thus, the probability that a container has the same destination as its predecessor is $P + (1-P) \cdot I/D$.

loaded string. If we define $p_i$ as the probability that no boxes bound for destination i will be present on the string, then the expected number of cuts per container can be expressed as

$$E[C] = \frac{1}{S} \cdot \sum_{i=1}^{D} 1 - p_i.$$

If containers are totally unsorted on the ship, the probability of retrieving a container that is not bound for destination i at any single move is approximately $1-N_i/N$ (assuming sampling with replacement). Because forming a string requires S such moves, the probability that a whole string can be formed without any containers bound for i is a binomial random variable with S trials and probability of success $1-N_i/N$. Thus, $p_i = (1-N_i/N)^S$, and the above expression for the expected number of cuts can be rewritten as

$$E[C] = \frac{1}{S} \cdot \sum_{i=1}^{D} 1 - \left(1 - \frac{N_i}{N}\right)^S.$$

At a design level, we are most interested in an upper bound for E[C]. It is easy to show that the number of destinations present on a string is maximal when all destinations are equally likely to be retrieved next.[11] This is intuitive, because the situation described makes the cargo is as "varied" as possible. That being the case, $p_i$ can be written as $(1-1/D)^S$, and thus

$$E[C] = \frac{D}{S} \cdot \left\{1 - \left(1 - \frac{N_i}{N}\right)^S\right\}. \tag{3.1}$$

If the number of cars per string is large compared to the number of possible destinations, we would expect all destinations to be represented on every string, and the expected number of cuts per car would be simply D/S. Expression (3.1) supports this observation: for $S \gg D$, $E[C] \approx D/S$.

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[11] The above function is convex in $\{N_1, ..., N_D\}$, and Lagrange multipliers can be used to maximize it. The Lagrangian is symmetric with respect to the $N_i$, therefore its saddle point should be symmetric. Thus all $N_i$ should be equal at the maximum.

For example, if containers bound for 8 destinations were to be unloaded onto train segments with 15 cars each, the expected number of cuts per car would be E[C]=0.46. If there were only 4 destinations, E[C] would be reduced to 0.26.

### 3.3.1.2. *Single Track, Sorted Ship*

To obtain a more general expression for E[C] in cases where the ship is not totally sorted (i.e., P>0), let us start by imagining that containers are retrieved from the ship in batches of constant size and that all containers in a batch are bound for the same destination. In this case, to load a string we need a fixed number "b" of batches. The expected number of cuts can then be estimated with an expression similar to (3.1). Instead of loading S independent containers to fill a string, however, we would be loading b independent batches only (each batch has a single destination). Thus $p_i = (1-1/D)^b$, and

$$E[C] = \frac{D}{S} \cdot \left\{ 1 - \left(1 - \frac{1}{D}\right)^b \right\}.$$

The assumption that containers are unloaded in batches of constant size is rather unrealistic, however. To overcome this, we introduce a parameter P that represents the probability that the next container to be unloaded belongs to the same batch as its predecessor. A batch can now be defined as a set of containers bound for a common destination that are unloaded in a sequence before a new random destination is selected.

In this case, the size of each batch is the outcome of a (geometric) random variable. Thus the number of batches per string, "b" is also a random variable, which makes it hard to determine E[C] exactly. An approximate expression for E[C] can still be obtained, however, based on E[b] and Var[b].

To determine E[b] and Var[b], let us consider the process of loading a string of railcars: the first box on the string will naturally be the first bound for its destination on the string. After the first,

S-1 boxes will be unloaded, and each will have a probability 1-P of breaking the current batch.

Thus, (b-1) is a binomial random variable with S-1 trials and probability of success (1-P), so that

$$E[b] = 1 + (S-1) \cdot (1-P), \text{ and} \tag{3.2a}$$

$$\text{Var}[b] = (S-1) \cdot P \cdot (1-P). \tag{3.2b}$$

Provided that the coefficient of variation of b is small and that the functions involved are relatively well-behaved, the following well-known approximation is valid:

$$E[C] = E\left[ \frac{D}{S} \cdot \left\{ 1 - \left(1 - \frac{1}{D}\right)^b \right\} \right] = E[f(b)]$$

$$\approx f(E[b]) + \frac{1}{2} \cdot \text{Var}[b] \cdot \left. \frac{d^2 f(b)}{db^2} \right|_{E[b]}. \tag{3.3}$$

The approximation is based on the first three terms of a Taylor series expansion of C (viewed as a function f(b)) about E[b].[12]

We can now substitute expressions (3.2) into (3.3), yielding

$$E[C] \approx \frac{D}{S} \cdot \left\{ 1 - \left(1 - \frac{1}{D}\right)^{1+(S-1)(1-P)} \right\}$$

$$- \frac{1}{2} \cdot \frac{D}{S} \cdot (S-1) \cdot P \cdot (1-P) \cdot \ln\left(1 - \frac{1}{D}\right)^2 \cdot \left(1 - \frac{1}{D}\right)^{1+(S-1)(1-P)}. \tag{3.4}$$

To illustrate the effect of P on E[C], let us recall the previous example, with S=15 and D=8, but now assuming that the ship is "slightly sorted," with P=0.5. In this case, Expression (3.4) predicts E[C]=0.34. This is a substantial reduction compared to 0.46, the value obtained for P=0.

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[12] For a more detailed discussion of this type of approximation, see for example Benjamin and Cornell (1970).

It is easy to see that it would be conservative to simplify it by eliminating the second term in Expression (3.4), which is always positive and therefore reduces the estimated E[C]. For reasonable values of S and D, the second term tends to be rather small anyway (it tends to 0 as P approaches 0 or 1, or when D is large). For our example, where P=0.5 and therefore its value should be comparatively large, the second term is 0.006.

For our suite of 192 test cases (described in Section 3.2), the maximum relative error incurred by neglecting the second term is about 12%, and the average is less than 3%. Because on most practical cases this error should be fairly small, and always on the conservative side, we will ignore the second term in Expression (3.4) from now on.

### 3.3.1.3.   Multiple Tracks, Unsorted Ship

If the algorithm used to allocate destinations to tracks results in an even distribution of the D destinations among K tracks, then the only difference between the multiple and single-track cases is that now each track will only receive D/K destinations. This is true in the case of the dynamic assignment algorithm used by the simulation (described in Sec. 3.2). It should also be true in any situation where all destinations are equally represented, because in these cases it would not be sensible to load the tracks unevenly.

On the basis of this observation, Expression (3.4) can be easily modified to handle the multiple-track case. The expression still applies to each track, except we must replace all instances of D, the total number of destinations, with D/K, the effective number of destinations that each track will receive. Thus, (neglecting the second term in (3.4)),

$$E[C] \approx \frac{1}{S} \cdot \frac{D}{K} \cdot \left\{ 1 - \left( 1 - \frac{K}{D} \right)^{1+(S-1)\cdot(1-P)} \right\}. \tag{3.5}$$

It is worthwhile to notice that when P is close to 1, Expression (3.5) reduces to E[C]≈1/S. This is not surprising: using extra tracks brings little benefit when unloading from ships that are

already sorted. For smaller values of P, however, the benefits can be significant: recalling our previous example with D=8, S=15, and P=0.5, let us now assume that there are three tracks available for discharge. Expression (3.5) yields E[C]=0.17, indicating that the two additional tracks could reduce the expected number of cuts per box to half the value obtained using a single track (E[C]=0.34).

In cases where the number of destinations per track is two or more, it may be advantageous to express the term $(1 - K/D)^{1+(S-1)\cdot(1-P)}$ as $\exp\{S\cdot(1-P)\cdot\ln(1-K/D)\} \approx \exp\{S\cdot(1-P)\cdot(-K/D)\}$. In this case, Expression (3.5) can be written (in approximate form) as

$$E[C] \approx \frac{D}{S \cdot K} \cdot \left\{1 - \exp\left(-\frac{S \cdot K}{D} \cdot (1-P)\right)\right\}.$$

The above expression is easier to manipulate and evaluate than (3.5), which it approximates quite well. For example, with the parameters D=8, S=15, P=0.5, and K=3, the formula yields E[C]=0.17, the same value obtained above with (3.5). For K=1, the formula gives E[C]=0.32, only slightly smaller than 0.34 obtained with (3.5).

Figure 3.2 shows how E[C] varies with S for cases with D = 8, P = 0.25 and 0.75, and K = 2, 4, and 6.
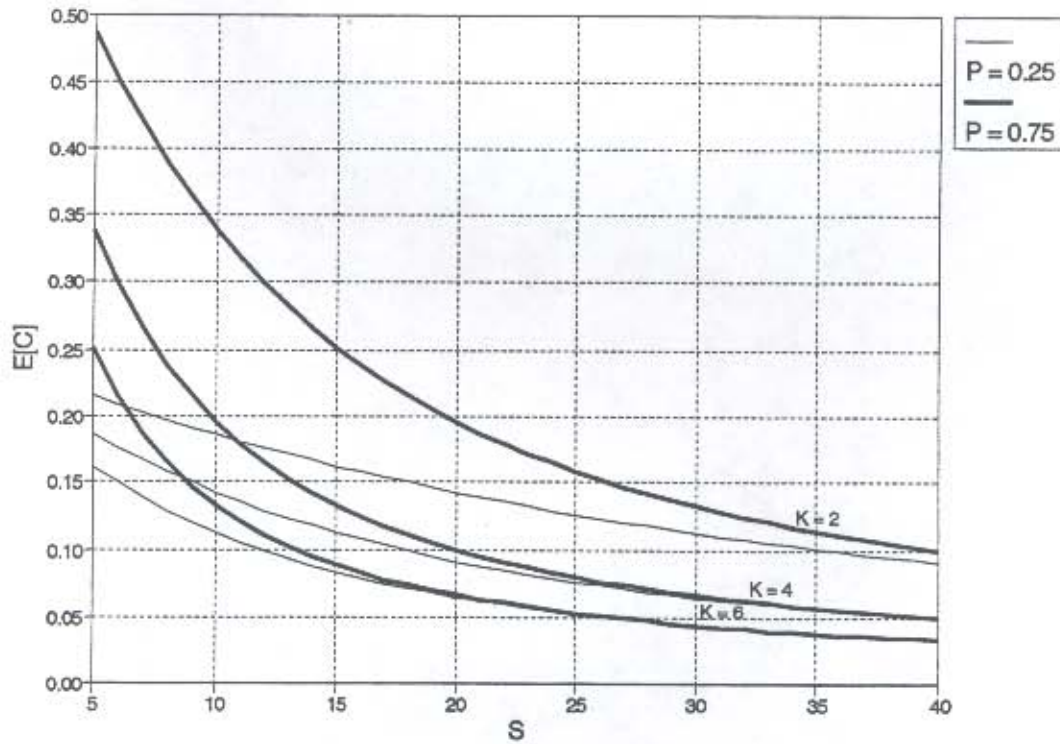
*Figure 3.2: E[C] as a function of S*

To validate Expression (3.5), we compared its results to those predicted by the simulation for the suite of 192 scenarios described in the Section 3.2. The results are illustrated in Figure 3.3.
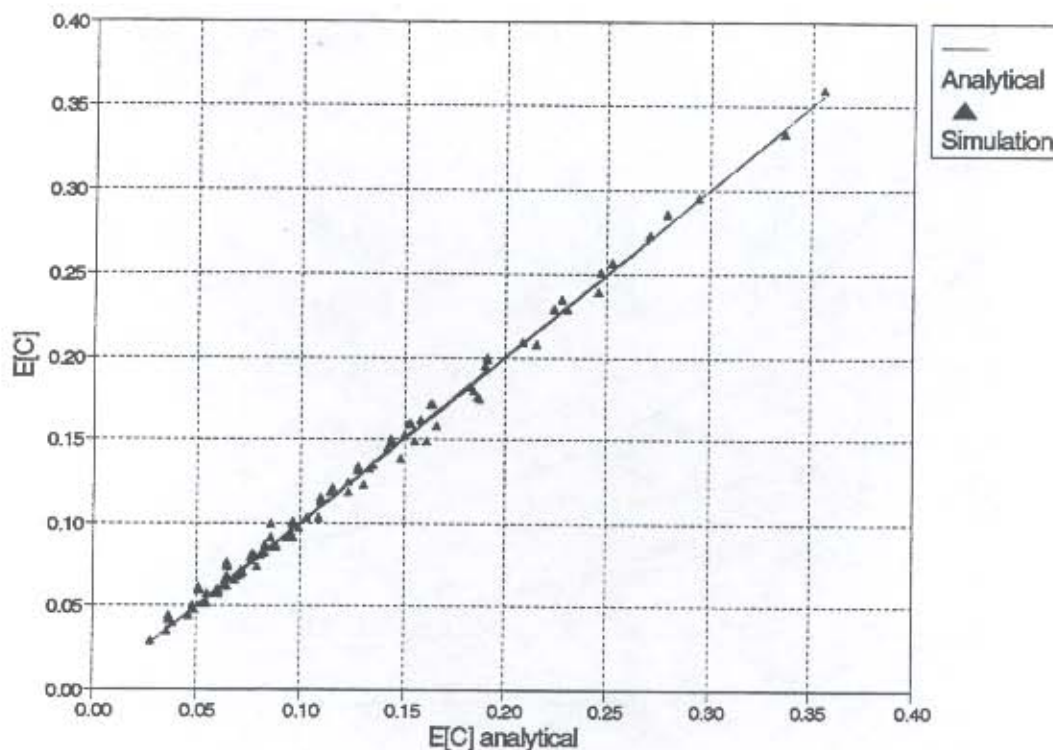
*Figure 3.3: Expected Number of Cuts per Railcar: Simulation vs. Analytical Expression.*

The abscissa of each symbol in the figure corresponds to the E[C] value calculated with Expression (3.5); the ordinate represents the simulation result (thus, symbols below the line with slope 1 reflect instances where the analytical formula over-predicted E[C]). The figure shows that the analytical predictions match the simulation quite well. The average difference between simulated and analytical results is close to 1% (the analytical method is conservative, as was to be expected), and the maximum discrepancy is about 12%.

Note that the expected number of cuts per box, E[C], is independent of the performance of the handling equipment. There are practical limits to the values of S that can be adopted, however. Long strings require more dockside track and more time spent positioning the railcars under the crane, which could cause crane delays and reduce the capacity of the system. The next sections will examine these issues.

### 3.3.2. Cycle Times

The productivity of the direct-transfer system described is a function of three elements: the waterside cycle times, the landside cycle times, and the size of the intermediate buffer between them. If the internal buffer is large enough to allow both waterside and landside systems to operate at their maximum rates, the productivity is determined by the side with the longest average cycle.

As explained in Section 3.1, the waterside cycles times are practically constant, depending only on the performance of the dock crane. The landside cycle times, however, are harder to evaluate, because they depend on the joint performance of the landside crane spreader and the pushers.

This section develops procedures for evaluating the expected value of the landside cycles and their variability. The results obtained will be useful in the evaluation of the overall system productivity and in the analysis of the internal crane buffer.

### 3.3.2.1. Pusher Cycles

To evaluate the landside cycles, we start by analyzing the performance of a single pusher operating on a single track. We assume that containers arrive constantly, and that the pusher never becomes idle. We will also maintain the earlier assumption that all destinations are equally likely so that Expression (3.5), derived in the previous section, still applies.

To account for the possibility that containers arrive in a less-than-random order (P>0), we need to consider two separate cases that may arise whenever the pusher starts a cycle:

a) The next container to arrive has the same destination of its predecessor. The probability of occurrence for this event is $P+(1-P)\cdot 1/D$. In this case, the cycle time for the pusher is a constant corresponding to the time required to move the segment by one railcar plus the time required to set the container on the train ($t_p+t_s$, from the notation introduced in Section 3.2).

b)   The next container is bound for a different destination (this event has probability (1-P)·(1-1/D)). In this case, the cycle time for the pusher will be the time required to move the segment by a random positioning distance plus the time required to set the container on the train.

In order to estimate the cycle times in the second case ("long" cycles), we need to examine the distance pushers must travel to position a railcar under the crane given that the next arriving container is bound for a different destination. The problem is similar to the evaluation of the expected distance between two random points along a line segment. A slight modification is required, however, to account for the fact that the railcar strings are not homogeneous.

As discussed in Section 3.2, every string consists of blocks of railcars, each with a single pre-assigned destination. We assume that every block is loaded at about the same rate, and thus the expected travel distance for the pusher will be an integer multiple of the expected block size. This assumption is reasonable only if P is small. As P grows, however, the likelihood of long cycles becomes low, so the error incurred by making the assumption becomes less significant.

Thus, an approximate expression for the expected duration of a cycle that requires repositioning can be written as

$$E[k] \cdot r \cdot t_p + t_s,  \tag{3.6}$$

where "k" is the number of blocks that must be pushed under the crane in order to position the string and "r" is the average number of railcars in a block.

Now, if we recall that E[C] is the expected number of blocks present on a string divided by a normalizing constant, S, we can use Expression (3.5) to evaluate the expected number of blocks per string, $E[n] = S \cdot E[C]$, and the average number of railcars in a block, $r = E[1/C] \approx 1/E[C]$. For example, if $S = 20$ and $E[C] = 0.1$, an average string would consist of 2 blocks of 10 railcars ($E[n] = 20 \cdot 0.1$ and $r = 1/0.1$).

In the event of a long cycle, every block except the current one is equally likely to receive the next container, and thus E[k] depends only on "n," the number of blocks per string. For any string composed of "n" blocks, E[k] can be calculated as the average distance (measured in blocks) between every pair of blocks in the string. The procedure is depicted in Figure 3.4, explained below.
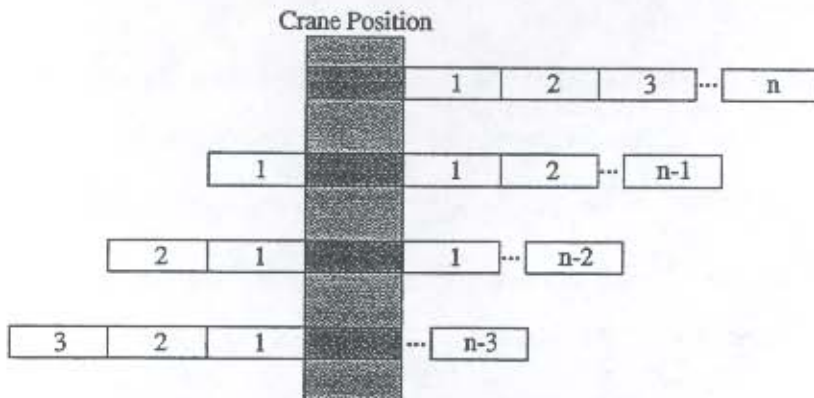


Figure 3.4: A Model for Evaluating Pusher Cycles

Each row in the figure depicts a string, and each rectangle represents a block of railcars. The position of the dock crane is also indicated, and, for each string, the block currently under the crane is grayed. Numbers inside the blocks correspond to the number of blocks that would have to be pushed under the crane if the next container had to be unloaded onto that block.

Because all blocks are equally likely to receive the next container, E[k] can be obtained simply by adding the numbers in the blocks and dividing the total by the number of non-current blocks. Exploiting the symmetry of the problem, we can write

$$E[k] = \frac{2}{n \cdot (n-1)} \cdot \sum_{i=1}^{n-1} i \cdot (n-i).$$

Expanding the summation and simplifying, we obtain

$$E[k] = \frac{n+1}{3}. \tag{3.7a}$$

We can use a similar procedure to evaluate $E[k^2]$, which will be useful later to determine the variance of the cycle times:

$$E[k^2] = \frac{2}{n \cdot (n-1)} \cdot \sum_{i=1}^{n-1} i^2 \cdot (n-i), \text{ which simplifies to}$$

$$E[k^2] = \frac{n \cdot (n+1)}{6}. \tag{3.7b}$$

Note that if the number of blocks per segment is large, the effect of each individual segment becomes small. In this case, expressions (3.7) approach $n/3$ and $n^2/6$, the exact values of $E[k]$ and $E[k^2]$ if k were the distance between two random points located along a line segment.

For small values of "n" such as the ones we are likely to encounter in our analysis, the difference is quite large and should not be ignored.

We can now combine expressions (3.6) and (3.7a) to write an expression for the expected pusher cycle, $E[T_p]$:

$$E[T_p] \approx p \cdot (t_p + t_s) + (1-p) \cdot \left( \frac{S + 1/E[C]}{3} \cdot t_p + t_s \right), \tag{3.8}$$

where p is the probability that the next container will have the same destination as its predecessor (p=P+(1-P)/D, as described before).

The derivation of Expression (3.8) involved a number of assumptions and approximations. To validate it, we compared its results to those predicted by the simulation for the same suite of 192 runs described in Section 3.1. The results are illustrated in Figure 3.3.
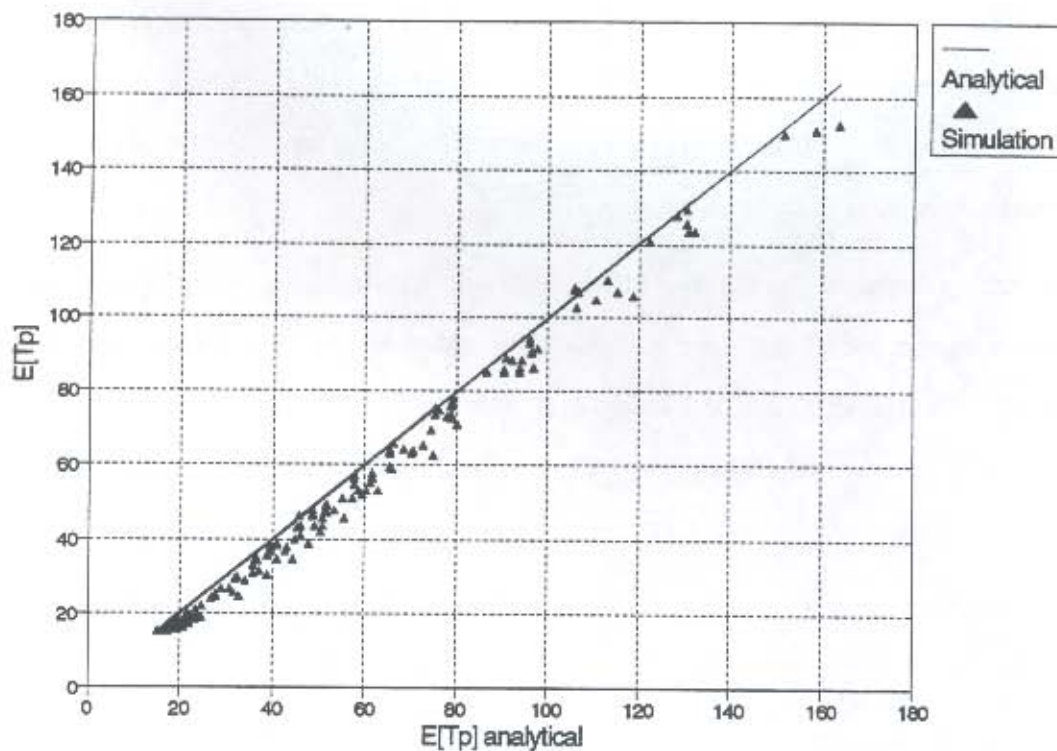
*Figure 3.5: Expected Pusher Cycle: Simulation vs. Analytical Expression.*

The abscissa of each symbol in the figure corresponds to the $E[T_p]$ value calculated with Expression (3.8); the ordinate represents the simulation result. As the figure shows, the analytical method replicates the simulation results fairly accurately. The pusher cycles, however, are only one component of the system's overall landside performance, which also depends on the operation of the landside crane spreader. This is the subject of the next section.

### 3.3.2.2. Landside Cycles and Productivity -- Multiple Tracks

As described earlier, the landside part of the direct-transfer system consists of pushers that position train segments under the dock crane and a landside crane spreader that transfers containers between the internal crane buffer and the rail track. To analyze its overall performance, we must consider how these two components interact.

To keep our analysis relatively simple, we assume that each track has a dedicated pusher. In reality, the number of pushers required to perform the operation could be reduced if they were allowed to serve multiple tracks. The issue of determining the minimum number of pushers needed to keep up with the crane is discussed later.

As containers are unloaded, the crane's landside spreader and the pushers work simultaneously to make containers and railcars "meet" under the crane, and whoever arrives first must wait for the other. The situation is further complicated by the fact that the pushers can start positioning string while the spreader is busy serving another track, but they cannot finish their cycles until the spreader arrives.

For analysis purposes, it is useful to classify pusher cycles into the following categories, according to where the crane will deposit the next box and to its destination:

a) **Same track, same destination**

The next container to arrive has the same destination as its predecessor. In this case, it should go to the same track and the landside spreader cycle (which is virtually constant) will certainly be longer than the pusher cycle, because the string only has to be moved by one railcar length. Thus, the spreader does not have to wait.

b) **Other track, same destination**

The next container to arrive must be placed on a different track but has the same destination as the last container unloaded onto that track. This case is equivalent to the previous one, because the pusher has at least one extra crane cycle to move the string by the length of a single railcar.

c) **Same track, other destination**

The next container must be unloaded onto the same track as its predecessor, but is bound for a different destination. This is the worst-case situation, because the pusher only has one

crane cycle to reposition the string, possibly by many railcars. In this case, the spreader will usually have to wait and the overall land cycle will be determined by the pusher.

**d)    Other track, other destination**

This situation is the most difficult one to analyze. If the destination track has not received any containers in the last few moves, its pusher probably had enough time to position the string, and the cycle will be the same as described for cases "a" and "b". If the track received a box one in one of the last cycles, however, then the crane may still have to wait for the pusher. In any case, the overall land cycle should be shorter than in situation "c", because the pusher had a head start of at least one crane cycle.

Before evaluating the cycles corresponding to each case, we will determine how often they occur. Figure 3.6, explained below, illustrates the possibilities.
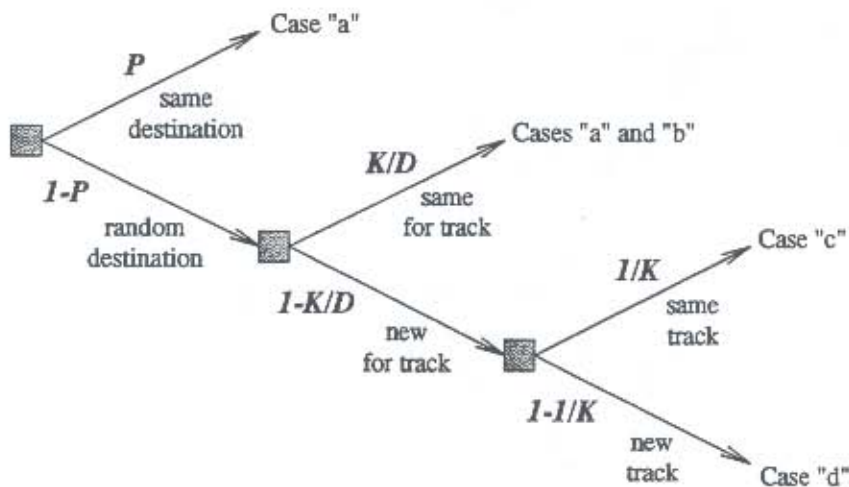


*Figure 3.6: Different Types of Landside Cycle.*

As Figure 3.6 indicates, each arriving box has a probability P of being bound for the same destination as its predecessor (case "a").

Alternatively (with probability 1-P), the container will have a random destination, and two further possibilities arise: the box may have the same destination as the last container unloaded

onto its track, in which case it requires little pusher movement (cases "a" or "b"). This will happen for one out of D/K destinations assigned to each track, so the probability for this situation is K/D.

Finally, if the box is bound for a new destination, it may still need to be unloaded onto the track that was used last (case "c"). This event will occur with probability $1/K$, and the remaining situation (case "d") has therefore a probability $1-1/K$.

Because cases "a" and "b" are equivalent, we can consider only the three cases (and their associated probabilities) listed below:

| Case | Probability | |
|------|-------------|---|
| Short cycles (cases "a" and "b") Any track, same destination. | $P_s = P + (1-P) \cdot (K/D)$ | (3.9a) |
| Long cycles (case "c") Same track, other destination.. | $P_l = (1-P) \cdot (1-K/D)/K$ | (3.9b) |
| Intermediate cycles (case "d") Other track, other destination. | $P_i = (1-P) \cdot (1-K/D) \cdot (1-1/K)$ | (3.9c) |

To evaluate the overall expected landside cycle times, we now need to determine the expected cycle for each of the three cases described on the table above.

The expected duration of a short cycle is determined by the maximum of two values:

- The time it takes the pusher to move the string by the length of one railcar and then receive the container $(t_p+t_s)$, or

- The time it takes the crane to pick a container from the buffer, travel to the destination track, set the container on the railcar, and travel back to the buffer.

In practice, the crane time will normally be the longer one. If the pushers were so slow that they required more than a crane cycle to move the string even by one railcar, it is unlikely that the operation would be feasible.

Given the equipment performance values adopted in the simulation (see Sec. 3.2), for example, the pushers would take 20 seconds to move the string by the length of one railcar (15 seconds to move the segment plus 5 seconds to receive the container). The minimum crane time would be 40 seconds (5 to pick the box from the buffer, 15 to lower the box, 5 to set it on the railcar, and another 15 to return to the buffer). The expected crane time will be greater than this if the number of tracks is large, because then some tracks will require it to travel longer in the horizontal direction. In general, assuming that the landside cycle will be determined by the crane, we can write

$$E[T_s] = 2 \cdot t_s + \frac{2}{K} \cdot \sum_{i=1}^{K} \max\{t_l, i \cdot t_k\}, \qquad (3.10)$$

where $E[T_s]$ is the expected value of the short landside cycles, $t_s$ is the time the crane takes to pick a box from the buffer or set it on a railcar, K is the number of tracks, $t_l$ is the minimum time it takes the spreader to reach a track (corresponding to its vertical movement), and $t_k$ is the time to move the spreader laterally over one rail track.

The table below lists values of $E[T_s]$ (in seconds) based on the constants used in the simulation, for K ranging from 1 to 6:

| K | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $E[T_s]$ | 40 | 40 | 40 | 43 | 46 | 50 |

Given our constants, a good approximation for E[Ts] is max{40,30+3·K}. In general, it should be trivial to obtain similar formulas based on specific equipment performance values and track configurations.

Long cycles occur when a track receives two containers bound for different destinations in a sequence. In this situation, pushers have to shift the train segment by at least one block, and the time required to accomplish this task will usually determine the duration of the landside cycle.[13]

Consequently, the expected duration of a long cycle can be determined with the same procedure used in the previous section to evaluate the pusher cycles (see Expressions (3.6) and (3.8)). We can write an approximate formula for the value of a long landside cycle, $T_l$, as

$$T_l = k \cdot r \cdot t_p + t_s.$$

Taking expectations and substituting (3.7a) into the above expression, we derive the formula for the expected duration of a long landside cycle:

$$E[T_l] = E[k] \cdot r \cdot t_p + t_s = \frac{S + 1/E[C]}{3} \cdot t_p + t_s. \tag{3.11}$$

Finally, we must examine the "intermediate" cycles (case "d"), where arriving containers require repositioning of a train segment that did not receive a box in the last crane cycle. As was mentioned earlier, this is by far the most difficult case to analyze.

Intermediate cycles will always be shorter than the "long" ones, because the pushers have at least one extra crane cycle to work with before the container arrives. Their actual duration, however, depends on "how long ago" a container arrived at the current track. If the number of intervening crane cycles is large, then the situation becomes identical to a short cycle. If this number is

---

[13] The time needed to push the string for the length of one block is given by $E[r] \cdot t_p + t_s$. This value would only approach $E[T_s]$ if $E[r] \leq (E[T_s] - t_s)/t_p$. For the constants we have been using, this would imply average blocks with about 3 railcars only, a very unlikely situation.

small, and the intervening cycles are short, then the overall cycle will probably be determined by the performance of the pusher instead.

Because of the above considerations, developing an analytical model for this particular cycle type would be very difficult. By examining the output from the simulation, however, we observe that in most cases where these cycles have a significant probability of occurrence (about 15% or more), there is a strong linear relationship between $T_i$ and $T_l$, the duration of the "intermediate" and "long" cycles, so that $T_i \approx 0.4\ T_l$. This empirical approximation seemed to be reasonably independent of the particular constants used in the simulation (e.g., $t_s$, $t_p$).

The results obtained above can now be combined into an expression to predict the expected duration of the overall landside cycles (or, equivalently, the peak attainable service rate of the landside component of the system):

$$
\begin{aligned}
E[T] &= P_s \cdot E[T_s] + P_i \cdot E[T_i] + P_l \cdot E[T_l] \\
&\approx P_s \cdot E[T_s] + (P_l + 0.4 \cdot P_i) \cdot E[T_l].
\end{aligned}
\tag{3.12}
$$

Expression (3.12) can be used to predict the expected duration of the overall landside cycles and its productivity. To evaluate (3.12), we must use almost every formula derived in this section so far. The following example shows the steps involved.

*Example:*

Let us consider a case where intermodal containers bound for 8 destinations are partially sorted on the ship (P=0.5) and must be unloaded onto 2 tracks using segments with 20 railcars each. The equipment performance constants adopted are those used in the simulation and listed in Section 3.2.

The first step is to determine the expected number of cuts per railcar. This can be done using Expression (3.5):

$$E[C] \approx \frac{1}{20} \cdot \frac{8}{2} \cdot \left\{ 1 - \left( 1 - \frac{2}{8} \right)^{1+(20-1)(1-0.5)} \right\} = 0.18.$$

This result matches the simulation almost perfectly. An average segment will, therefore, contain about $20 \cdot 0.18 = 3.6$ blocks with $1/0.18 = 5.56$ railcars each.

Next, we use Expressions (3.9) to determine the probabilities of each type of cycle:

$$P_s = 0.5 + (1-0.5)\,(2/8) = 0.62,$$
$$P_l = (1-0.5)\,(1-2/8)\,/\,2 = 0.19, \text{ and}$$
$$P_i = 1 - 0.62 - 0.19 = 0.19.$$

These results show that most cycles will be short. The expected value of a short cycle is determined using Expression (3.10). For the values used in our example,

$$E[T_s] = 40 \text{ seconds.}$$

Finally, we need to evaluate the expected value of a long cycle. This is done using Expression (3.11):

$$E[T_l] = \frac{20 + 1/0.18}{3} \cdot 15 + 5 = 132 \text{ seconds.}$$

Finally, these results can be combined using Expression (3.12) to obtain the expected overall landside cycle times:

$$E[T] = 0.63 \cdot 40 + (0.19 + 0.4 \cdot 0.19) \cdot 132 = 60 \text{ seconds.}$$

Again, this result matches the simulation quite well (60 vs. 57 seconds). In principle, the landside portion of the system could handle 60 containers per hour, a rate that compares favorably against common dockside crane productivities (usually between 30 and 45 boxes/hour).

The procedure described above was repeated to compare the analytical results to those predicted by the simulation for the same batch of runs described before. For all test cases, the analytical method replicates the simulation results very accurately, as illustrated in Figure 3.7.
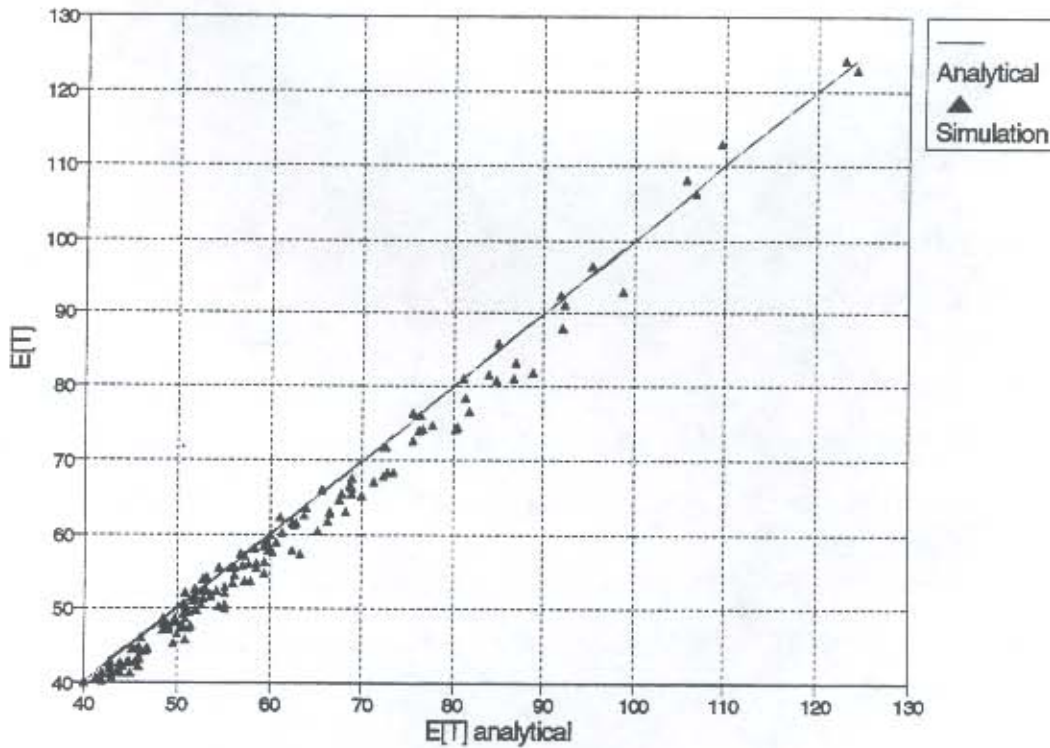
*Figure 3.7: Expected Landside Cycle: Simulation vs. Analytical Expression.*

The abscissa of each symbol in the figure corresponds to the E[T] value calculated with Expression (3.12); the ordinate represents the simulation result. If the internal crane buffer had infinite capacity, the methods developed so far would be sufficient for estimating the proposed system's throughput. Whenever a long landside cycle occurred, the waterside spreader could continue unloading containers onto the buffer, and the landside would eventually catch up. The system's average throughput would therefore be determined by the component with the longest average cycle only, and could be estimated as $1/\max\{t_w, E[T]\}$.

With a limited buffer, however, the waterside and landside systems would not always be able to operate independently. Whenever the buffer filled up, the waterside spreader would have to stop unloading boxes until the landside caught up, and the system's overall throughput would decrease.

The next section develops methods for dimensioning the buffer and quantifying its effect on overall system throughput.

### 3.3.3. Buffer Requirements and Dock Throughput

The main objective of this section is to determine the relationship between the size of the internal crane buffer and the overall productivity of the system.

The main function of the internal crane buffer in the proposed design is to absorb fluctuations in the landside cycles times, effectively decoupling the waterside operation from the landside. The effectiveness of this decoupling depends mainly on three factors:

B   The size of the buffer. As was mentioned before, an infinite buffer would result in perfect independence between the land and waterside subsystems. Smaller buffers would naturally be less effective.

$\rho$   The ratio between the expected landside and waterside cycles ($E[T]/t_w$). If the landside operations were much faster than the waterside ($\rho \approx 0$), the crane would never have to wait for the pushers. Conversely, if the waterside were much faster ($\rho \gg 1$), the pushers would never have to wait for the crane. Either way, the overall productivity of the system would be determined by its slower component, and the buffer would not bring much benefit. The buffer becomes essential when the expected cycles have similar duration ($\rho \approx 1$). Without a buffer, both sides would often have to wait for each other, and the overall productivity of the system would be lower than that of either one.

$\gamma$   The coefficient of variation of the landside cycles (defined as the ratio between their standard deviation and expected value). Naturally, the more variable the landside cycles are, the more important the buffer becomes.

### 3.3.3.1. The Variance of the Landside Cycle Times

We have already developed a formula (3.12) for the expected duration of the landside cycles E[T], which can be used to determine the value of ρ. The same approach can be used to estimate their variance, necessary to calculate γ. Analogously to (3.12), we can write

$$E[T^2] = P_s \cdot E[T_s^2] + P_i \cdot E[T_i^2] + P_l \cdot E[T_l^2].$$

For simplicity, we assume that the short cycles ($T_s$) are constant. We also assume that our earlier approximation for the intermediate cycles, $T_i \approx 0.4\,T_l$, still holds. Thus

$$E[T^2] \approx P_s \cdot T_s^2 + (P_l + 0.4^2 \cdot P_i) \cdot E[T_l^2].$$

Recalling from Section 3.3.3, that $T_l = k \cdot r \cdot t_p + t_s$, $E[k^2] = n \cdot (n+1)/6$, $E[n] = S \cdot E[C]$, and $r = 1/E[C]$, we can write

$$E[T^2] \approx P_s \cdot T_s^2 + (P_l + 0.4^2 \cdot P_i) \cdot \left( t_s^2 + \frac{2 \cdot t_s \cdot t_l}{E[C]} + \frac{t_l^2 \cdot S \cdot (S+1/E[C])}{6} \right). \tag{3.13}$$

Note that the above expression is only an approximation. It assumes that the variability of the cycle times is due only to the existence of different types of cycles and to the fact that varying numbers of blocks will need to be pushed under the crane during the long cycles. Short cycles are assumed to be constant and the variability of the block sizes is neglected. The formula also relies on the previous approximation $T_i = 0.4 \cdot T_l$.

Expression (3.13) can be used with (3.12) to estimate the coefficient of variation of the landside cycle times:

$$\gamma = \sqrt{\frac{E[T^2]}{E[T]^2} - 1}. \tag{3.14}$$

As before, we compared the analytical results to those obtained from the simulation. The comparison, depicted in Figure 3.8, reveals that the formula is fairly accurate. (Its precision

could be slightly increased by removing our earlier assumption of constant $T_s$, but the resulting formula would be rather cumbersome.)
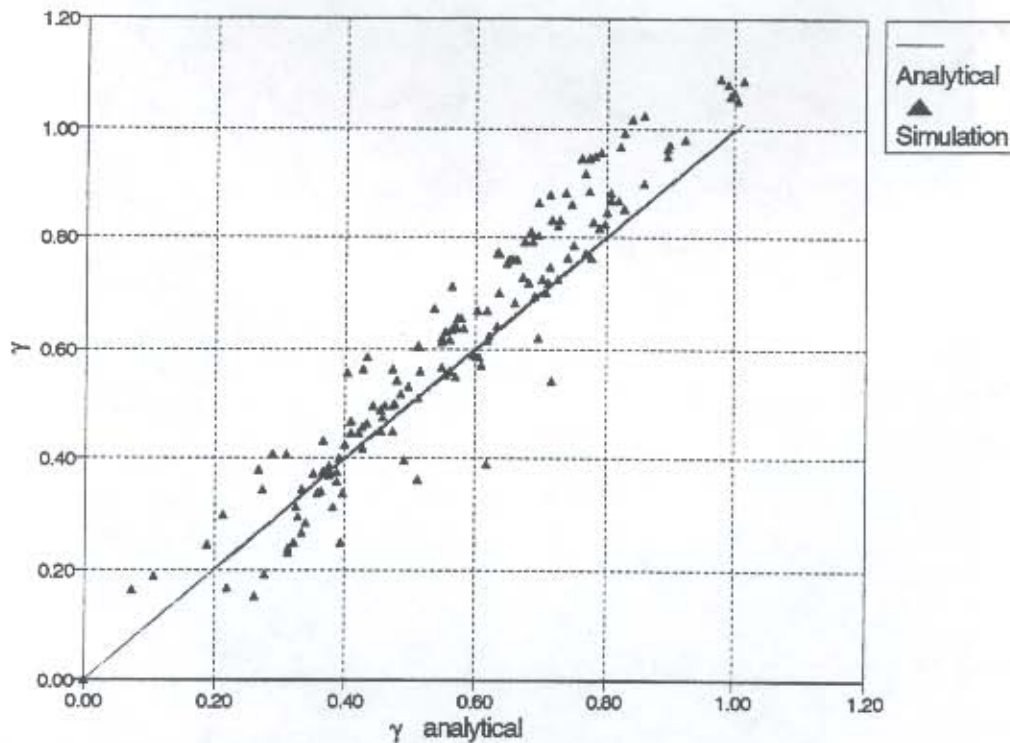


*Figure 3.8: Landside Cycle's Coefficient of Variation: Simulation vs. Analytical Expression.*

### 3.3.3.2. The Effect of B, ρ, and γ on Dock Throughput

The operation of the landside system described is actually fairly complicated. It has K+1 servers -- one pusher per track plus the landside spreader -- operating sometimes in series (e.g., the spreader sets a box on a railcar, then a pusher starts moving the string) and sometimes in parallel (e.g., two pushers positioning separate strings).

By describing the landside operation in terms of B, $\rho$, and $\gamma$ only, we reduce this complexity (at the expense of some accuracy) and the problem becomes similar to a standard D/G/1/c[14] queueing model.

Unfortunately, most of the queueing literature addresses issues related to the distribution of queue lengths and server utilization. These factors are not particularly relevant in our problem. We are not concerned, for example, about whether the crane buffer will contain 3 or 4 boxes for a fraction of the time. Rather, we wish to determine how much throughput will be lost due to the limited capacity of the buffer.

Newell (1982), presents a set of very powerful methods for analyzing the properties of equilibrium and time-dependent queues. The methods are approximations based on diffusion equations, which ignore the discrete nature of the queue lengths.

Of particular interest to us is the following expression for the equilibrium rate at which customers flow through a system with a queue of limited capacity[15]:

$$\frac{d\,E[D(t)]}{dt} = \lambda - \frac{(\mu - \lambda) \cdot \exp(-2 \cdot c / L_o)}{1 - \exp(-2 \cdot c / L_o)}, \text{ where} \qquad (3.15)$$

$$L_o = \frac{\gamma_D^2 + \rho \cdot \gamma_A^2}{1 - \rho}.$$

$\mu$ is the service rate, $\lambda$ is the customer arrival rate, c is the queue capacity, and $\gamma_A$ and $\gamma_D$ are the coefficients of variation of the inter-arrival and service times, respectively.

When the queue has infinite capacity (c = +∞), the formula reduces to the smaller of $\lambda$ and $\mu$ ($\lambda$ when $\rho < 1$ and $\mu$ when $\rho > 1$). In other words, the system throughput will match the arrival rate

---

[14] The notation stands for deterministic arrivals, general independent service times, a single server, and a limited queue capacity.

[15] The first term in the formula in the 1982 edition of Newell's book contains a typographical error: the first term should be $\lambda$, not $\mu$.

when the service times are short, or the service rate when customers arrive faster than they can be processed.

When c is small, however, the throughput decreases. When $\rho<1$, the decrease is due to the fact that some customers are turned away when the queue is full -- or, in our case, that the crane must stop unloading containers because the buffer is full. Conversely, when $\rho>1$, the decrease occurs because the buffer sometimes becomes empty and the server (the landside spreader) goes idle.

For convenience, it is useful to express the system's throughput as a fraction $\phi$ of the maximum possible throughput, $1/\max\{t_w, E[T]\}$ (which could be achieved with an infinite buffer).

To derive an expression for $\phi$ as a function of B, $\rho$, and $\gamma$, we divide expression (3.15) by the maximum system throughput ($\lambda$ when $\rho<1$ and $\mu$ when $\rho>1$). We also set $\gamma_A = 0$, because the crane cycles are assumed to be deterministic, and $\gamma_D = \gamma$, which can be calculated with (3.14). After some simple manipulations, we find

$$\phi = \begin{cases} \dfrac{\rho-\alpha}{\rho\cdot(1-\alpha)} & \text{for } \rho<1 \\[4mm] \dfrac{\rho-\alpha}{1-\alpha} & \text{for } \rho>1 \end{cases}, \tag{3.16}$$

$$\text{where } \alpha = \exp\left(-2\cdot B \cdot \frac{1-\rho}{\gamma^2}\right).$$

Figure 3.9 depicts the relative throughput $\phi$ as a function of $\rho$ for systems with different buffer sizes and landside cycle variability.
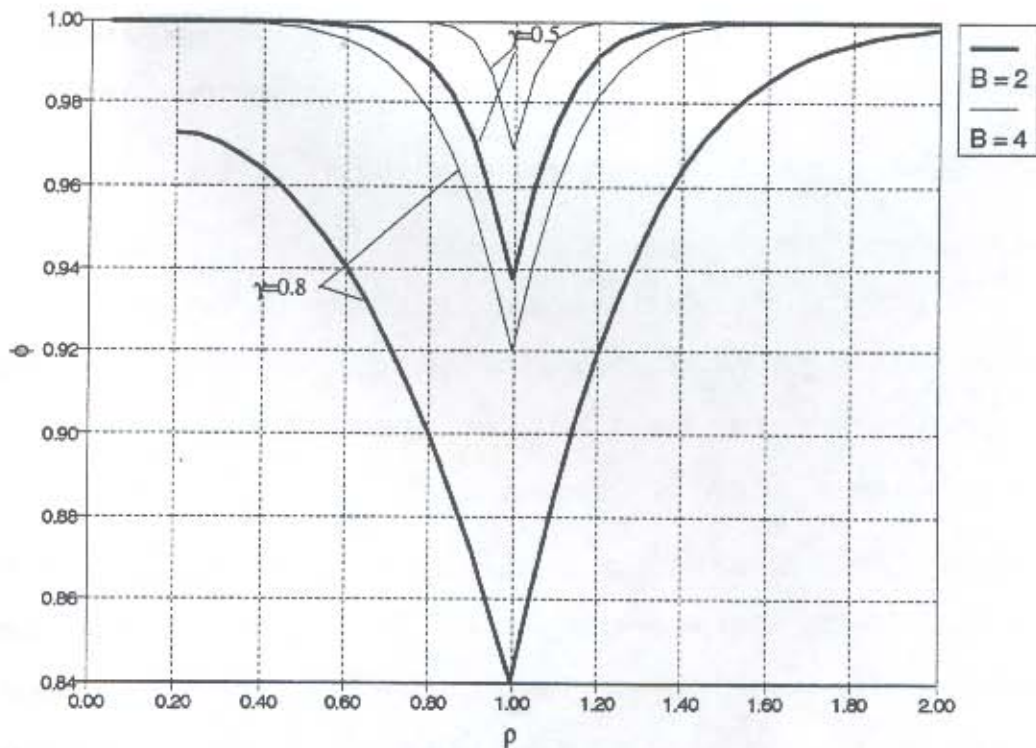
*Figure 3.9: Relative dock throughput as a function of* $\rho$ .

The figure shows that $\phi$ increases with B and decreases when $\gamma$ is large and when $\rho$ is close to 1. This was to be expected, as explained in the beginning of this section. Recall, however, that expression (3.16) are based on diffusion equations that neglect the discrete nature of the queue lengths. If the buffer is relatively small (say 2 to 4 slots), therefore, the above expression may not be very accurate. In the next subsection, we use the simulation to verify and calibrate expression (3.16).

### 3.3.3.2.  Simulation Results

As we discussed before, the effect of the buffer size is most important for values of $\rho$ close to one. To increase the number of simulation runs with $\rho$ near one, a new batch of 150 parameter sets was developed with shorter waterside cycles ($t_w$ = 60 seconds) and longer strings (up to 40

railcars each).[16] Each set of parameters was used in 15 separate simulation runs for each buffer size, and the maximum, minimum, and average throughputs were recorded for each set.

Figures 3.10a, b, and c depict the results obtained with a buffer of size 2, 4 and 6, respectively.

Each vertical bar in the graphs corresponds to a set of 15 runs. The "x" coordinate of the bar is the value of $\rho$. The "y" coordinates of the top and bottom of the bar correspond to the maximum and minimum values of $\phi$ obtained for the set. The "y" coordinate of the numbers near the center of each bar corresponds to the average $\phi$. The numbers themselves indicate the value of $\gamma$ for each set of parameters, multiplied by 10 to reduce clutter.

For example, the bar highlighted in Figure 3.10a corresponds to a set of 15 simulation runs. For all 15 runs, $\rho=1.48$ (the "x" coordinate of the bar) and $\gamma=0.9$ (a tenth of the value near the center of the bar). The maximum and minimum values of $\phi$ are 0.97 and 0.88 (the "y" coordinates of the top an bottom of the bar), and the average $\phi$ is 0.92 (the "y" coordinate of the number 10 near the center of the bar).

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[16] This new batch of parameters is also listed in Appendix IV (data set #2).
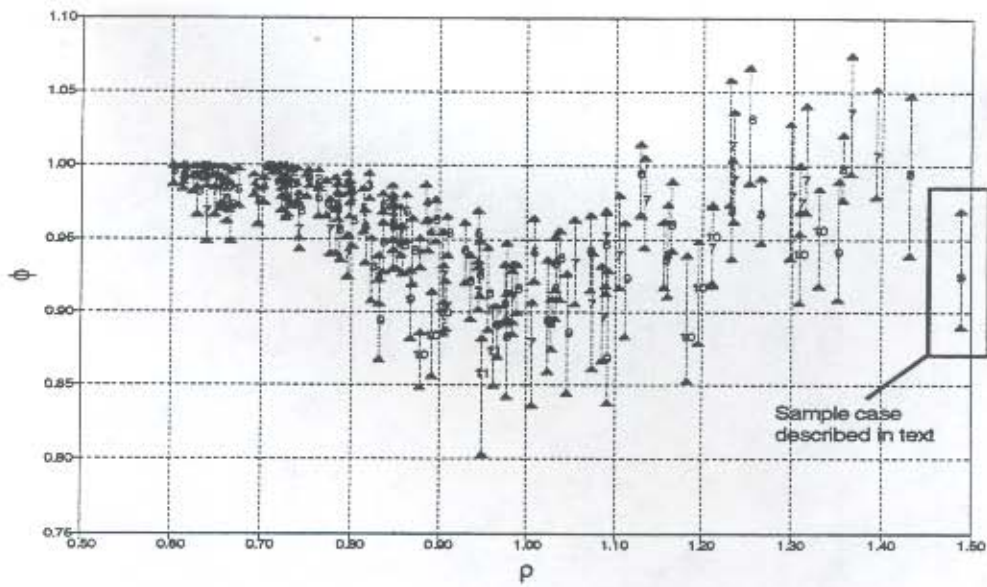
*Figure 3.10a: Relative dock throughput versus ρ   for B=2.*
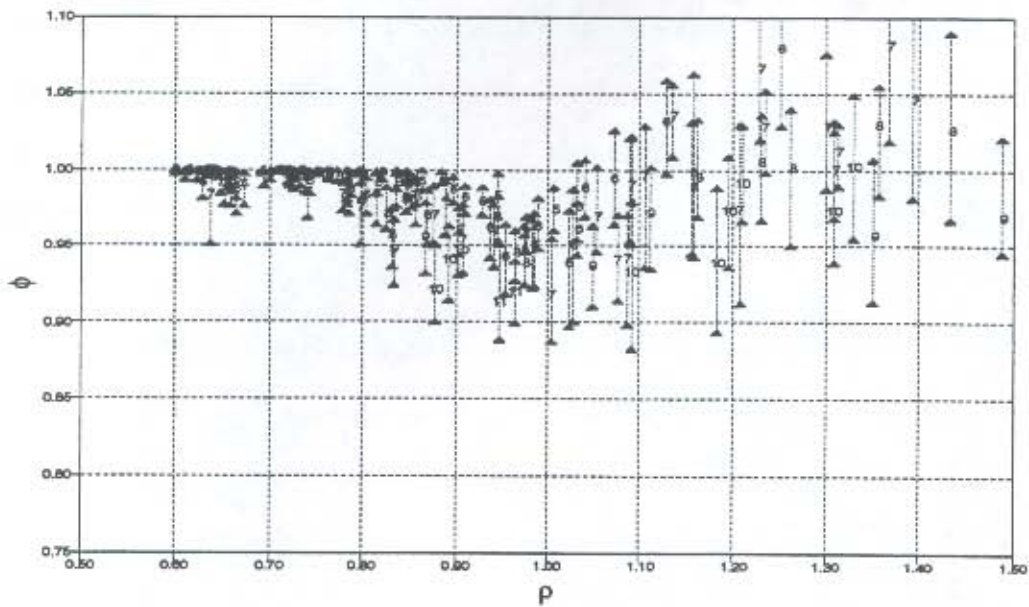


*Figure 3.10b: Relative dock throughput versus ρ   for B=4.*
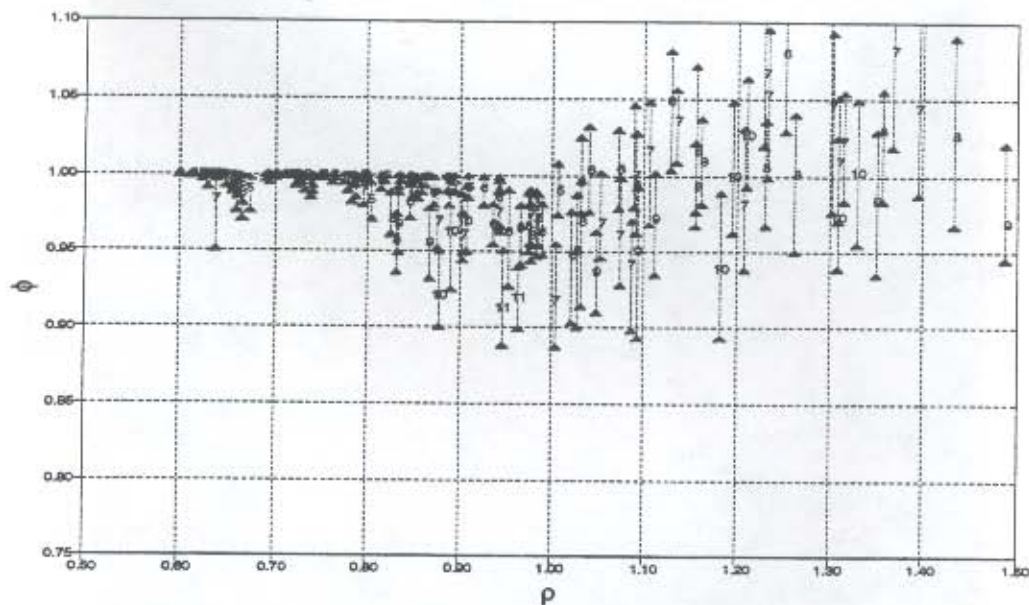
*Figure 3.10c: Relative dock throughput versus ρ for B=6.*

Figures 10a, b, and c exhibit shapes similar to those in Figure 9, obtained with the analytical formulas. Small values of ρ indicate that the landside operates much faster than the waterside. Because containers are quickly removed from the buffer as they arrive, the waterside spreader never has to wait and thus the dock throughput is very close to the maximum, $1/t_w$, regardless of buffer size. The ϕ values fall in a narrow interval because the system throughput is determined by $t_w$, which is constant.

As ρ increases towards 1, the difference between the waterside and landside cycles becomes small. Fluctuations in the landside cycle often make them longer than $t_w$, and unless the waterside spreader can continue unloading containers into the buffer, it will have to slow down. The smaller the buffer, the more sensitive the system will be to the increase in ρ (compare Figs. 3.8a and b).

High variability in the landside cycles also makes the system more sensitive to ρ, because landside cycles longer than $t_w$ become more frequent. The figures confirm this observation: bars with low γ values are closer to the maximum throughput line (ϕ=1).

The relative dock throughput $\phi$ reaches a minimum when $\rho$ equals 1. In this case, the waterside and landside cycles are equal, and thus each subsystem must often wait for the other (unless the buffer between them is very large), and the overall system throughput becomes significantly smaller than that of either subsystem.

When $\rho$ is much larger than 1, the landside cycles are significantly longer than the waterside cycles and therefore determine the productivity of the system. In these cases, the landside rarely has to wait for the waterside, regardless of how many containers can be stored in the buffer, so the B has little effect on $\phi$. The dock throughput again approaches its maximum possible value, now $1/E[T]$, but the values of $\phi$ are more scattered than when $\rho$ was small. This happens because now the system throughput is determined by the landside cycles, which are random.

Note that cases where $\rho \gg 1$ would probably be avoided in practice, because in such situations vessels and dock cranes would spend a significant amount of time waiting for the pushers. To avoid this, the terminal planner could reduce $\rho$ by deploying faster pushers, more tracks, or shorter strings of railcars.

A quick inspection of Figs. 3.8 shows that a two-slot internal crane buffer should be enough to maintain more than 95% of the system's peak throughput for values of $\rho$ up to about 0.75. A four-slot buffer could be used to operate at the same level with $\rho$ up to 0.85.

Comparing the simulation results to the ones yielded by Expression (3.16) reveals that the formula is quite accurate for B = 4 and 6, but tends to underestimate $\phi$ when B = 2. This was to be expected and is due to the nature of the diffusion equations, discussed earlier. In the next subsection, the simulation results are used to calibrate (3.16).

### 3.3.3.3.  Calibration of the Analytical Model

Since the accuracy of Expression (3.16) is related to the buffer size B, a new parameter $\beta$ was added to the $\alpha$ coefficient in (3.16). The new coefficient has the following form:

$$\alpha' = \exp\left(-2 \cdot B \cdot \beta \cdot \frac{1-\rho}{\gamma^2}\right).$$

A commercial numerical optimization procedure was used to determine the value of the new parameter $\beta$.[17] The criterion used was to minimize the sum of squared differences between $\phi$ values obtained with the simulation and calculated with the formula.

Based on the 450 sets of simulation results (depicted in Figs 3.10), the optimization procedure yielded $\beta = 1.32$. The calibrated model for $\phi$ can thus be written as:

$$\phi = \begin{cases} \dfrac{\rho - \alpha'}{\rho \cdot (1-\alpha')} & \text{for } \rho < 1 \\[3mm] \dfrac{\rho - \alpha'}{1 - \alpha'} & \text{for } \rho > 1 \end{cases}, \tag{3.17}$$

where $\alpha' = \exp\left(-2.64 \cdot B \cdot \frac{1-\rho}{\gamma^2}\right).$

Again, we compared the analytical results to those obtained from the simulation. The comparison is depicted in Figure 3.11.

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[17] The procedure used was the quasi-Newton gradient search in the Quattro Pro 4.0 spreadsheet.
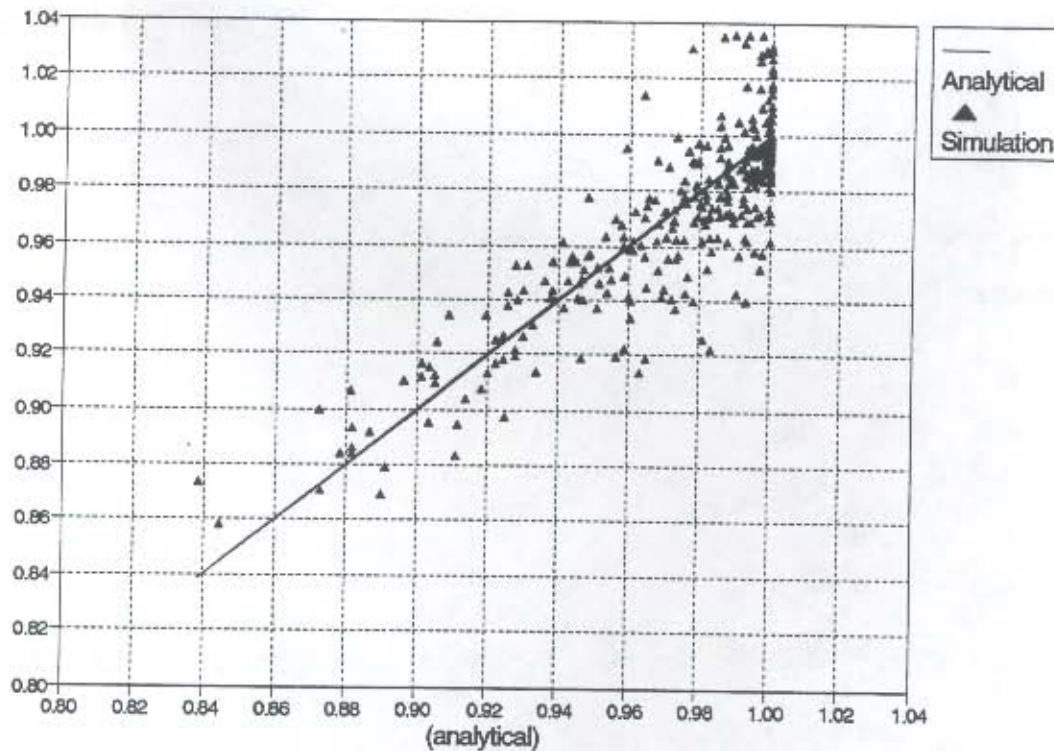
*Figure 3.11: Relative dock throughput: Simulation versus Analytical Expression.*

The abscissa of each symbol in the figure corresponds to the $\phi$ value calculated with Expression (3.17); the ordinate represents the simulation result. The figure shows that the expression is yields reasonably good results. A significant portion of the discrepancies depicted are caused by the fluctuations in the value of $\phi$ when $\rho > 1$ (see Figs. 11). Some discrepancies also result from the approximations made in the derivation of the formula for the variance of the landside cycles (3.13).

Expression (3.17) can be used to aid in the process of dimensioning the internal crane buffer. Given a set of operating parameters, one would use Expressions (3.12) through (3.14) to estimate $\rho$ and $\gamma$, and then (3.17) to determine a buffer size that would result in an acceptable throughput. If the buffer size determined using this procedure were found to be too large (for structural

reasons, for example), the terminal designer could reduce the buffer requirements by altering the terminal's design parameters as described above.

*Example:*

Let us continue analyzing the example introduced in Section 3.3.2 (page 47). The design parameters for that problem were D=8, P=0.5, K=2, and S=20, which led to the following results:

- $E[C] = 0.18$ cuts/car,

- $P_s = 0.62$, $P_l = P_i = 0.19$, and

- $E[T] = 60$ seconds.

Thus, $\rho = E[T]/t_w = 0.67$, a fairly low value. To estimate $\gamma$, we use formulas (3.13) and (3.14):

$$E[T^2] = 0.62 \cdot 40^2 + (0.19 + 0.4^2 \cdot 0.19)$$
$$\times \left( 5^2 + \frac{2 \cdot 5 \cdot 15}{0.18} + 15^2 \cdot 20 \cdot \frac{20 + 1/0.18}{6} \right) = 5406 \text{ sec}^2, \text{ so}$$

$$\gamma = \sqrt{\frac{5406}{3600} - 1} = 0.71.$$

A quick glance at Figure 3.8a reveals that, for the values of $\rho$ and $\gamma$ calculated above, a buffer of size 2 could be used with little impact on system throughput. For illustration purposes, we used the analytical formula (Expr. (3.17)) to build a table of absolute and relative system throughput values for $\rho$=0.67, $\gamma$=0.71, and buffer sizes ranging from 1 to 6. Absolute throughput values are expressed in containers per hour.

| Buffer Size | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|
| $\phi$ | 0.89 | 0.98 | 1.00 | 1.00 | 1.00 | 1.00 |
| Throughput | 35.75 | 39.36 | 39.89 | 39.98 | 40.00 | 40.00 |

Note that extra buffer capacity brings diminishing benefits in terms of productivity (e.g., going from a single-slot to a 3-slot buffer increases throughput much more than going from 3 to 5 slots). Together with Figures 3.10a, b, and c, the table suggests that a buffer with three or four slots should be enough to handle most practical operations.

## 3.4. Additional Considerations

The analysis presented so far covered planning issues and investigated the feasibility of the proposed scheme without too much concern about operational details. This subsection discusses some of these aspects.

### 3.4.1. Double-Stack Railcars

One of the most prevalent trends in the intermodal industry today is the increasing popularity of double-stack railcars. The main advantage of these "stack-trains" is that they can carry twice as many containers as conventional trains of same length. Long trains require more siding track at crossings and more working track at yards.

Double-stack railcars could be used with the proposed scheme with two restrictions. The first is related to the fact that containers may have different lengths (20 and 40 feet are prevalent) and current double-stack railcars can only be loaded according to certain patterns. Because of the way in which containers are interlocked, it is not possible to load two twenty-foot boxes on top of a forty-foot.

This is not a serious restriction in situations where most intermodal containers have the same length. Also, improved double-stack railcars allowing for any loading pattern could be designed.[18]

The second restriction is that typical double-stack railcars come in indivisible sets of platforms (usually five). This is done to reduce their overall length, because only a single axle is needed between each pair of platforms. The use of such cars reflects the preference of some operators for sorting trains by moving containers from car to car rather than breaking and switching blocks.

Generally, such multi-platform railcars would be incompatible with the proposed direct-transfer operation, which relies heavily on the creation of blocks of varying lengths. The use of multi-platform railcars would only be possible in situations where the expected block sizes were large compared to the size of the strings. For example, if each unloading track could be assigned to a single destination or if containers were sorted on the vessel.

Given that the above restrictions are addressed as suggested, the direct transfer operation proposed could benefit substantially from using double-stack railcars, because twice as many containers could be loaded onto strings with the same physical length.

The analysis presented in earlier subsections would also apply to double-stack cars, except that one would differentiate the expected number of cuts per railcar, $E[C]$, from the expected number of cuts per container, $E[C'] \approx E[C]/2$.

Also, the procedure for pre-assigning containers to railcars should be refined to account for the fact that each platform now holds a *pair* of boxes. On average, every other block would have an empty slot in it, and $E[C']$ would be slightly larger that $E[C]/2$. To estimate $E[C']$, recall that the number of containers per block can be written as:

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[18] According to Prof. Robert Leachman, some such cars are already in use.

$$\frac{1}{E[C']} = \frac{2}{E[C]} - \frac{1}{2},$$

or twice the number of cars per string minus half a container corresponding to the empty slot on every other block. Thus,

$$E[C'] = \frac{2}{4 - E[C]} \cdot E[C].$$

Because E[C] will normally be a small number, say comparable with 0.1, the approximation suggested above (E[C'] ≈ E[C]/2) should be very accurate in practice.

### 3.4.2. Unloading Strategy

There are many ways to improve the performance of the direct-transfer scheme suggested in this chapter at the operational level. These improvements would require more detailed information about the operation and could be explored in future research efforts.

The first possibility would be to take advantage of the fact that not all import containers are intermodal. By interspersing domestic and intermodal containers while unloading the vessel, the pushers would always have at least two crane cycles to position the string instead of one. This would correspond to cutting the ratio between the landside and waterside cycles (denoted by $\rho$ in the previous subsection) in half.

Alternatively, vessel unloading plans could be developed in such a way that only one of the dockside cranes would unload intermodal containers at any given time. This way, all tracks could be assigned to a single crane, and the number of destinations per track could be substantially reduced. Consequently, the expected number of cuts per container would also decrease.

Another improvement would be to reduce the variance of the pusher cycles by developing better container-to-railcar allocation algorithms. The simulation program assigns containers

sequentially within each block. A better approach would be to assign containers to the nearest railcar within the appropriate block or to minimize the maximum travel distance for the pusher by considering the whole string.

Finally, depending on the physical configuration of the buffer, it may be possible to eliminate the first-in first-out requirement and retrieve containers from the buffer in the most favorable order. To achieve this, the landside spreader would always pick the container bound for a track that is ready (or almost ready) to receive it. This optimization has a very attractive feature: it becomes more effective as the buffer fills up, because then the landside spreader has more choices to pick from.

# 4. Economic Comparison

In previous chapters, we have divided container terminals into three categories and examined their operation. Methods were also developed to evaluate the performance of an innovative direct-transfer system.

This chapter develops a simple model for comparing the economics of each terminal design under varying operating conditions. The scope of the model is restricted to the operation of a single terminal. It is assumed that all intermodal containers arriving on a ship are transported to a rail yard (by truck or by train) where a convoy of one or more trains is formed and immediately dispatched. This assumption does not always hold true, because some rail yards consolidate cargo from several ships in order to dispatch fewer, longer trains. During the consolidation process, containers arriving at the rail yard by truck may be stored on grounded stacks, while those arriving by rail can either remain in the railcars or be transferred to stacks and reloaded later. This type of operation is discussed briefly in the next chapter.

Section 4.1 describes the overall model and its basic assumptions. Sections 4.2, 4.3, and 4.4 develop the parts of the model that deal with handling and transportation costs, storage area requirements (rent costs), and transportation times (inventory costs), respectively.

Finally, Section 4.5 uses the model to compare the designs and to determine the conditions under which each alternative is more attractive. Additional qualitative aspects of each operation -- including their environmental impacts and effects on highway congestion -- are also discussed.

## 4.1.  Economic Model

The economic model proposed measures the total cost of moving a container through each of the systems under study. From vessel to remote rail yard in the case of intermodal containers, or from the vessel to the terminal gate in the case of domestic containers. It is assumed that costs incurred in other parts of the transportation process are independent of the terminal design.

Transportation costs are divided into three main categories:

**Handling and Transportation Costs:**

These are costs related to the motion of containers, such as the cost to transfer a box from the ship to the dock or from the terminal to the remote rail yard. They include the capital costs for the handling equipment as well as maintenance and labor.

**Rent Costs:**

These are costs related to the provision of storage space for in-transit containers and railcars. They include the cost of purchasing, developing, and maintaining the terminal storage areas.

**Waiting (or Inventory) Costs:**

The opportunity cost of the capital tied up in equipment and cargo while the ship is being loaded and unloaded and while containers and railcars are in transit or in storage.

In addition to the above costs, other factors are considered outside the model, in a qualitative fashion. These additional factors include the terminal impacts on the environment and surrounding communities (particularly on the highway system), and the terminal's potential for automation.

One of the main difficulties in developing an economic model such as the one that follows is that few ports are willing to contribute the necessary information regarding their operations, productivity, and costs. It is a common perception that by disclosing this type of data, ports would be giving away their competitive edge. Nevertheless, general information is available from a variety of other sources, and a limited amount of data is available from promotional material published by some ports.

The economic model is based on the operation of the largest semi-direct transfer terminal in the U. S., Port of Tacoma's North Intermodal Yard. The operation is described in a promotional

video produced by the port (Port of Tacoma's Intermodal Advantage, January 1991), and is summarized below.

The operation starts with the arrival of a convoy of 3 trains into the terminal, where 4 miles of track can accommodate up to 300 double-stack railcars at once, which translates into 600 FEU.

The vessel only arrives about 8 hour later. This offset ensures that the ship will not be delayed even if the trains arrive a few hours late. It also allows the operators to start unloading the trains so that, when the ship comes in, they will be ready to be loaded with import containers.

A typical ship unloads a total of about 1000 import containers and receives a similar number of exports. The fraction of intermodal containers is therefore close to $600/1000 = 0.6$.

The equipment used consists of three dock cranes, each served by a fleet of 4 straddle-carriers.[19] An additional 9 straddle-carriers are used to service the trains. The reason for using separate fleets of strads to serve the ship and the trains is probably analogous to the reason why a double-hoist crane is needed in the direct-transfer operation described earlier. It creates an intermediate buffer between the almost constant ship service times and the more variable train loading and unloading cycles.

According to the video, it takes 8 hours to perform 650 moves (loading and unloading), for an average terminal productivity of 80 moves per hour. This translates into 27 moves per hour for the cranes and 4 moves per hour for the strads. It is important to note that the strads are capable of 10 to 15 moves per hour in non-intermodal operations. The low productivity observed is a result of two factors: (i) the tracks are located at the back of the terminal, so travel distances are longer for intermodal moves, and (ii) the large number of strads operating around the trains

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[19] Straddle-carriers, also known as "strads", are small and fast rubber-tired cranes. They are very versatile, being able to pick or set containers on the dock, on stacks up to two or three boxes high, or on railcars.

interfere with one another. This congestion will probably increase when the port carries out a proposed terminal expansion in the near future.

All this background information will be useful in the development of the economic model. The most important characteristic of the whole operation, however, is that there is a one-to-one correspondence between ships and train convoys: virtually all intermodal containers brought by a vessel are loaded onto a single convoy, and, conversely, all export containers brought by a convoy are loaded onto a single ship. This implies that vessel and train schedules must be coordinated so that they are present at the terminal at the same time. This is an obvious requirement for the execution of semi-direct and direct transfers.

Based on these observations, the following assumptions are made regarding the operation of all terminals under study:

- All terminals use straddle-carriers (strads). This simplifies the analysis because straddle-carriers, together with dock cranes, suffice to perform all container handling tasks. If desired, it should be easy to modify the model to reflect operations based on other types of equipment.

- On-terminal rail tracks are used exclusively for intermodal traffic, which flows through a single inland intermodal rail yard. This assumption is justified by the fact that handling domestic rail within the terminals would be a waste of valuable terminal area.

- Vessels call according to a fixed schedule. They unload a fixed quantity of import containers and receive an equivalent number of exports. A fixed fraction of the containers is intermodal.

Figures 4.1, 4.2, and 4.3 depict the conceptual models used and the differences between the indirect, semi-direct, and direct intermodal transfer operations.
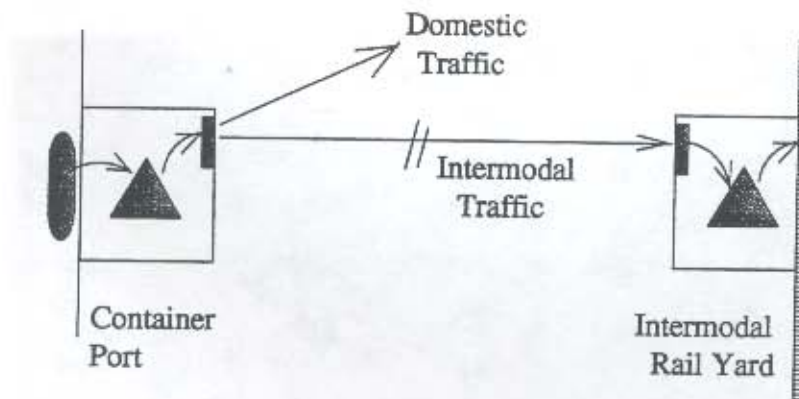
*Figure 4.1: Indirect-Transfer Operation*
*(off-terminal rail access)*

Figure 4.1 depicts the process of receiving domestic and intermodal containers at an indirect transfer terminal. Import containers arrive aboard the vessel and are transfered by dock cranes and straddle-carriers to an on-terminal storage area (depicted as a triangle).

After the ship has been fully unloaded, containers are gradually transfered to trucks which exit the terminal through a gate facility (depicted as a gray rectangle). The domestic containers are taken to local destinations, and the intermodal ones are taken to the intermodal rail yard. The process of transfering containers from the terminal to the intermodal rail yard by truck is called "drayage."

Upon arrival at the rail yard, the trucks park the containers in a storage area. The trains are then loaded by strads and dispatched to their destinations.

Export operations occur in a similar fashion, simultaneously but in the opposite direction.
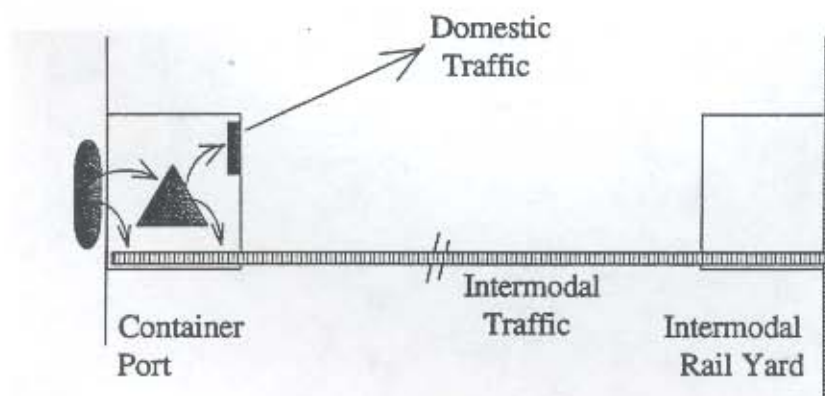
*Figure 4.2: Semi-Direct Transfer Operation*
*(on-terminal rail access)*

Figure 4.2 depicts the process of receiving domestic and intermodal containers at a semi-direct transfer terminal. Domestic containers are processed in the same manner as in the indirect-transfer terminal.

Intermodal imports are taken by the straddle-carriers to railcars on tracks at the back or side of the terminal. Alternatively, if there is enough storage area and few straddle-carriers available, they may also be placed in storage with the domestic containers and transfered to the train after the ship has been unloaded.

When the train is fully loaded, it is dispatched to the remote rail yard, where it can be further processed or simply continue its trip. No container storage or handling is required at the remote rail yard.

Export operations occur in a similar fashion, simultaneously but in the opposite direction.
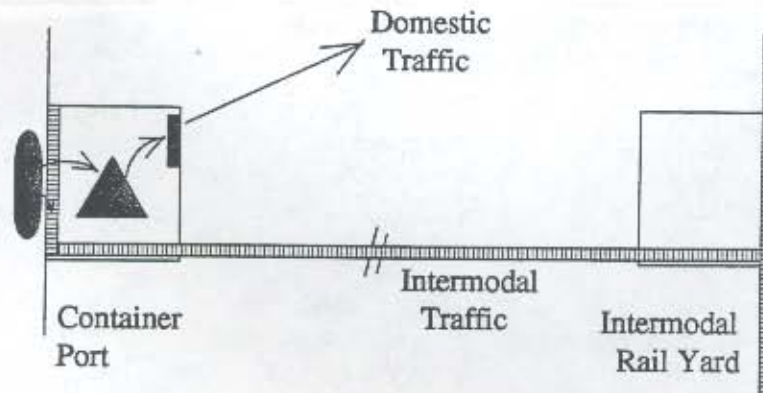
*Figure 4.3: Direct-Transfer Operation*
*(on-dock rail access)*

Figure 4.3 depicts the process of receiving domestic and intermodal containers at a direct transfer terminal. Domestic containers are processed in the same manner as in the indirect-transfer terminal.

Intermodal imports are unloaded by the dock cranes directly onto railcars (no straddle-carriers are required). When the train is fully loaded, it is dispatched to the remote rail yard, where it can be further processed or simply continue its trip. Alternatively, train segments can be dispatched as they are loaded. Because the train is loaded in segments, as described in Chapter 5, some extra railcar swiching may be required at the remote yard.

Export operations may be performed as in the semi-direct transfer terminal. Alternatively, it may also be possible to unload the train directly. This would be especially easy in situations where intermodal trains contain large numbers of identical containers (e.g., same size, weight, and destination). In such cases, pusher operations would be simplified and there would be little risk of delaying the vessel.

The table below summarizes the advantages and drawbacks of each type of terminal with respect to the main costs described in the beginning of this section and to additional factors that will be considered only qualitatively. Table entries refer to intermodal operations only, since domestic operations are identical for all terminal types.

| | Indirect | Semi-Direct | Direct |
|---|---|---|---|
| **Handling and Transportation** | - handling, gate processing and box inspection at the terminal and at the railyard | +no gate processing, single handling and inspection | +no gate processing, single handling and inspection |
| | - drayage required | +no drayage required | +no drayage required |
| | +no train loading equipment required at the terminal | - many straddle-carriers or additional cranes needed for train loading | +train is loaded by dock crane |
| | +no further train classification required | +no further train classification required | - further train classification may be required |
| **Rent** | - intermodal containers in terminal storage | +no intermodal containers in terminal storage | +no intermodal containers in terminal storage |
| | +no track space | - track space for full intermodal shipload | *track space for fraction of intermodal shipload |
| **Waiting** | - long for containers (because of restricted truck access to the terminal and driver work schedule) | +short for containers | +short for containers |
| **Environmental** | - increases highway congestion and safety problems, emissions | +no impact on highways | +no impact on highways |
| | +no rail right-of-way | - rail right-of-way required | - rail right-of-way required |
| **Other** | +conventional equipment | +conventional equipment | - non-standard equipment |
| | - least flexible operation | *moderately flexible (can operate as indirect) | +most flexible (can operate as indirect or semi-direct) |
| | - limited potential for automation | - limited potential for automation | +good potential for automation |
| | +little coordination required between dock cranes and straddle-carriers | *moderate coordination required between dock cranes and straddle-carriers | - perfect coordination required between dock cranes and pushers |

## 4.2. Handling and Transportation Costs

To estimate the handling costs per container, we assume that each piece of handling equipment incurs a fixed unit cost for every move. This cost is a function of the equipment's capital cost, maintenance, labor, utilization factor, and productivity.

For example, the cost of a dock crane move, $C_c$, is estimated as follows:[20]

| Unit Cost for a Single-Hoist Dock Crane | | |
|---|---|---|
| Capital cost for single-hoist dock-crane | 7 | million $ |
| Annual capital cost (20 years at 15%) | 1.12 | million $ |
| Utilization factor | 2300 | work hours/year |
| Hourly capital cost | 487 | $/hour |
| Labor (2 operators) | 80 | $/hour |
| Maintenance | 25 | $/hour |
| Total hourly cost | 592 | $/hour |
| Productivity | 35 | moves/hour |
| **Cost per move** | **17** | **$/move** |

Thus, $C_c$ = 17 $/move, a cost that is independent of the number of cranes and of terminal throughput. The advantage of estimating costs in this fashion is that it frees us from having to determine the optimal number of dock cranes and straddle-carriers for each terminal. A port that is busier than another would have more pieces of equipment, but we assume that their individual productivity and utilization factors would be similar.

A spreadsheet with the detailed derivation of all unit handling costs used in the comparisons is included in Appendix V. These costs are summarized in the table below:

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[20] Dock crane costs, utilization, and productivity values were obtained from a 1991 terminal planning study done by Liftech Consultants Inc. for Virginia International Terminals (1991) and are used by permission.

| Symbol | Equipment | Handling Cost ($/move) |
|--------|-----------|------------------------|
| $C_c$ | Single-hoist dock crane | 17 |
| $C'_c$ | Double-hoist dock crane and pushers | $21 + 3 \cdot K$ |
| $C_s$ | Straddle-carrier ("regular" moves) | 10 |
| $C_d$ | Drayage (truck transportation) | $62 \cdot (1+L/V)$ |
| $C_n$ | Cuts at the rail yard | 20 |

The unit cost for the double-hoist crane includes the cost of the pushers. Because we assume that there will be one pusher per track, this cost is a function of the number of tracks K. It is assumed that the capital cost of a pusher is 0.65 million dollars, the same as the cost of a straddle-carrier.

The cost for the double-hoist crane is based on a productivity of 40 moves per hour, slightly higher than that of a single-hoist crane. This productivity is corrected under the direct-transfer scheme to account for losses due to the limited size of the crane buffer.

The cost for the straddle-carriers assumes a productivity of 12 moves per hour (consistent with the Port of Tacoma's data described before), reflecting the assumption that three strads will be used against each dock crane. The actual number of strads required per dock crane naturally depends on a number of factors including the productivity of the cranes, the speed of the strads, and the terminal layout. However, three strads per crane seems to be a fairly common number in use at many terminals, and will be adopted in our analysis.[21] These observations apply to strad moves between storage areas and vessels or trucks (regular moves). As mentioned before, their productivity goes down when working against trains.

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[21] The port of Tacoma and the Matson terminal in Honolulu, for example, use nine to twelve strads against three dock cranes. A generic simulation of a strad-based terminal developed by Liftech Consultants for VIT indicates that the number of strads required per dock crane is not very sensitive to the layout of the terminal. The average productivity of a straddle-carrier operating in a typical terminal is about half that of a dock crane. The cycle times for the strads are variable, however, so an additional strad is often deployed to avoid delaying the dock crane during long strad cycles.

The drayage cost is a function of V, the average truck speed (assumed to be 40 mph), and L, the distance between the terminal and the rail yard. This cost also includes a one hour delay incurred by the truck at the terminal and at the rail yard which corresponds to gate processing, locating, and connecting the chassis to the tractor.

The cost of a train cut is based on an estimate by Keaton (1991).

### 4.2.1. Indirect-Transfer

Using this approach, the handling and transportation costs per container for the indirect-transfer terminal can be estimated by adding the cost of each handling step along the container's path. As illustrated in Fig. 4.1, these steps are:

- A dock crane move from the vessel to the dock.

- A strad move from the dock to the storage area.

- A second strad move from the storage area to a truck.

These steps are common to all containers. Intermodal boxes boxes require the following additional steps:

- A truck move from the terminal to the remote rail yard (drayage). This cost depends on the distance between the terminal and the rail yard.

- A final strad move to load the train at the rail yard. We will assume that this move costs the same as a strad move from the dock to the terminal storage. This is justified because the strads can retrieve containers from the storage area in any order. By organizing the train loading moves, it should be easy to avoid interference between the straddle-carriers.

We can thus estimate the cost of moving an average container through our indirect-transfer system as:

$$C_{Ih} = C_c + 2 \cdot C_s + I \cdot (C_d + C_s), \tag{4.1}$$

where $C_c$ is the dock crane cost, as described above, $C_s$ is the strad cost, $C_d$ is the drayage cost, and I is the fraction of intermodal containers.

### 4.2.2. Semi-Direct Transfer

The handling steps for intermodal containers in the semi-direct transfer system are (refer to Figure 4.2):

- A crane move from the vessel to the dock.

- A strad move from the dock to the train.
  As seen earlier, this move will usually take more time than the regular strad moves.
  To account for this in the model, we multiply the cost of a regular move, $C_s$, by a constant $k_s$.
  The value of $k_s$ depends on many factors, including terminal layout, but in most practical situations it should probably be between 2 and 5.[22]

- A train move from the terminal to the remote rail yard. Instead of evaluating this cost directly, we assume that it is proportional to the drayage cost $C_d$. We can thus account for this cost by multiplying $C_d$ by a constant $k_d$. The value of $k_d$ will depend on regional factors as well as on the truck and rail technology used, but we would expect it to be between 0.4 and 0.6.[23]

Domestic containers are handled the same way as in the indirect transfer system. These costs are combined in the expression below:

$$C_{Sh} = C_c + 2 \cdot (1-I) \cdot C_s + I \cdot (k_d \cdot C_d + k_s \cdot C_s), \qquad (4.2)$$

---

[22] For the Port of Tacoma example, $k_s$ can be determined by dividing the regular strad productivity, 12, by the intermodal productivity, 4, yielding $k_s = 3$. This value is likely to increase when the North Intermodal Yard is expanded.

[23] The linehaul rail costs might be even lower than this. According to Gilman (1988), the cost of drayage for a forty-foot container in the U.S. is approximately 80p per mile, compared to 30 to 50p for rail transportation, which gives $k_d = 0.4$ to 0.6. Values suggested by Ashar (1990) for the Port of Los Angeles, however, reflect a $k_d$ close to 0.20.

where $k_t$ and $k_s$ are the factors discussed above, used to account for the difference between train and truck transportation costs and for the longer strad cycles required to load the train.

### 4.2.3. Direct Transfer

Before examining the handling steps required in the direct transfer system, we need to determine how to account for the handling costs of the pushers. Their operation is somewhat different from that of other pieces of handling equipment. If intermodal and domestic containers are unloaded simultaneously, the pushers must be available throughout the unloading process, regardless of the proportion of intermodal boxes. For our purposes, therefore, the pushers can be considered as parts of the dual-hoist crane system and their costs accrue even while the dock crane unloads domestic containers.

To increase the utilization of the pushers, it could be advantageous in practice to organize the unloading operation so that only a few cranes unload intermodal boxes at any time. The pushers could then be assigned to those cranes and would not waste time waiting for domestic containers to be unloaded. This should be especially easy in situations where the ship is sorted, but we will not consider this option because it would require too many assumptions about the operation of the terminal.[24]

The handling steps for domestic containers in the direct transfer system are similar to those of the other systems, except that a dual-hoist crane is used to unload the containers instead of a regular crane.

For intermodal containers, the steps are quite different (refer to Figure 4.3):

- A dual-hoist crane move from the vessel to the rail track, accompanied by a pusher move, used to position the string of railcars under the crane.

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[24] In addition to increasing pusher productivity, this would also increase the number of tracks available to each crane. As shown in Chapter 5, increasing the number of tracks would reduce E[C], the number of cuts required per railcar.

- A train move from the terminal to the remote rail yard.

- Additional sorting effort at the remote rail yard. This cost is a function of the number of cuts required per railcar (E[C], examined in Chapter 5), and of the type of equipment used at the rail yard.

The following expression summarizes the costs:

$$C_{Dh} = C'_c + (1-I) \cdot 2 \cdot C_s + I \cdot (k_d \cdot C_d + E[C] \cdot C_u),$$  (4.3)

where $C'_c$ is the cost of a dual-hoist crane move, including the pusher costs, and $C_u$ is the cost of each train cut.

The train classification costs are difficult to evaluate. Keaton (1991) estimates a cost of $20 per cut, but this depends on the size, track configuration, and equipment in use at the rail yard.

The train classification process also causes delays and associated inventory costs. If the classification is to be performed at a busy rail yard, the delays may include the time waiting to use the sorting facility. These costs may be avoided altogether if the sorintg is performed at the back of the terminal, while the train is being loaded. This would require some additional trackage at the back of the terminal (probably in a herring-bone configuration).

Our economic analysis assumes that the cuts are performed at the remote rail yard and that there are no waiting delays. It will be seen that the additional time spent in the sorting process is very small.

## 4.3.    Rent Costs

The rent costs reflect the cost of purchasing and developing the area required for storage of in-transit containers and railcars. To estimate the rent cost per move, we start by determining the maximum accumulation of containers in the terminal at any time. The area is then obtained as a function of the container accumulation and of the container storage density. Finally, land costs in the terminal area and terminal throughput are used to compute the rent costs per move.

The maximum accumulation of import containers at the terminal depends on three factors:

- How often ships arrive,

- How many containers they unload, and

- How fast these containers are retrieved from the terminal.

A simple model for container accumulation can be developed if we assume that the headway between ships, H, and the size of a shipload, A, are constants. We also assume that containers brought by a single ship are retrieved from the terminal at a constant rate such that it would take n headways to retrieve all boxes unloaded from a single ship. The model is depicted in Figure 4.4, explained below.
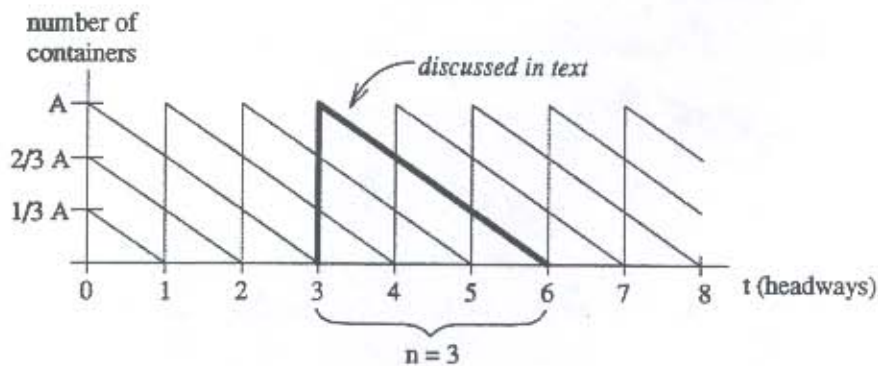


*Figure 4.4: Container accummulation model.*

Figure 4.4 shows the container arrival and departure pattern for a case where n=3. The horizontal axis represents time -- measured in ship headways -- and the vertical axis indicates the number of containers in storage. At every integer headway, vertical lines mark vessel calls, when A containers arrive. The following sloping lines correspond to containers being retrieved.

At any point in time, there are "n" groups of containers brought by different ships present in the terminal. Containers from each group are retrieved at a rate $A/n$ boxes per headway, so that the overall retrieval rate is A, equal to the arrival rate.

As Figure 4.4 shows, the maximum accumulation of containers in the terminal occurs immediately after each ship arrival. At time 3, for example, the total number of boxes in storage is 2A, a full shipload that arrived at t=3, plus 2/3 of a shipload remaining from t=2, plus 1/3 remaining from t=1.

It is easy to see that for an arbitrary value of n the maximum accummulation is

$$N = \frac{A}{n} \cdot \sum_{i=1}^{n} i = \frac{A \cdot (n+1)}{2}.$$

The above expression assumes that n is an integer greater than zero. If containers are retrieved at such a rate that it takes less than a headway to remove the whole shipload, then the maximum accumulation will naturally be equal to one shipload. This will often be the case, especially for intermodal containers which tend to be retrieved at fast rates. We thus define $n^+$ as the smallest integer such that $n^+ \geq n$, and rewrite the above expression as

$$N = \frac{A \cdot (n^+ + 1)}{2}. \tag{4.4}$$

Given our assumptions, this expression is exact when n is less than 1 and when n is an integer, Otherwise is slightly overestimates the accumulation.

Expression 4.4 also applies to export containers. If separate storage areas are used for import and export boxes, as is often the case in practice, the storage requirement may be calculated separately and added together.[25]

The assumptions of constant ship headways and loads is fairly consistent with current practice. Although headways and shiploads may vary, it is is clearly in the interest of the terminal operators to space ships of similar sizes evenly apart.

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[25] If import and export containers were mixed in storage, it is easy to show that the maximum accumulation would be $N = A/2$ $(n_i + n_e)$, where $n_i$ and $n_e$ are the number of headways required to bring the exports and to remove the imports from the terminal, respectively.

The assumption regarding uniform retrieval rates for all containers on the ship, however, does not usually hold in practice. There are usually different categories of containers that are retrieved at different rates. For example, it may be important to retrieve intermodal containers from the terminal quickly in order to keep a train schedule, while some domestic containers bound for inland warehouses may be left at the marine terminal for several weeks.

To illustrate this fact, Figure 4.5 shows the actual arrival and retrieval pattern of containers at a terminal for two ships, the Ever General and Marie Maersk.[26]
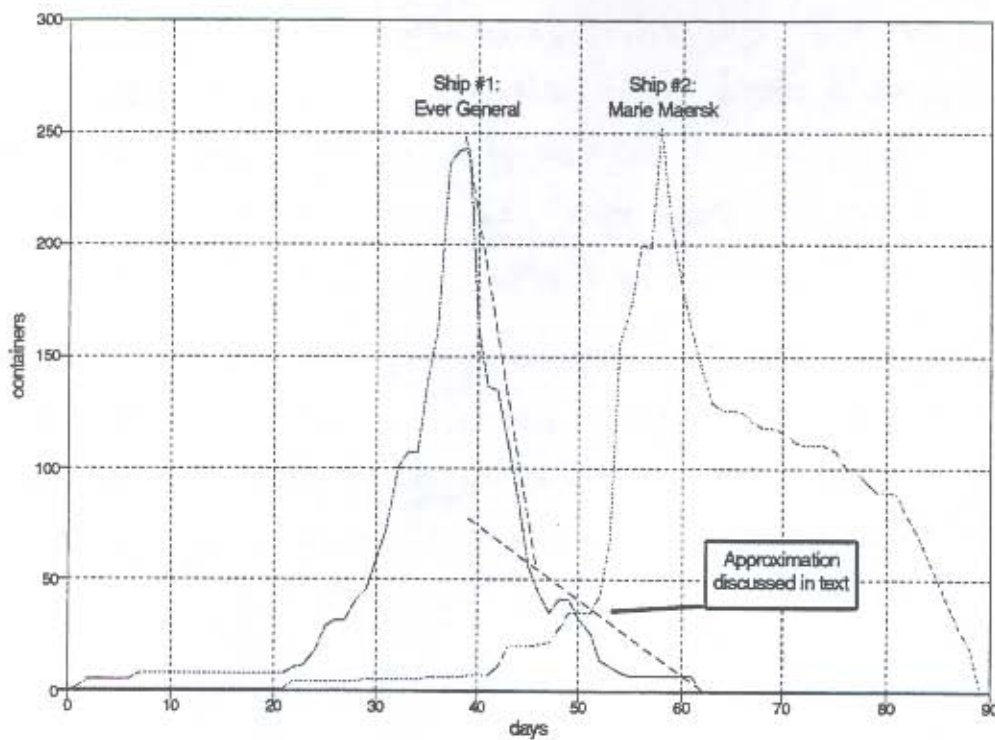


*Figure 4.5: Container arrival and departure patterns for two ships*

[26] Source: Virginia International Terminals.

Each peak in the container counts depicted corresponds to a ship arrival. To the left of the peaks, the curves show the arrival of export containers; to the right, import containers being retrieved from the terminal. Both ships depicted bring and retrieve about 250 containers each.

Note how the arrival and retrieval rates vary with time for both ships. Exports begin to trickle in up to a month before ship arrival. Large batches of exports, however, only arrive during the last week. Imports are retrieved quickly for the first week after the ship arrival, and then at a much slower rate, so that the last containers are only retrieved after spending three or four weeks in the terminal.

The container accumulation model presented above can be easily extended to deal with situations where batches of containers are removed from the terminal at distinct (but uniform) rates. One can imagine that container batches of different sizes and with different retrieval rates are brought by separate ships that arrive simultaneously. In this case, one could simply use Expr. 4.4 to calculate the accumulations for each batch and then add them all together.

Let us consider, for example, the case of the Ever General (the first ship in Fig. 4.4). We could imagine that the ship brings two batches of containers of sizes $A_1 = 75$ and $A_2 = 175$, to be retrieved in 24 and 9 days respectively. The approximation is indicated in Fig 4.4. If ships arrived every 3 days, then $n_1 = 24/3 = 8$ and $n_2 = 9/3 = 3$. The total continer accumulation in this case would be

$$N = \frac{A_1 \cdot (n_1^+ + 1)}{2} + \frac{A_2 \cdot (n_2^+ + 1)}{2} = \frac{75 \cdot 9}{2} + \frac{175 \cdot 4}{2} = 689 \text{ containers.}$$

In our model, we will assume that intermodal and domestic containers are retrieved at different rates. The total accumulation can be expressed as:

$$N = \frac{A \cdot (1-I) \cdot (n^+ + 1)}{2} + \frac{A \cdot I \cdot (n'^+ + 1)}{2} = \frac{A}{2} \cdot [n^+ + 1 - I \cdot (n^+ - n'^+)], \qquad (4.5)$$

where, as before, A is the number of containers brought by a vessel, I is the fraction of intermodal containers, and n and n' are the number of headways required to remove all domestic and intermodal containers from the terminal, respectively.

Once the number of storage slots required has been determined, the storage area required can be obtained based on the terminal's container storage density. This density depends on the layout of the storage area, particularly on the container stacking height. The stacking height is itself a function of the type of container handling equipment deployed in the terminal.

If land is relatively inexpensive, containers may be parked on chassis, and not stacked at all. This reduces storage density but saves on handling equipment. Conversely, if land is expensive, it may be economical to use more sophisticated stacking equipment to increase density and reduce the storage area requirements. The table below shows typical values of storage density for commonly used types of container handling equipment:

| Handling Equipment | Storage Density (FEU/acre)[27] | |
|---|---|---|
| Rail-mounted gantry cranes | 250 - 300 | (5-high) |
| Rubber tired gantry cranes | 200 - 250 | (4-high) |
| Straddle-carriers | 150 - 170 | (2-high) |
| Single-Stack Railcars | 18 | |
| Double-Stack Railcars | 36 | |
| Chassis | 70 - 80 | |

Note that the rail storage densities are very low, even compared to normal wheeled storage. This is because traffic lanes must be provided between tracks for strads or other equipment to access

[27] These values include the area required for access lanes. Rail densities based on the Port of Tacoma's North Yard semi-direct terminal. According to a promotional video put out by the port (Port of Tacoma's Intermodal Advantage, January 1991), the port's 17-acre rail yard has a capacity for 61 double-stack, five platform cars. This translates into 36 TEU/acre. Other densities were suggested by Richard Woodman, terminal planner and principal with JWD Inc.

the trains and constitutes one of the main objections to the on-terminal rail concept. It is also one of the reasons for the growing popularity of double-stack railcars, which reduce the area required to form the trains and the travel distances for handling equipment.

The indirect transfer operating scheme described earlier requires that enough track be available at the back of the terminal to accommodate the whole convoy. The direct transfer scheme does not strictly require that, because trains are served under the crane, a few segments at a time. As was mentioned before, however, it may be desirable to provide this room for two reasons: (i) for flexibility, so the terminal can be perform as a semi-direct transfer terminal, and (ii) so the train can be fully sorted at the back of the terminal before it is dispatched. The best alternative may be to provide some trackage at the back of the terminal for unloading train segments and preparing them for the loading process, but not enough for the whole convoy. These options will be considered later, in the analysis of the model.

We will not explore the trade-off between stacking equipment cost and storage area requirements in our model. Consistent with the earlier assuption of straddle-carrier based operation, we will adopt 150 FEU/acre for storage density.

The cost of land varies widely depending on the region where the terminal is located and on the characteristicas of the area surrounding it. Typical land values found in the literature range from 150,000 to 750,000 $/acre (see for example Ashar, 1990 and Hochstein, 1988).

Having determined the number of storage slots required, the container storage density, and the value of land in the region where the terminal is located, the average rent costs per move can be determined as the ratio between the yearly capital costs for the land – plus initial development and maintenance – and the terminal throughput.

Our model does not include the cost of providing the rail access itself. This cost may be significant in some cases where the region around the terminal is densely populated, but it is often the case that existing rights-of-way can be used for the rail access, incurring little or no

additional cost except for the cost of actually laying the tracks. Also, many large ports have rail access for their break-bulk terminals. In these cases, the cost of extending the tracks to the intermodal container facility should be small.

## 4.4.  Inventory Costs

The delay experienced by a ship during the loading/unloading process is well recognized as an important factor in the overall transportation cost, to the point that reducing vessel turn time is one of the main priorities for shippers and terminal operators. This is easy to understand given that modern container vessels may cost up to 80 or 100 million dollars (see Gilman, 1988).

The inventory costs for loaded containers are much harder to estimate, because they are related to the value of the cargo they carry. These costs are often neglected in the literature, but, as we shall see, they also represent a significant portion of the overall transportation costs.

### 4.4.1.  Unit Inventory Costs

The table below shows the value of import and export containers cargoes shipped through U.S. ports in 1978.[28] The last column contains the vales of $C_i$, the unit cost of holding a container of the corresponding value for one hour. The costs include an extra 10,000 dollars for the cost of the containers themselves, and assume an interest rate of 15%.

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[28]  Source: E. G. Frankel, Inc. (1978).

| | Value ($/ton) | Value ($/FEU)[29] | $C_l$ ($/FEU/hour)[30] |
|---|---|---|---|
| Imports Maximum | 7,803 | 156,060 | 2.84 |
| Minimum | 868 | 17,360 | 0.47 |
| Average | 3,420 | 68,400 | 1.34 |
| Exports Maximum | 2,374 | 47,480 | 0.98 |
| Minimum | 170 | 3,400 | 0.23 |
| Average | 1,054 | 21,080 | 0.53 |

The table shows that the value of loaded containers varies widely. Imports are significantly more expensive, reflecting the fact that the U.S. tends to import industrialized goods (clothing and electronics) and to export raw materials (mainly lumber and foodstuffs). On average, the capital tied up in containerized cargo costs between 0.53 and 1.34 dollars per container-hour. For terminals dealing with hundreds of thousands of containers per year, it is apparent that these costs are significant and must be considered in the economic analysis.

Daily capital costs for modern container ships are easier to determine. According to the literature, the hourly capital cost for a 3000 TEU ship is in the range of $850 to $1000 (see for example Gilman, 1988, or Sabria, 1986). In addition to this, one should take into account the cost of all containers aboard the ship that are to be unloaded at downstream ports. This number will typically be close to 1000, bringing the total hourly cost of holding the ship, $C_v$, to about 1800 to 2000 dollars per hour.

Finally, according to the literature, the hourly cost of an empty railcar, $C_r$, is in close to 0.70 dollars per hour (Keaton, 1991).

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[29] Assuming 20 tonnes/FEU.

[30] These estimates include an extra $10,000 for the cost of the container itself, and assume an interest rate of 15%.

## 4.4.2. Transport Times

Having determined how much a typical loaded container is worth, the next step in the evaluation of the inventory costs is to determine how much time an average box spends in each type of system.

The easiest way to accomplish this is with cumulative-count curves.[31] Cumulative-count curves describe in one diagram how the number of items (e.g., containers and railcars) in various logistic states varies with time.

Figure 4.6, explained below, depicts the transportation process for import containers in an indirect-transfer terminal.

The horizontal axis represents time, and the vertical axis indicates container counts. Different shadings are used to represent the various logistic states a container may be in (e.g. waiting on the ship to be unloaded, in transit between the terminal and the rail yard, etc.). Slanted lines between the states correspond to to handling tasks (e.g. unloading the ship, retrieving boxes from the terminal, etc.). The slope of the each line corresponds to the handling rate for the process.

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[31] These curves are extremely convenient yet rarely used in the inventory and queueing literature. For a complete description of their properties and applications, see Newell (1982) and Daganzo (1991).
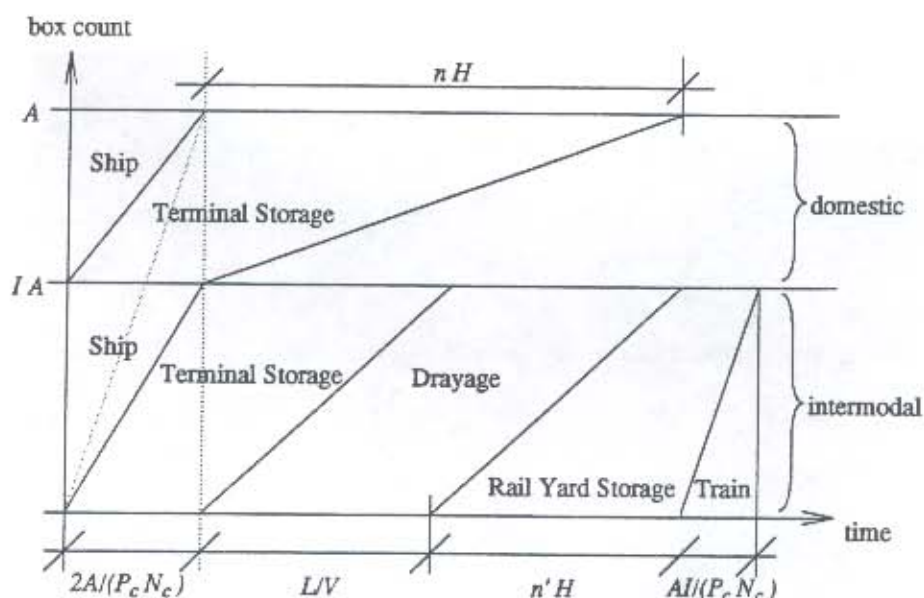
*Figure 4.6: The transportation process for import containers in an indirect-transfer terminal*

Figure 4.6 is divided in two portions. The top depicts domestic import operations; the bottom, intermodal imports. The figure indicates that, at time 0, all containers are on the ship. Domestic and intermodal containers are then unloaded simultaneously from the ship and transfered to the terminal storage area at a rate $P_c \cdot N_c/2$, where $P_c$ is the productivity of the dock cranes (in moves per hour) and $N_c$ is the number of cranes used to unload the ship. The rate is divided by 2 to account for the fact that, while unloading import boxes, the cranes also load exports. Thus, the last box is unloaded at time $2 \cdot A/(P_c \cdot N_c)$.

The figure reflects the assumption that no containers are retrieved until the unloading process is complete. This is reasonable because container retrievals must be arranged in advance, and most operators would not be able to determine exactly at what time a specific container would be unloaded. Even if this were possible, however, the unloading time is fairly small compared to the retrieval and drayage times.

The top portion of Figure 4.6 shows that domestic containers are then retrieved from storage by trucks. Using the notation introduced in Section 4.3, the time required to retrieve all domestic containers is $n \cdot H$. After this, the containers leave the portion of the system that is under study.

Intermodal containers, depicted on the bottom of Figure 4.6, are typically retrieved at a faster rate. Still using the notation from Section 4.3, the time required to retrieve all intermodal containers is $n' \cdot H$.

After retrieval, trucks take the intermodal containers to the inland rail yard. This process takes $L/V$ time units, where L is the distance between the terminal and the rail yard and V is the speed of the trucks.

Upon arrival at the rail yard, the boxes are again placed in storage. Because the drayage time is the same for all containers, the arrival rate at the rail yard is equal to the retrieval rate from the terminal.

When the last container arrives at the rail yard, the train can be loaded. The equipment used to load the train is assumed to have the same productivity as the equipment used to unload the vessel. Thus, the train loading process takes $A \cdot I/(P_c \cdot N_c)$ time units.

Figure 4.6 can be used to calculate the average transit time for domestic and intermodal containers. The top of the figure shows that the average time a domestic container spends in the system is $2 \cdot A/(P_c \cdot N_c)$, the time it takes to unload (and reload) the ship, plus $n \cdot H/2$, halfway between the shortest and longest retrieval times. The bottom of the figure shows that the transit time is the same for all intermodal containers. It can be calculated by adding all the intervals shown along the time axis from vessel arrival to train departure. The transit times can thus be written as

$$\frac{2 \cdot A}{P_c \cdot N_c} + \frac{n \cdot H}{2} \quad \text{for domestic containers, and}$$

$$\frac{2 \cdot A}{P_c \cdot N_c} + \frac{L}{V} + n' \cdot H + \frac{A \cdot I}{P_c \cdot N_c} \quad \text{for intermodal containers.}$$

The average inventory cost for import containers using the indirect-transfer scheme can thus be written as the weighed average of the above quantities multiplied by the unit inventory cost:

$$C_i \cdot \left[ \frac{A \cdot (I^2 + 2)}{P_c \cdot N_c} + I \cdot \left( \frac{L}{V} + n' \cdot H \right) + (1 - I) \cdot \frac{n \cdot H}{2} \right].$$

To this value, we add the total cost of holding the ship, $C_v \cdot 2 \cdot A / (P_c \cdot N_c)$, divided by the total number of containers loaded and unloaded, $2 \cdot A$, which gives us the following expression for the average inventory cost per move using the indirect-transfer scheme:

$$
\begin{aligned}
C_{Ii} = C_i \cdot & \left[ \frac{A \cdot (I^2 + 2)}{P_c \cdot N_c} + I \cdot \left( \frac{L}{V} + n' \cdot H \right) + (1 - I) \cdot \frac{n \cdot H}{2} \right] \\
& + C_v \cdot \frac{1}{P_c \cdot N_c}.
\end{aligned}
\tag{4.6}
$$

The same procedure can be used to evaluate the transportation times for the semi-direct and direct terminal schemes. Figure 4.7, below, shows a cumulative-count diagram that applies for both schemes:
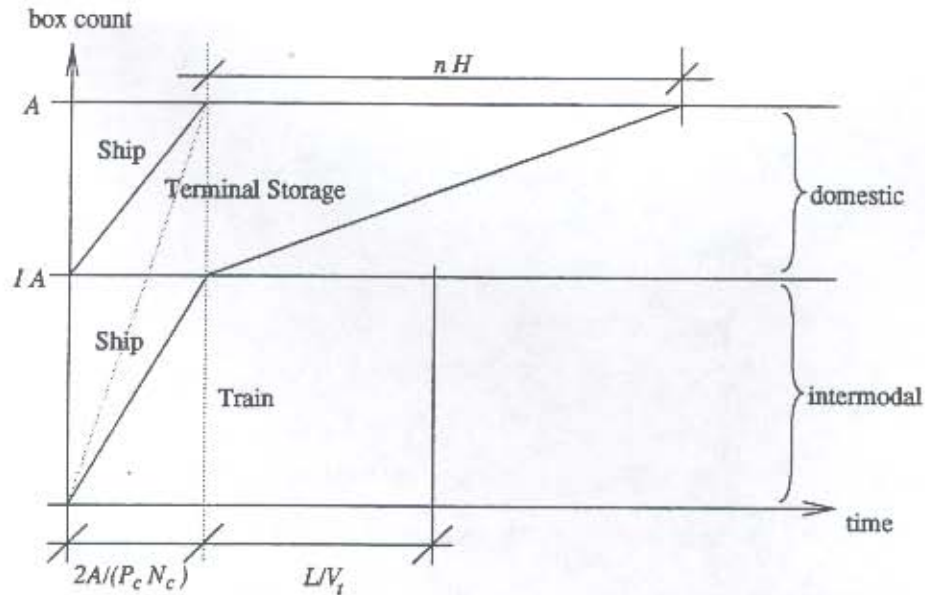
*Figure 4.7: The transportation process for import containers
in a semi-direct or direct-transfer terminal*

Figure 4.7 is similar to 4.6, except that intermodal containers no longer spend any time in storage either at the terminal or at the rail yard. The figure indicates that containers are unloaded from the ship and placed immediately on the train. After the ship has been fully unloaded (at time $A/(2 \cdot P_c \cdot N_c)$), the train is dispatched and takes $L/V_t$ time units to reach the rail yard, where $V_t$ is the average train speed, usually lower than the truck speed.[32]

The expression for the average inventory cost per container moved under the semi-direct scheme is similar to (4.6), except for the terms that correspond to the intermodal storage times, which have been replaced by the railcar inventory costs.

---

[32] Typical train speeds range between 25 to 35 mph (see Keaton, 1991). Although the trucks actually travel faster, they can be delayed by traffic, and the train cannot depart until the last one arrives. Also, trucks spend additional time at the terminal and at the rail yard going through gate processing, inspection, and looking for the right box or parking spot.

$$C_{si} = C_i \cdot \left[ \frac{2 \cdot A}{P_c \cdot N_c} + I \cdot \frac{L}{V_t} + (1-I) \cdot \frac{n' \cdot H}{2} \right]$$
$$+ C_v \cdot \frac{1}{P_c \cdot N_c} \tag{4.7}$$
$$+ C_r \cdot I \cdot \left[ \frac{2 \cdot A}{P_c \cdot N_c} + \frac{L}{V_t} \right].$$

The inventory costs for the direct-transfer scheme are the same as those for the semi-direct, provided that the strings can be classified at the terminal, while the ship is unloaded. If that cannot be done, then the inventory costs for the direct-transfer scheme are obtained by adding to Expr. (4.7) the extra time spent by the containers and railcars during the additional classification required at the remote rail yard:

$$C_{Di} = C_i \cdot \left[ \frac{2 \cdot A}{P_c \cdot N_c} + I \cdot \frac{L}{V_t} + (1-I) \cdot \frac{n' \cdot H}{2} + A \cdot I \cdot E[C] \cdot t_u \right]$$
$$+ C_v \cdot \frac{1}{P_c \cdot N_c} \tag{4.8}$$
$$+ C_r \cdot I \cdot \left[ \frac{2 \cdot A}{P_c \cdot N_c} + \frac{L}{V_t} + A \cdot E[C] \cdot t_u \right],$$

where $t_u$ is the time required to perform a cut in the classification yard. Although $t_u$ is typically very small, the cuts are performed one at a time, so the actual train delay caused by the classification process is $t_u$ times the number of cuts required.

The value of $t_u$ depends on the type of rail yard where the classification takes place. Beckmann (1956), for example, suggests a regression model for classification delays at hump yards where $t_u$ is about 0.35 minutes, but this value may be outdated. For flat yards, where traction is required

to perform the cuts, this value should be substantially higher, but actual data was not available. In any case, as we mentioned before, the terms with $t_u$ could be eliminated if the final classification were to be performed at the back of the terminal, during the train loading process.

The cost model embodied in the above expressions for handling, rent, and inventory costs was implemented on a computer spreadsheet (listed in Appendix V). The next section presents the results obtained and discusses additional factors not explicitly included in the model.

## 4.5.    Comparison and Discussion

In order to compare the costs of moving containers through terminals of each type, a base operating scenario was developed and used as input to the economic model described in previous sections. Individual parameters were then modified, one at a time, to determine their effect on overall operating costs.

The base scenario reflects an operation similar to the one described in the beginning of this chapter, corresponding to the operation of a high-throughput terminal (about 110,000 import moves per year). The parameters that define the base scenario are listed below:

| A | boxes to be unloaded | 600 |
|---|---|---|
| B | crane buffer size | 2 |
| $C_i$ | holding cost for box | 1 $/hour |
| $C_l$ | labor cost | 40 $/hour |
| $C_r$ | holding cost for railcar | 0.75 $/hour |
| $C_v$ | holding cost for loaded vessel | 2000 $/hour |
| D | number of intermodal destinations | 6 |
| $D_s$ | strad storage density | 150 FEU/acre |
| $D_t$ | train storage density | 36 FEU/acre (double-stack cars) |
| H | ship headway | 2 days |
| I | intermodal fraction | 0.5 |
| i | discount rate | 0.15 |
| K | number of tracks under crane | 2 |
| $k_s$ | intermodal vs regular strad move | 3 |
| $k_t$ | train vs truck transportation cost | 0.5 |
| L | distance from term to rail yard | 20 miles |
| LV | land value | 1,000,000 $/acre |
| n | headways to unload domestic | 5 |
| n' | headways to unload intermodal | 0.5 |
| $N_c$ | number of cranes | 3 |
| P | ship sorting level | 0.50 |
| S | number of railcars in a string | 20 |
| $t_u$ | time per cut | 1 minute |
| u | utilization | 2300 work-hours/year |
| V | truck speed | 40 mph |
| $V_t$ | train speed | 30 mph |

Figure 4.8 summarizes the results obtained when the above values are used as input to the economic model. The figure shows total costs and the components due to handling, rent, and inventory expenses:
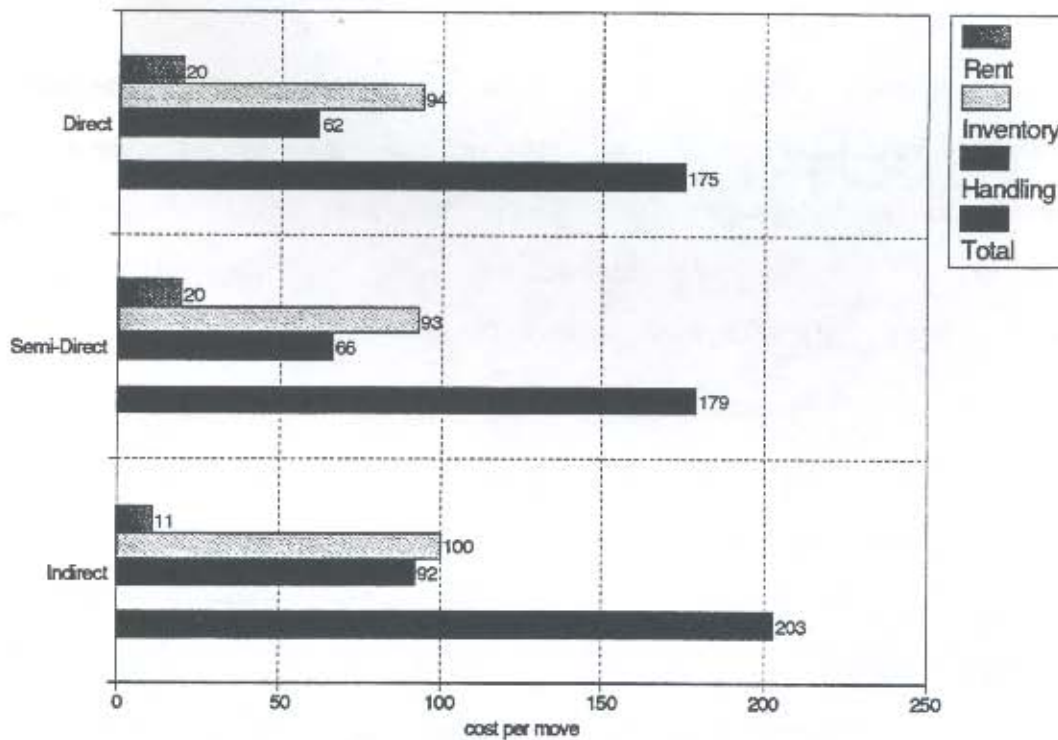
*Figure 4.8: Economic comparison of the three schemes*

The figure shows that, for the scenario under study, both the semi-direct and the direct-transfer systems have a significant cost advantage (about $30 per move, or 15%) over the indirect-transfer scheme.

It is interesting to compare these costs to estimates available in the literature. Ashar (1991) published estimates from a third source that suggest an on-dock facility at the Port of Long Beach would save about $75 per move over the current indirect transfer approach. In his critique of these estimates, Ashar concludes that a more realistic estimate would be substantially lower, between $20 and $30. The values yielded by the model matches the latter estimate closely, even though they are based on a substantially different operation and include different cost items. This suggests that the results obtained are robust.

### 4.5.1. Differences between the Indirect-Transfer and Other Systems

The model indicates that the indirect-transfer terminal has lower rent costs than the other two alternatives. This was to be expected, since it is the only approach that does not require on-terminal rail tracks. It is important to notice, however, that even though the land value assumed is quite high (1 million dollars per acre), the rent costs represent only a relatively small fraction (between 5% and 10%) of of the overall cost for each alternative.

The indirect-transfer terminal has by far the highest handling costs, mainly because of the drayage component. The model indicates that the drayage cost alone accounts for more than half the overall handling costs per intermodal container. This is not surprising: one of the major incentives for shippers and terminal operators to develop on-dock rail schemes has been the desire to avoid these costs.

The indirect-transfer terminal also has the highest inventory costs, incurred mostly while containers await retrieval in the temporary storage areas at the terminal and at the rail yard. These costs could be reduced by improving the flow of trucks through the terminal so that containers could be retrieved at faster rates. This would require fast gate and terminal processing, as well as optimal scheduling of truck arrivals at the terminal.

Faster gate processing is being pursued through innovative technologies such as electronic data interchange (EDI) and automatic equipment identification (AEI). Scheduling truck arrivals, on the other hand, poses a problem because shippers and terminal operators typically have very little control over trucker's work schedules. Trucks tend to arrive at the terminal in batches (typically one in the morning and one early in the afternoon), causing congestion and long delays.

### 4.5.2.  *Differences between the Direct and Semi-Direct Transfer Systems*

The difference between the semi-direct and direct transfer systems is much smaller.  The trade-off between the two is a question of which is cheaper to maintain and operate, a fleet of straddle-carriers or a fleet of pushers.

This question is difficult to answer, because the pushers are not standard pieces of equipment. Assuming that a pusher costs about the same as a straddle-carrier (0.65 million) and that the strad cycles between the dock and the train are about 2.5 times longer than between dock and storage $(k_s \approx 2.5)$, then both schemes have similar handling costs under the base scenario parameters.

In cases where costs are similar, the semi-direct transfer scheme would have some advantages: the operation is simple, fairly efficient, and proven in practice.

The direct-transfer approach, however, also offers important benefits.  When intermodal traffic is intense, for example, semi-direct transfer operations could create congestion in the terminal.  The direct-transfer scheme, on the other hand, performs best when intermodal traffic is intense, because the double-hoist cranes and pushers can be better utilized and a significant portion of container traffic is diverted from the container yard.

Also, the semi-direct transfer approach is labor-intensive, both in terms of strad operators and clerks required to give instructions to each one during operation.  Hiring and maintaining a large group of skilled operators requires a significant commitment on the part of the port, including negotiating wages, work schedules, and safety regulations.  This may or may not be a problem depending on the relationship between port management and labor unions.  The direct-transfer approach, on the other hand, could be extensively automated, possibly eliminating a significant portion of the terminal's labor costs.

The base scenario assumes that the train storage density is the same for the direct and semi-direct transfer terminals.  Even assuming that double-stack railcars will be used, this density is rather

low (36 FEU/acre), because it includes traffic lanes between the tracks for the straddle-carriers, a necessity under the semi-direct transfer scheme. The traffic lanes are not required by the direct-transfer operation described, although they may be desirable for flexibility. If the traffic lanes were to be eliminated from the direct-transfer design, train storage density could be roughly doubled, significantly reducing the rent costs for the direct-transfer scheme (for the base scenario described above, the reduction would be of about 5 dollars per move, or 25% of the total rent costs).

The results presented above reflect the parameters in the base scenario. The following subsections focus on each individual parameter and evaluate their effect on the overall cost for each alternative. This analysis will help determine which terminal design is indicated under different operating conditions.

### 4.5.3. Train Classification Costs

The model indicates that the additional effort involved in cutting the train contributes very little to the operating costs under the direct-transfer scheme (less than 2% of the total). This observation holds not only for the base scenario but for any reasonable combination of the relevant parameters (D, S, K, and P). This is a very important result: it means that the pusher effort may be reduced by adopting shorter train segments without increasing terminal operating costs significantly. It also means that ships would not have to be especially sorted for the direct-transfer operation to be competitive.

The actual costs of cutting and classifying the train could be higher than those predicted by the model, however. If, for example, the train had to make an additional stop to undergo classification at a busy rail yard, significant delays could be incurred. This could be avoided by performing the final classification on the tracks at the back of the terminal, as described before. Also, the cutting process may have hidden costs caused by damage to the cargo in the containers

during the train classification process. These costs are very difficult to measure, and could be prevented with the development of better rail equipment.

The model also reveals that the loss of crane productivity due to the limited size of the internal buffer is negligible under the base scenario. As shown in the example in Section 3.3.3.3, a buffer with two container slots allows the crane to work with virtually no delays ($\phi = 0.99$) under most reasonable combinations of operating parameters.

## 4.5.4. The effect of Pusher Technology

The economic comparison is based on the assumption that one pusher will be used for each loading track. This is conservative, especially when the number of tracks is large (say 6 or more) because it is highly unlikely that all pushers will be needed at the same time.

If the pushers were able to serve multiple tracks, it would be possible to reduce the total number of pushers required, making the direct-transfer scheme more competitive. For the base scenario described, with a total of six tracks (two per dock crane), the potential savings would be modest: the economic model shows that, in this case, the pushers only account for about 3% of the total cost per move, including capital, maintenance, and labor costs. For terminals with more tracks, or with a higher fraction of intermodal moves, however, the saving could be significant.

The number of pushers required to serve a given number of tracks can be estimated with a simple probabilistic model similar to the one developed by Easa to analyze the operation of tugboats at harbors (Easa, 1987). Using the notation introduced earlier, the rate at which the dock cranes discharge containers onto the loading tracks can be written as $N_c / t_w$. Thus, assuming that all K tracks are equally utilized, each one receives containers at a rate $N_c / (t_w \cdot K)$. Every container unloaded onto a track requires a pusher move of average duration $E[T_p]$, so the utilization factor for any track can be expressed as

$$\rho_p = \frac{E[T_p]}{t_w} \cdot \frac{N_c}{K},$$

(4.9)

a value that corresponds to the fraction of time each track is busy receiving (or preparing to receive) containers. If we assume that containers arrive independently at each track, then the total number of busy tracks at any point in time can be seen as a random variable with a binomial distribution, and the probability of "i" tracks being busy at any time is given by

$$p(i) = \rho_p^i \cdot (1-\rho_p)^{K-i} \cdot \frac{K!}{i! \cdot (K-i)!} , \quad 0 \le i \le K.$$

(4.10)

Because of the assumption regarding independent arrivals, Expr. (4.10) is exact only when separate cranes are used to unload containers onto each track ($N_c$=K). In practice, each crane will normally serve many tracks, and (4.10) will overestimate the probability of many tracks being used at once.

In order to evaluate the impact of using less than one pusher per track, let us consider a situation where four tracks are served by only two pushers. The system will operate without delays as long as the total number of busy tracks is two or less. Whenever three tracks need pushers simultaneously, only two can be served, and the system's throughput will decrease temporarily to 2/3 of the maximum. Similarly, when all four tracks need pushers, only two can be served, reducing the throughput by 1/2. On average, the resulting relative system productivity can thus be expressed as

$$1 - [p(3) \cdot 1/3 + p(4) \cdot 1/2],$$

or, more generally,

$$\phi_p = 1 - \sum_{i=E+1}^{K} p(i) \cdot (1 - E/i) ,$$

(4.11)

where $\phi_p$ is the average system throughput, expressed as a fraction of its maximum attainable value, and E is the total number of pushers available.

Figure 4.9 depicts the relationship between $\phi_p$ and E for various levels of track utilization $\rho_p$ in a case where K = 12. The curves were obtained with Expr. (4.11).
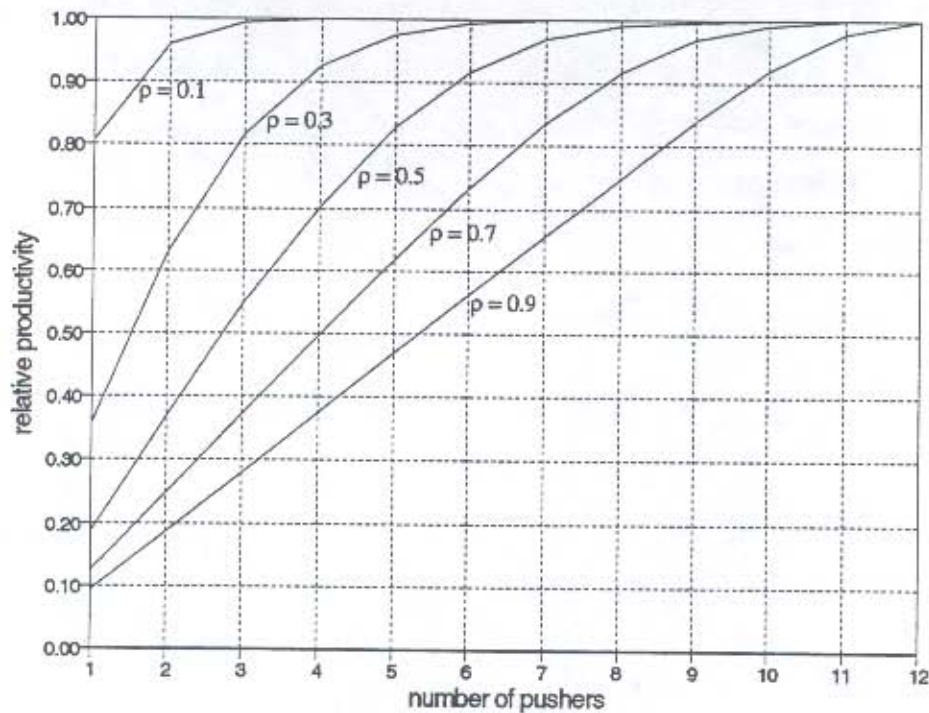


*Figure 4.9: $\phi_p$ as a function of E and $\rho_p$.*

The figure shows that the number of pushers required to serve all tracks without loss in productivity increases with track utilization, as was to be expected.

Note that the expected time required for the pushers to switch tracks should be included in the value of $E[T_p]$. This time will be variable, because the pushers will often have to drive around

railcars on intermediate tracks. It will also depend on the performance characteristics of the pushers, including their acceleration, speed, and time required to hook up and release the railcars.

To illustrate the application of Expr. (4.11), let us consider an example.

*Example*

Consider a direct-transfer terminal where three dock cranes with $t_w = 70$ seconds unload containers onto four tracks each ($N_c = 3$, $K = 12$). Assume that the expected pusher cycle $E[T_p]$ was calculated with Expr. (3.8) and determined to be equal to 70 seconds. In order to calculate the coefficient of utilization for the tracks, we should add to this value the expected time needed by the pushers to switch tracks.

If pushers could switch tracks instantaneously, Expr. (4.9) would give $\rho_p = 0.25$. Figure 4.9 shows that in this (unrealistic) case, three or four pushers would suffice to serve all twelve tracks with no significant loss in throughput.

If the expected time required to switch tracks were equal to 70 seconds, Expr. (4.9) would give $\rho_p = 0.5$, and, according to Figure 4.9, the number of pushers required would be eight or nine.

### 4.5.5. *The effect of Crane Technology*

The direct-transfer system described is the only scheme that requires use of expensive dual-hoist cranes, because of their internal buffering capability. It may be advantageous, however, to deploy dual-hoist cranes for the other schemes as well, because their higher productivity reduces ship turn time and associated inventory costs.

This trade-off is naturally very sensitive to the difference in productivity between the two crane technologies.[33] For the base scenario proposed, using dual-hoist cranes to perform indirect and

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[33] The model assumes 40 and 35 moves per hour for the dual and single-hoist cranes, a difference of 15%. Some authors suggest that, in the future, productivity increases of up to 50% may be attainable (Hochstein, 1988).

semi-direct transfer operations does not affect overall cost. The extra productivity generates savings of about 4 dollars per move, which are counterbalanced by approximately equal additional handling costs.

This conclusion contradicts the general tendency towards taking any measure that reduces the ship turn time, but is corroborated in practice by the fact that very few terminals actually use dual-hoist cranes.

### 4.5.6. The effect of Labor Costs

As was mentioned earlier, the direct-transfer terminal is the least labor-intensive of the three designs, and is thus the least sensistive to increases in labor costs. The semi-direct approach requires many strad drivers and yard clerks, and the indirect approach requires extensive labor to perform the drayage operations. Even considering that road hauler wages are typically lower than those of unionized port workers, both approaches would certainly be adversely affected by labor cost increases.

### 4.5.7. The effect of the Fraction of Intermodal Traffic

When I is low, the cost per move is mostly determined by the domestic operations. The direct-transfer scheme has the highest costs in this case, because it uses more expensive cranes and under-utilized pushers.

As I grows, both the direct and the semi-direct terminals require more land for the rail tracks. This cost is offset, however, by lower transportation costs between the terminal and the rail yard and -- in the case of the direct-transfer terminal -- of the better utilization of specialized intermodal equipment (i. e. pushers and buffered cranes).

Figure 4.10 illustrates these observations. It shows the cost per move for each alternative for varying levels of I, the fraction of intermodal containers.
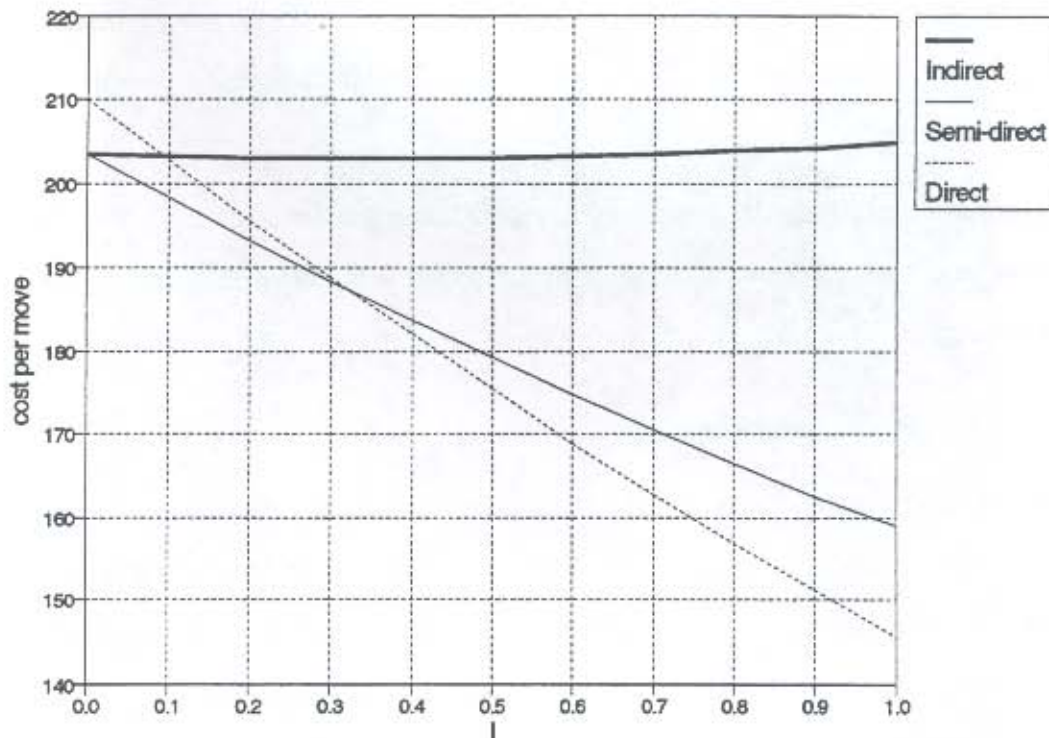
*Figure 4.10: The effect of I on terminal costs*

The figure shows that, for the scenario under study, the indirect-transfer scheme is dominated by the others for all values of I (except when I = 0, in which case the indirect and semi-direct options are identical). When the intermodal fraction is small (less than 0.3), the semi-direct transfer yields the lowest cost. Otherwise, the direct-transfer approach is the most effective alternative.

### 4.5.8. The effect of Terminal Throughput

The difference between the indirect transfer system and the other approaches also depends on the terminal's throughput, which is a function of the size of a typical ship load and on the frequency of ship calls. For a terminal of a given size, higher throughputs generally mean lower costs per move, because fixed costs are spread over more containers.

As discussed in Section 4.4, more frequent ship calls require extra storage area and increase overall land costs for all terminal types (the unit rent costs remain the same). Semi-direct and direct-transfer terminals have an advantage in this respect, however. Because intermodal trains may leave the terminal as soon as the ship is unloaded, extra storage is needed only for domestic containers. Thus, extra ship frequency increases track utilization and reduces unit rent costs for semi-direct and direct-transfer terminals.

Larger ship loads create a need for longer trains and more tracks at the terminal. This could make the indirect transfer scheme more attractive -- because it allows for denser storage -- except for the fact that the extra traffic could create (or intensify) truck congestion at the terminal and surrounding areas.

### 4.5.9. The effect of the Distance Between Terminal and Rail Yard

Longer distances between the terminal and the inland rail yard favor terminals with rail access, because per-mile transportation costs are lower for trains than for trucks. This must always be true, otherwise there would be no justification for long-haul intermodal traffic.

### 4.5.10. Environmental Impacts

Environmental impacts are not included in the model, but they do give a significant advantage to semi-direct and direct schemes. Using rail to perform the short haul segment between the terminal and the remote rail yard would reduce emissions and congestion, as well as increase the safety of the highway system surrounding the port.[34]

Furthermore, if the more direct schemes were found to be significantly more economical than the indirect approach, the intermodal market share would also increase. This would result in some

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[34] The promise of reduced environmental impacts have prompted some European countries to actively promote intermodal transportation over conventional truck-based systems.

decrease in the volume of trucks delivering domestic containers, which would also have positive environmental impacts.

On the reverse side, it should be emphasized that the model does not include the economic and environmental costs of providing the rail access to the terminal.

### 4.5.11. Port Competitiveness Considerations

Despite the difficulty in quantifying these effects in a rational manner, marketing factors are the overriding concern of port planners. If direct-transfer terminals were perceived by shippers to be more efficient or advanced than competing terminals, they would probably be able to gain market share.

The importance of this aspect is illustrated by several examples in practice. A study conducted by the Port of Long Beach recommended an on-dock rail yard based on the fact that competing ports would do so in the near future. The conclusion was that, if Long Beach failed to follow suit, a significant portion of its intermodal traffic would be diverted to competing ports (Ashar, 1991).

### 4.6. Final Observations

Perhaps the most promising advantage of the direct-transfer approach would be a potential reduction in the terminal land requirements and associated rent costs. This would be especially attractive in areas where additional land for rail tracks is too expensive or simply not available and where large numbers of intermodal containers arrive on each ship. To achieve this, the terminal would only provide enough room for a few train segments to be emptied and prepared for reloading at any one time. Some flexibility would be lost, because it would no longer be possible to carry out semi-direct operations at the terminal. On the other hand, the terminal would not need to be modified if longer trains were to be adopted. Also, the terminal land would be used efficiently even if trains of different sizes had to be handled on a regular basis.

The results indicate that the direct-transfer scheme proposed could be a viable option for providing a high-throughput intermodal terminal under appropriate conditions (e.g., existing rail access in the vicinity of the terminal, high levels of intermodal traffic, saturated road system). It is possible that even better alternatives could be developed combining the best features of each terminal. This will be discussed in the last chapter.

# 5. Conclusions and Further Research

This chapter summarizes the results obtained from the present research and suggests topics for future investigation. Section 5.1 presents the main findings from the research, emphasizing how they fit into the global context of container terminal analysis. Section 5.2 discusses topics for future research. Topics are suggested both at a microscopic level, i.e., detailed operational analysis of a single terminal, and at a macroscopic level, examining multi-terminal ports and rail networks.

## 5.1. Main Findings

The main objectives of this research were to investigate the operational feasibility of direct-transfer intermodal container terminals and to determine the conditions under which this option would be economically attractive.

The operational analysis presented in Chapter 3 was developed from a planning perspective. The methods presented are designed to capture the main aspects of the problem with the fewest possible parameters, and are thus best suited for the planning stages of terminal design, when many substantially different options must be investigated without too much concern for detail. The analysis focuses on addressing and quantifying commonly perceived difficulties associated with direct-transfer operations.

### Train Loading and Sorting

The main objection commonly raised against direct-transfer terminals is related to operational difficulties arising from the need to sort trains while loading them, without resorting to intermediate storage buffers and without increasing ship turn time.

The operating strategy described in Section 3.1 accomplishes this objective. Trains are divided into strings of railcars which are sorted as they are loaded. When all strings are loaded, they are

merged to form sorted trains. The sorting level that can be achieved during the unloading operation is measured by the expected number of cuts required per railcar when assembling the trains, $E[C]$. The examples in Section 3.3.1 show that, under typical operating conditions[35], $E[C]$ would be close to 0.1, so, on average, a cut would be required for every 10 cars. The cost of performing these cuts is included in the economic analysis developed in Chapter 4 and discussed below.

The strategy proposed requires the use of double-hoist dock cranes with an internal buffer. The buffer insulates the waterside crane cycles, which have fairly constant duration, from the landside cycles, which are random. To avoid delaying the cranes and increasing ship turn time, the average landside cycles must be shorter than the (assumed constant) waterside cycles. Naturally, the efficiency of the operation described requires that the performance of the dock cranes and pusher tractors be compatible. Methods for evaluating the landside cycles are presented in Section 3.3.2.

Even in situations where the average landside cycles are shorter than the waterside cycles, the crane may be delayed during occasional long landside cycles. The loss of crane productivity due to this phenomenon depends on the variability of the landside cycles and on the size of the internal crane buffer. Section 3.3.3 shows that, under typical operating conditions, a buffer with two or three slots would be enough to reduce crane productivity losses to negligible levels (about 2% or less).

The analysis clearly demonstrates that the operation is technically feasible. Even if the operating conditions are unfavorable (i.e., many intermodal destinations, few tracks), the terminal operator would still be able to unload the ship in a timely manner, by using shorter railcar strings. This,

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[35] By "typical operating conditions" we mean a system with equipment performance parameters comparable to those listed in Section 3.2, six to ten intermodal destinations, one to three tracks per crane, and train segments 15 to 25 railcars long.

however, would result in poorer sorting and extra costs down the line. These costs are included in the economic analysis developed in Chapter 4 and discussed below.

**Land Requirements**

Another common objection against direct-transfer stems from the perception that providing on-dock rail terminals would require too much expensive and scarce waterfront property. The economic analysis presented in Chapter 4 addresses this issue.

The economic analysis compares direct-transfer terminals to two more conventional alternatives: terminals with rail access away from the docks (semi-direct transfer) and terminals without rail access (indirect transfer). The economic model presented includes costs that are often neglected, such as the inventory costs incurred while loaded containers remain in storage or aboard the vessel. Cost components are computed regardless of who incurs them (e.g., the shipper, the terminal operator, the road hauler, or the railroad).

The model shows that direct and semi-direct transfer terminals do tend to have higher rent costs, mainly due to the poor storage density that can be achieved with rail (even using double-stack technology). However, these higher costs are more than offset by significant savings in inventory and handling costs.[36] Savings in handling are mainly due to the elimination of the drayage component of the journey, as was to be expected.

Even though the rent costs are small compared to the other costs components, waterfront property is typically scarce, and may be impossible to purchase or lease regardless of price. In these cases, it may still be possible to implement direct-transfer terminals operating with rail yards located in the vicinity of the terminal. This is possible because the direct-transfer scheme does not require any vehicle traffic between the dock and the rail yard (except of course for the

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[36] This observation holds even for when land is extremely expensive. The base scenario studied in Chapter 4, for example, assumes a land value of $1 million per acre.

railcars and some form of traction). This option would become even more interesting if the rail yard served multiple terminals within a port. This idea is explored further in the next subsection.

**Other Economic Factors**

According to our economic model, the need to perform train cuts under the direct-transfer does not have a great impact on the direct-transfer system costs. It should be noted, however, that this conclusion is based on the assumption that trains are dispatched to their destinations as soon as they are loaded.[37] If loaded railcars were to spend long periods of time waiting for consolidation at the rail yard (in order to form long single-destination trains), the additional costs due to poor railcar utilization and low storage density at the rail yard would be significant. The next subsection elaborates on this issue and suggests ways to deal with this potential problem.

The direct-transfer scheme has the lowest labor costs of the three alternatives, because it does not require drivers for a fleet of trucks or straddle-carriers. The labor costs could be reduced even further if the operation of the pushers and dock crane were to be at least partly automated.

The extra cost of the dual-hoist dock cranes (required by the direct-transfer scheme) is canceled by inventory savings due to their higher productivity and consequent reduction in ship turn time. As a result, the choice of single or dual hoist cranes does not have a significant impact on overall operating costs.

The economic analysis shows that each type of terminal design is most adequate under certain circumstances. The indirect-transfer design, for example, is most effective for terminals where intermodal traffic is low, the cost of providing rail access to the terminal is prohibitive, or if vessel and train schedules were such that other types of transfer would not be effective. The semi-direct and direct-transfer approaches, on the other hand, would be ideal for ports with easy

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[37] This type of operation is not unusual: the Port of Tacoma, for example, operates its North Intermodal Yard in this fashion.

or preexisting rail access, high intermodal throughput, and coordinated vessel and train schedules. Finally, highly automated ports could extract the maximum benefit from the direct-transfer approach by increasing efficiency and reliability while reducing labor costs.

The direct and semi-direct alternatives are by far the best from an environmental viewpoint. Less truck traffic in the vicinity of the terminal would reduce emissions, increase road safety, and reduce congestion. They may also give ports a competitive advantage in terms of marketing which is quite real, although difficult to measure objectively.

## 5.2. Future Research Topics

The research presented indicates that, under favorable conditions, direct-transfer terminals would be a viable option for performing efficient intermodal operations. This subsection discusses issues that would need to be addressed before actually implementing such terminals. These topics for future research are divided in two categories: microscopic and macroscopic studies. The first addresses operational aspects of the operation of a single terminal that were left out of our planning-oriented research. The second examines systems with multi-terminal ports connected to a rail network.

### 5.2.1. Microscopic-Level Research Topics

**Rail Technology**

The current widespread popularity of multi-platform, double-stack railcars should not preclude the development of new types of rail technology. It would probably be difficult to improve these trains significantly in terms of capacity and associated economies of scale that can be attained during the line-haul portions of the transportation process. However, there are alternatives --

available and proposed -- that could perform better by running smaller and more frequent trains.[38]

A good example of innovative rail technology is the "Iron-Highway" concept presented by Stevens and Engle (1991). Iron-highway trains are composed of short, self-powered railcars designed so that containers may span multiple cars. Because they are self-powered, such railcars would eliminate the need for pusher tractors when used with the direct-transfer terminal proposed. The rail tracks along the dock could be designed to sense and control the motion of the railcars.

In recent years, the trend in intermodal container handling has been towards using handling equipment to move containers between railcars rather than cutting and reforming trains. Some reasons for this are the emergence of multi-platform railcars (that cannot be cut) and the fact that containers can be stored more densely on the ground or on chassis than on railcars. It is likely, however, that with new inventory control and terminal operating systems, many intermodal containers will not have to spend much time in storage. Sorting railcars may be more attractive in such cases, especially if new technologies were developed to make the cutting process smoother (to reduce cargo damage) and faster.

## Operating Strategies

The analysis of the direct-transfer operation presented in Chapter 3 was based on a number of conservative assumptions made in order to increase the generality and reduce the complexity of the problem. There are many ways in which particular operations could be significantly improved with respect to the basic strategies described.

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[38] Shorter trains have higher crew costs per box moved, but they can travel at faster speeds and tend to reduce inventory costs. The choice of rail technology can thus be seen as a classic economic order quantity (EOQ) type of problem. Shorter and more frequent trains can provide higher levels of service at higher rates. Longer trains can provide low-cost transportation for low-value items.

For example, more sophisticated procedures could be developed to assign intermodal destinations to loading tracks and containers to railcars within strings. The strategy used by the simulation to perform the latter task is rather simplistic. It consists of pre-defining the block sizes and then sequentially assigning containers to railcars within the appropriate block. Better strategies could be developed to take advantage of short cycles, when the pushers have time to spare, to position the string so as to reduce future long cycles. Figure 5.1 illustrates this point.
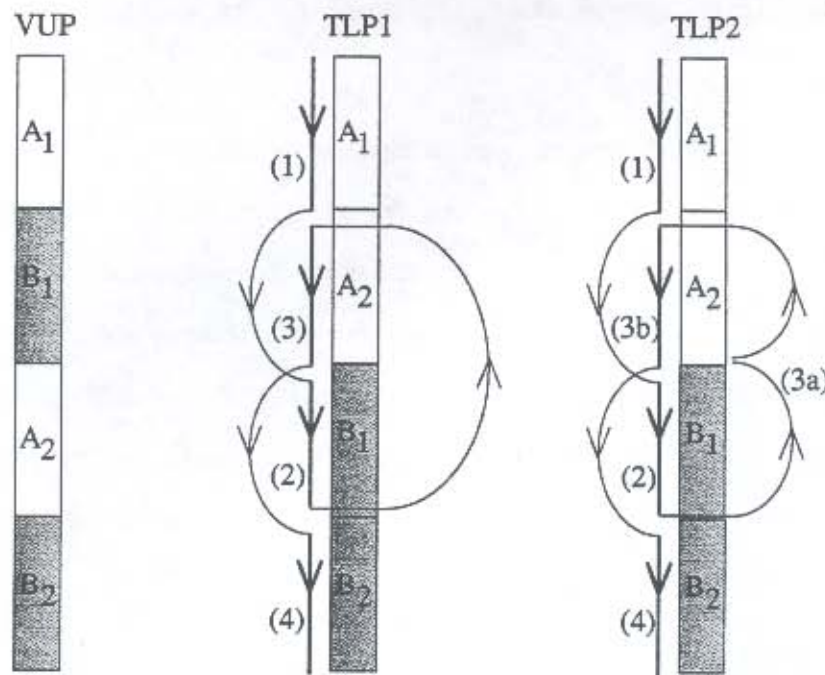


*Figure 5.1: Strategies for Assigning Containers to Railcars*

The figure shows a vessel unloading plan (labeled "VUP") with four batches of containers. The first and third batches ($A_1$ and $A_2$) consist of containers bound for destination A; the second and fourth batches ($B_1$ and $B_2$) are bound for B. The figure also depicts two train loading plans (TLP1 and TLP2) that could be used to produce a sorted train. The arrows in the train loading plans correspond to sequences of pusher moves.

The first train loading plan depicted (TLP1) corresponds to the strategy used by the simulation. It consists of the following steps:

1.  Load batch $A_1$.

2.  Shift the train by one-quarter of its length and load batch $B_1$.

3.  Shift the train by one-half of its length and load batch $A_2$.

4.  Shift the train by one-quarter of its length and load batch $B_2$.

Note that step 3 has a positioning move that requires the pusher to shift the string by half of its length, possibly delaying the crane.

The second unloading plan (TLP2) takes advantage of a short cycle, when the pusher has time to spare, to break step 3 into two steps:

3a. Shift the train by one-quarter of its length and load a single container from batch $A_2$.

3b. Shift the train by one-quarter of its length and load the remaining boxes in batch $A_2$.

This simple example illustrates the type of optimization that could be used to create or improve train loading plans. The problem clearly lends itself to a "minimax" formulation.

Our analysis assumed that the crane buffer would be managed according to a last-in, first-out discipline, so the landside crane spreader had no choice over which box to remove from the buffer. Depending on the design of the buffer, it could be possible to provide spreader access to all containers. This would allow the landside spreader to select the most favorable container from the buffer, effectively reducing the duration of the landside cycles and possibly reducing the required number of cuts required to classify the train.

Finally, we have not considered the fact that, during the vessel unloading process, domestic containers are unloaded intermixed with the intermodal ones. While unloading domestic containers, the crane would give the pushers extra time to perform their task. Depending on the

vessel unloading plan, this could reduce the number of pushers required (see discussion in Section 4.5.4) or allow the operator to use longer strings.

### 5.2.2. *Macroscopic-Level Research Topics*

The analysis presented was restricted in scope to a single terminal. This is justified because, even though ports normally have many terminals, they are often operated independently by different shipping lines and stevedoring companies. One would expect that the efficiency of the whole system could be increased if the activities of all terminals were coordinated. For example, one or more terminals could be especially equipped and dedicated to the handling of intermodal traffic. Vessel schedules could be coordinated among terminals to allow handling equipment, chassis and railcars to be shared among terminals, thus increasing equipment utilization and reducing over-capacity.

The potential benefits of this type of cooperation are so significant that agreements between competing shipping lines are becoming increasingly popular. One typical form of cooperation is cargo-sharing, where shipping lines agree to carry each other's containers aboard their vessels, eliminating overlapping routes and increasing ship utilization (see, for example, Frankel, 1981). It is also common for a shipping line to receive and handle a competitor's vessel at their private terminal, provided of course that there is capacity available.

An important topic for future research would be to investigate how to extract the maximum benefit from this type of cooperation. Figure 5.2 depicts one possible scenario:
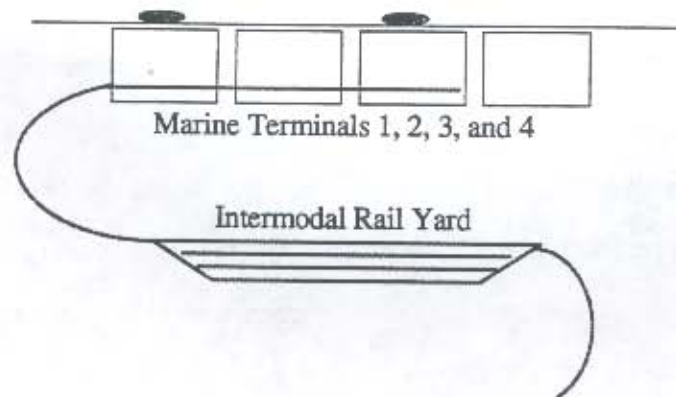
*Figure 5.2: A Multi-Terminal Port System*

The figure shows four terminals served by a common intermodal rail yard. Vessels would call at each terminal and intermodal boxes would be dispatched by truck or rail to the rail yard. There trains would be formed and dispatched according to one of the following strategies:

1. Hold boxes from many ships and consolidate them to form long single-destination trains.

2. Dispatch many small single-destination trains after each ship call

3. Dispatch a single long train with multiple destinations after each ship call.

Each strategy has its strengths and drawbacks, as summarized below:

| Strategy | Train crew costs | Rent+inventory costs | Train cuts, trip time |
|----------|------------------|----------------------|-----------------------|
| 1 | low | HIGH | low |
| 2 | HIGH | low | low |
| 3 | low | low | HIGH |

It is very likely that the best option would be a combination of the above strategies. The direct-transfer terminal proposed would be most suitable under options (2) and (3), because containers would arrive from the marine terminal already on railcars and ready to be dispatched.

If strategy (1) were to be adopted, it could be advantageous to remove the boxes from the railcars and store them in stacks in order to reduce the land requirements at the rail yard and to avoid tying up railcars for long periods of time. In this case, there would be a fleet of railcars being constantly shuttled back and forth between the terminals and the rail yard. These railcars could be especially designed to facilitate the direct-transfer operation. For example, they could be self-powered, automated vehicles.

The container industry is growing and changing very rapidly. Much research is needed in order to develop systems that are efficient, reliable, and non-disruptive to their surroundings. This study is a contribution in that direction.

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## Appendix I - List of Symbols

$\alpha$    Coefficient used to calculate $\phi$.

$\alpha'$    Calibrated coefficient used to calculate $\phi$.

$\gamma$    Coefficient of variation of of the landside cycle times (mean to standard deviation ratio).

$\phi$    Fraction of the maximum possible throughput attainable by the direct-transfer system due to limitations in the size of the crane buffer.

$\phi_p$    Fraction of the maximum possible throughput attainable by the direct-transfer system due to limitations in the availability of pusher tractors.

$\rho$    Ratio of average landside to waterside cycle times.

$\rho_p$    Track utilization.

A    Number of import containers in a typical shipload.

B    Capacity of the crane buffer.

C    Number of cuts required per railcar.

C'    Number of cuts required per container.

$C_c$    Cost of a single-hoist dock crane move.

$C_c'$    Cost of a double-hoist dock crane move.

$C_d$    Cost of transporting a container from the marine terminal to the intermodal rail yard by truck (drayage cost).

$C_{Dh}$ Handling cost for moving an average container through a direct-transfer terminal.

$C_{Di}$ Inventory cost for moving an average container through a direct-transfer terminal.

$C_{Dr}$ Rent cost for moving an average container through a direct-transfer terminal.

$C_i$    Cost of holding a loaded container for one hour.

$C_i$    Hourly cost of holding a loaded container.

$C_{Ih}$    Handling cost for moving an average container through an indirect-transfer terminal.

$C_{Ii}$    Inventory cost for moving an average container through an indirect-transfer terminal.

$C_{Ir}$    Rent cost for moving an average container through an indirect-transfer terminal.

$C_r$    Hourly cost of holding an empty railcar.

$C_s$    Cost of a "regular" straddle-carrier move.

$C_{Sh}$ Handling cost for moving an average container through a semi-direct transfer terminal.

$C_{Si}$ Inventory cost for moving an average container through a semi-direct transfer terminal.

$C_{Sr}$ Rent cost for moving an average container through a semi-direct transfer terminal.

$C_u$    Cost of performing one train cut (at the terminal or at the rail yard).

$C_v$    Hourly cost of holding a loaded vessel.

D    The total number of intermodal destinations.

E    The total number of pusher tractors available.

H    Time between ship arrivals (headway).

I     Fraction of intermodal containers in a ship.

k    Number of blocks that must be pushed under the crane in order to position a string of railcars.

K    The number of rail tracks available under each dockside crane.

$k_d$    Ratio between rail and truck transportation costs.

$k_s$    Ratio between the cost of intermodal and "regular" straddle-carrier moves.

L    Distance between the marine terminal and the inland intermodal rail yard.

n    Number of blocks (or, equivalently, destinations present) in a string of railcars.

N    Number of intermodal import containers on a typical ship. Also used to represent the maximum accumulation of containers at the terminal.

n    Time (in headways) required to remove all domestic containers from on-terminal storage.

n'    Time (in headways) required to remove all intermodal containers from on-terminal storage.

$N_c$    Number of dockside cranes.

$N_i$    Number of intermodal import containers bound for destination i on a typical ship.

P    A parameter capturing the probability that the next container to be unloaded off the ship has the same destination as its predecessor.

$P_c$    Productivity of a dockside crane (moves per hour).

$P_i$    Probability of an "intermediate" pusher cycle.

$P_l$    Probability of a "long" pusher cycle.

$P_s$    Probability of a "short" pusher cycle.

r    Average number of railcars in a block.

S    The number of railcars on a direct-transfer string.

T    Duration of a landside cycle.

$T_i$    Duration of an "intermediate" pusher cycle.

$t_k$    Time to move the landside crane spreader over one rail track.

$T_l$    Duration of a "long" pusher cycle.

$t_l$    Time to lift or lower the landside crane spreader.

$T_p$    Duration of a pusher cycle.

$t_p$    Time it takes the pusher to move the train segment by one railcar.

$T_s$    Duration of a "short" pusher cycle.

$t_s$    Time to set or pick a container on the crane buffer or on a railcar.

$t_u$    Time needed to perform one train cut (at the terminal or at the rail yard).

$t_w$   Cycle time for the waterside crane spreader (assumed constant).

V   Average speed of a truck.

$V_t$   Average speed of a train.

## Appendix II - Simulation Program

```
/*

  DT.C
  --------

  Direct Vessel-to-Rail Transfer Operation.
  Uses the MOSAIC simulation library.

*/

#include <stdlib.h>
#include <stdio.h>
#include <assert.h>
#include <mosaic.h>

/* performance and geometry *****************************************/
//#define CYCLE
#ifdef CYCLE
#define SHIPCRANECYCLE    30    /* seconds (120 normally) */
#else
#define SHIPCRANECYCLE    90    /* seconds (120 normally) */
#endif
#define PICKFROMSHIP       5    /* seconds */
#define DROPINBUFFER       5    /* seconds */
#define PICKFROMBUFFER     5    /* seconds */
#define SETONCAR           5    /* seconds */
#define TCRANEGANTRYSP   3.0    /* in feet/second */
#define PUSHERSPEED      4.0    /* in feet/second (6.667 in TICTF) */

#define APRON             15    /* distance from buffer to track 0 (ft)
*/
#define MINTCTIME         15    /* min time for crane to lower spreader
*/
#define INTERTRACK        15    /* in feet */
#define CARLENGTH         60    /* in feet */


/* constants and limits *********************************************/
#define TRUE       1
#define FALSE      0
#define MAXT      12               /* maximum number of tracks */
#define MAXD      50               /* maximum number of destinations */
#define MAXDICON   8               /* number of destination-coded icons */
#define MAXBUFF   30


/* signals *********************************************************/
#define BOXINBUFFER  1000000L   /* signal */
#define BOXOFFBUFFER 1000001L   /* signal */
#define TRACKSIGNAL  2000000L   /* signal */


/* icons *********************************************************/
#define IC_NOTHING   -1
#define IC_ESPREADER  0
#define IC_LSPREADER  1
#define IC_ARROW      2
#define IC_BOX        3
```

```
#define IC_EMPTYCAR    4
#define IC_LOADEDCAR   5

/* data structure definition ******************************************/
struct PLANLINE {
  int dest,                    /* destination for the box */
      track,                   /* assigned track */
      order;
};

struct TRACK {
  int currpos,                 /* current car under crane */
      movesleft,               /* moves remaining */
      planptr;                 /* next box in the plan */
};


/* simulation structures **********************************************/
struct QUEUE *CraneBuffer,     /* where containers wait for service */
             *OverShip,        /* ship crane over ship hold */
             *OverBuffer,      /* ship crane over box buffer */
             *TrainCrane,      /* measure train crane ut */
             *Pusher,          /* measure pusher ut */
             *AtBuffer,        /* train crane at box buffer */
             **AtTrack,        /* train crane at a track */
             **PusherStat,     /* show active pushers */
             **TrackPlan;      /* pushers need to know who's coming */

struct PLANLINE *Plan;         /* ship unloading plan */

struct TRACK Track[MAXT];      /* keep track of tracks */

int TrackPop[MAXT],            /* current population of each track */
    TrackAsg[MAXT][MAXD],      /* dynamic assignment */
    BuffPop[MAXBUFF+1],        /* track buffer frequency */
    CurrTrack,
    CurrDest;

int LastTrack = -1,            /* used to track landside cycles */
    LastDest[MAXT],
    PrintCycles;

/* input data *********************************************************/
int N = 1500,                  /* number of boxes arriving */
    S = 20,                    /* length of a string */
    D = 3,                     /* number of destinations */
    T = 2,                     /* number of tracks per crane */
    P = 20;                    /* prob of same destination for next box */


/* output *************************************************************/
int CutsReq = 0,               /* total number of cuts required */
    NMoves = 0;                /* count actual moves */


/*-------------------------------------------------------------
  createPlan
  ----------
  Allocates memory for the plan vector and initializes it
  by creating random destinations.
*/
```

```
void createPlan (void) {
  static dest = -1;
  int box;

  /* allocate memory for plan */
  Plan = calloc (N, sizeof (struct PLANLINE));
  if (!Plan) {
    printf ("\nOut of memory");
    exit (1);
  }

  /* randomize boxes into plan */
  for (box = 0; box < N; box++) {
    if (dest < 0 || uniform (0, 100) > P)
      dest = random (D);
    Plan[box].dest = dest;
  }
} /* createPlan */


/*---------------------------------------------------------------
  selectTrack
  -----------
  Selects a track for the current box, based on its
  destination and on the state of the system.
*/
int selectTrack (int d) {
  int t, track, tot;

  /* if d is already assigned to a track, return it */
  for (t = 0; t < T; t++)
    if (TrackAsg[t][d] > 0)
      return t;

  /* not assigned yet, so assign it now */
  track = 0;
  tot = TrackAsg[track][D];
  for (t = 1; t < T; t++)
    if (TrackAsg[t][D] < tot) {
      track = t;
      tot = TrackAsg[track][D];
    }

  /* update structures */
  CutsReq++;
  TrackAsg[track][D]++;
  TrackAsg[track][d] = TrackAsg[track][D];

  /* return the track selected */
  return track;
} /* selectTrack */


/*---------------------------------------------------------------
  assignTracks
  ------------
  Loops through all boxes in the plan and assigns them to
  their corresponding tracks.
*/
void assignTracks (void) {
  int box, track, dest;
```

```
    for (box = 0; box < N; box++) {
      track = selectTrack (Plan[box].dest);
      Plan[box].track = track;
      Plan[box].order = -TrackAsg[track][Plan[box].dest];
      TrackPop[track]++;
      if (TrackPop[track] >= S) {
        TrackPop[track] = 0;
        for (dest = 0; dest <= D; dest++)
        TrackAsg[track][dest] = 0;
        Plan[box].track += MAXT;
      }
    }
} /* assignTracks */


/*-------------------------------------------------------------
  fillTrackPlan
  -------------
  Selects the next S (or possibly less) boxes from the
  plan and places then in the TrackPlan queue.

  Advances the track's plan pointer and resets the
  track's current position and amount of work to be done.
*/
void fillTrackPlan (int t) {
  int i;
  struct ENTITY *box;

  Track[t].currpos = Track[t].movesleft = 0;

  for (i = Track[t].planptr; i < N; i++) {

    /* ignore other tracks */
    if (Plan[i].track % MAXT != t) continue;

    /* add container to plan (sorted by destination) */
    Track[t].movesleft++;
    box = new_entity (i, Plan[i].order, 0, NULL);
    box->icon = IC_EMPTYCAR;
    dropinq (box, TrackPlan[t]);

    /* stop if last in block */
    if (Plan[i].track >= MAXT) {
      i++;
      break;
    }
  }
  Track[t].planptr = i;
} /* fillTrackPlan */


/*-------------------------------------------------------------
  nextBox
  -------
  Returns the position within the block where the next box
  must be placed (or -1 if the plan is empty).

  Entities in the plan queue are sorted by destination and
  have type=service order.  To find the next one, scan the
  list for the smallest order.  Ignore entities with icon
  IC_LOADEDCAR, because they have been serviced.
*/
```

```c
int nextBox (int t) {
  struct ENTITY *box;
  int i,
      minorder = N + 1,
      retval = -1;

  for (i = 0; i < qpop (TrackPlan[t]); i++) {
    box = entinq (TrackPlan[t], i);
    if (box->icon >= IC_LOADEDCAR) continue;
    if (box->type < minorder) {
      minorder = box->type;
      retval = i;
    }
  }
  return retval;
} /* nextBox */


/*----------------------------------------------------------------
  checkBoxOff
  -----------
  Marks the currently active box in the plan as serviced
  by changing its type to N + 1 and decrements the
  number of moves remaining for the track.
*/
void checkBoxOff (int t) {
  struct ENTITY *box;
  int icon;

  box = entinq (TrackPlan[t], nextBox (t));
  icon = IC_LOADEDCAR + Plan[box->type].dest % MAXDICON;
  set_icon (box, icon, TrackPlan[t]);
  Track[t].movesleft--;
} /* checkBoxOff */


/*----------------------------------------------------------------
  dispatchBlock
  -------------
  Resets a track and returns the time required to move it
  out of the sorting area.
*/
TIMETYPE dispatchBlock (int t) {
  struct ENTITY *box;
  int ncars = 0;
  TIMETYPE time;

  /* get rid of the entities first (and count them) */
  while (qpop (TrackPlan[t])) {
    box = qhead (TrackPlan[t]);
    leaveq (box, TrackPlan[t]);
    free (box);
    ncars++;
  }

  /* calculate time to move out */
  time = ncars - Track[t].currpos;
  assert (time <= S);
  time = (time * CARLENGTH) / PUSHERSPEED;

  /* done */
  return time;
```

```
} /* dispatchBlock */


/*==============================================================
   shipCrane
   ---------
   Simulation script for the (single) ship crane
*/
void shipCrane (struct ENTITY *e) {
    static struct ENTITY *box;
    int p;

    SCRIPT (e)

      /* initialize crane entity */
      e->icon = IC_ESPREADER;
      enterq (e, OverShip);

      /* loop over the whole plan */
      for (NMoves = 0; NMoves < N; NMoves++) {

        /* create a box */
        box = new_entity (NMoves, 0, 0, NULL);
        box->icon = IC_BOX;
        CurrTrack = Plan[box->type].track % MAXT + 1;
        CurrDest  = Plan[box->type].dest  % MAXD + 1;

        /* carry it to the buffer */
        set_icon (e, IC_LSPREADER, OverShip);
        transferb (e, OverShip, OverBuffer, SHIPCRANECYCLE / 2);
        dropinq (box, CraneBuffer);
        p = qpop (CraneBuffer);
        if (p > MAXBUFF)
          p = MAXBUFF;
        BuffPop[p]++;
#ifdef CYCLE
        while (qpop (CraneBuffer) > 30)
          wait (e, BOXOFFBUFFER);
#endif
        delayent (e, DROPINBUFFER);
        set_icon (e, IC_ESPREADER, OverBuffer);

        /* signal train crane */
        send_signal (BOXINBUFFER, 1);

        /* trolley back to the ship */
        transferb (e, OverBuffer, OverShip, SHIPCRANECYCLE / 2);
        delayent (e, PICKFROMSHIP);

      } /* for */

      /* all done, destroy crane */
      leaveq (e, OverShip);
      dispose (e);

    ENDSCRIPT
} /* shipCrane */


/*==============================================================
   trainCrane
   ----------
```

```
    Simulation script for the (single) train crane
*/
void trainCrane (struct ENTITY *e) {
    static struct ENTITY *box;
    static int track;
    static TIMETYPE time, stime;
    static int ctrack, cdest;

    SCRIPT (e)

      /* initialize */
      e->icon = IC_ESPREADER;
      enterq (e, AtBuffer);

      /* eternal loop */
      for (;;) {

        /* wait until a box is available at the buffer */
        while (qpop (CraneBuffer) == 0)
        wait (e, BOXINBUFFER);
        enterq (e, TrainCrane);

        /* save info to print cycle times */
        box = qhead (CraneBuffer);
        stime = TimeNow;
        ctrack = Plan[box->type].track % MAXT;
        cdest  = Plan[box->type].dest  % MAXD;

        /* take box out of the buffer */
        box = qhead (CraneBuffer);
        leaveq (box, CraneBuffer);
        send_signal (BOXOFFBUFFER, 1);
        set_icon (e, IC_LSPREADER, AtBuffer);
        delayent (e, PICKFROMBUFFER);

        /* take box to the appropriate track */
        track = Plan[box->type].track % MAXT;
        time = (APRON + track * INTERTRACK) / TCRANEGANTRYSP;
        if (time < MINTCTIME)
          time = MINTCTIME;
        transferb (e, AtBuffer, AtTrack[track], time);

        /* signal track and wait for handshake with pusher */
        send_signal (TRACKSIGNAL + track, 1);
        wait (e, TRACKSIGNAL + track);

        /* set track on rail car and free pusher */
        delayent (e, SETONCAR);
        send_signal (TRACKSIGNAL + track, 1);

        /* box moved, trolley back to the buffer */
        free (box);
        set_icon (e, IC_ESPREADER, AtTrack[track]);
        transferb (e, AtTrack[track], AtBuffer, time);
        leaveq (e, TrainCrane);

        /* print cycle time if requested */
        if (!PrintCycles) continue;
        if (LastTrack == -1) {
          LastTrack = ctrack;
          continue;
        }
```

```c
        if (LastTrack == ctrack) {
          if (LastDest[ctrack] == cdest)
            printf ("\n\"stsd\",");
          else
            printf ("\n\"stod\",");
        } else {
          if (LastDest[ctrack] == cdest)
            printf ("\n\"otsd\",");
          else
            printf ("\n\"otod\",");
        }
        printf (" %lu", TimeNow - stime);
        LastTrack = ctrack;
        LastDest[ctrack] = cdest;
      } /* eternal for */
    ENDSCRIPT
} /* trainCrane */


/*================================================================
   trainPusher
   -----------
   Simulation script for the pushers (one per track)
*/
void trainPusher (struct ENTITY *e) {
   static int box;
   static int track = 0;
   TIMETYPE time;

   SCRIPT (e)

     /* initialize */
     e->type = track++;
     enterq (e, PusherStat[e->type]);

     /* eternal loop */
     for (;;) {

       /* fill current track plan */
       fillTrackPlan (e->type);

       /* find position of next box to arrive */
       FINDBOX:
       box = nextBox (e->type);
       if (box < 0) break;

       /* position block to receive the box */
       set_icon (e, IC_ARROW, PusherStat[e->type]);
       time = abs (box - Track[e->type].currpos);
       assert (time <= S);
       time = (time * CARLENGTH) / PUSHERSPEED;
       set_icon (e, IC_ARROW, PusherStat[e->type]);
       delayent (e, time);
       set_icon (e, IC_NOTHING, PusherStat[e->type]);
       Track[e->type].currpos = nextBox (e->type);

       /* ready with this: wait for train crane to arrive, handshake */
       if (e->user)
         leaveq (e, Pusher);
       if (qpop (AtTrack[e->type]) == 0)
       wait (e, TRACKSIGNAL + e->type);
       send_signal (TRACKSIGNAL + e->type, 1);
```

```c
            /* wait for train crane to set box on car */
            wait (e, TRACKSIGNAL + e->type);

            /* check box off track plan */
            checkBoxOff (e->type);

            /* start next: if block is not done, go find next box */
            e->user = 1;
            enterq (e, Pusher);
            if (Track[e->type].movesleft)
            goto FINDBOX;

            /* dispatch block and loop */
            set_icon (e, IC_ARROW, PusherStat[e->type]);
            time = dispatchBlock (e->type);
            delayent (e, time);
            set_icon (e, IC_NOTHING, PusherStat[e->type]);
        } /* eternal for */

        /* all done, destroy pusher */
        leaveq (e, Pusher);
        leaveq (e, PusherStat[e->type]);
        dispose (e);

    ENDSCRIPT
} /* trainPusher */


void Pointer (void) {
    char *formstr = "   `Go On  `Exit   ";
    struct FIELD f[2];

    defbuttonb (f, " Go On ");
    defbuttonb (f + 1, " Exit ");
    doform (0, 0, formstr, f, 0, NULL, 1);
    if (LastField == 1)
        TimeEnd = TimeNow;
} /* Pointer */


/*-------------------------------------------------------------
    Main Program
*/
void main (int argc, char *argv[]) {
    int i, ctr, b90, b95, b99;

    /* read parameters from command line */
    if (argc < 6) {
#ifdef CYCLE
        printf ("\nUse: CYC N S D T P [x]"
#else
        printf ("\nUse: DT N S D T P"
#endif
            "\nwhere"
            "\n  N is the number of containers to be unloaded"
            "\n  S is the number of boxes per string of railcars"
            "\n  D is the number of destinations"
            "\n  T is the number of available tracks"
            "\n  P is the probability that a box has the same"
            "\n    destination as its predecessor"
            "\n  x nothing runs animation"
```

```
                "\n      'c' forces printing of landside cycles"
                "\n        anything else runs terse simulation\n\n");
        exit (0);
    }
    N = atoi (argv[1]);
    S = atoi (argv[2]);
    D = atoi (argv[3]);
    T = atoi (argv[4]);
    P = atoi (argv[5]);
    if (argc > 6 && *argv[6] == 'c')
        PrintCycles = 1;

    /* initialize */
    randomize ();            /* random number generator */
    createPlan ();           /* create unloading plan (Plan) */
    assignTracks ();         /* assign tracks */

    /* create queues */
    TrainCrane = new_queue ("Train Crane",   INFINITE_CAP, Q_STATS);
    Pusher =    new_queue ("Pusher",         INFINITE_CAP, Q_STATS);
    CraneBuffer = new_queue ("Buffer",       INFINITE_CAP, Q_ANIM |
Q_STATS);
    OverShip    = new_queue ("OverShip",     INFINITE_CAP, Q_ANIM);
    OverBuffer  = new_queue ("OverBuff",     INFINITE_CAP, Q_ANIM);
    AtBuffer    = new_queue ("AtBuffer",     INFINITE_CAP, Q_ANIM);
    AtTrack     = new_qblock (MAXT, "AtTrack", INFINITE_CAP, Q_ANIM);
    PusherStat  = new_qblock (MAXT, "Pusher" , INFINITE_CAP, Q_ANIM);
    TrackPlan   = new_qblock (MAXT, "TrkPlan", INFINITE_CAP, Q_ANIM);

    /* create cranes and pushers */
    createb (1, 0, shipCrane);
    createb (1, 0, trainCrane);
    createb (T, 0, trainPusher);

    /* run simulation */
    if (argc == 6) {
        linkvar (&NMoves,    0);
        linkvar (&CurrTrack, 1);
        linkvar (&CurrDest,  2);
        linkvar (&TimeNow,   3);
        animate (0, INFINITE_TIME, "dt.prs", 1, 0, Pointer);
    } else
        simulate (0, INFINITE_TIME);
    printf ("\n\nDone:"
        "\n%5d boxes unloaded"
        "\n%5d destinations ( sorting level %d %% )"
        "\n%5d tracks"
        "\n%5d block size"
        "\n%5d number of cuts required ( %5.3lf cuts/box )\n\n",
        NMoves, D, P, T, S, CutsReq, CutsReq / (double) NMoves);

    ctr = b90 = b95 = b99 = 0;
    for (i = 0; i < MAXBUFF; i++) {
        ctr += BuffPop[i];
        if (b90 == 0 && ctr >= N * 0.90)
            b90 = i;
        if (b95 == 0 && ctr >= N * 0.95)
            b95 = i;
        if (b99 == 0 && ctr >= N * 0.99) {
            b99 = i;
            break;
        }
```

```
      }
      printf ("\nBuffer Utilization"
              "\nB90= %d B95= %d B99= %d", b90, b95, b99);
      show_stats ("DT simulation results", "", stdout);
    } /* main */
```

# Appendix III - Sample Simulation Output

```
DT 1000 20 6 2 50 (command line)
...
Done:
 1000 boxes unloaded
    6 destinations ( sorting level 50 % )
    2 tracks
   20 block size
  147 number of cuts required ( 0.147 cuts/box )


Buffer Utilization
B90= 1 B95= 1 B99= 1
```

```
MOSAIC v 2.01       Result Summary
```

| Project | DT simulation results |
|---|---|
| Run ID | |
| Time, Date | Mon Apr 13 23:19:52 1992 |
| Run ended at time | 100050 |
| Entities created | 2004 (2001 remaining) |
| Elapsed Time | 00:00:17.30 |

```
                          Queues
```

**Gross number of entities:**

| NAME | MIN | AVG | MAX | STD |
|---|---|---|---|---|
| Train Crane | 0 | 0.47 | 1 | 0.50 |
| Pusher | 0 | 0.51 | 2 | 0.56 |
| Buffer | 0 | 0.07 | 2 | 0.27 |

**Net number of entities:**

| NAME | MIN | AVG | MAX | STD |
|---|---|---|---|---|
| Train Crane | 1 | 1.00 | 1 | 0.00 |
| Pusher | 1 | 1.06 | 2 | 0.24 |
| Buffer | 1 | 1.02 | 2 | 0.15 |

**Gross Dwell Times:**

| NAME | MIN | AVG | MAX | STD | NOBS |
|---|---|---|---|---|---|
| Train Crane | 40 | 47.02 | 215 | 23.05 | 1000 |
| Pusher | 15 | 51.33 | 255 | 57.90 | 1000 |
| Buffer | 0 | 7.33 | 190 | 12.79 | 1000 |

**Net Dwell Times:**

| NAME | MIN | AVG | MAX | STD | NOBS |
|---|---|---|---|---|---|
| Train Crane | 40 | 47.02 | 215 | 23.05 | 1000 |
| Pusher | 15 | 51.33 | 255 | 57.90 | 1000 |
| Buffer | 5 | 7.46 | 190 | 12.87 | 982 |

# Appendix IV - Simulation Data Sets

Data set #1:

| Run# | D | T | S | P |
|---|---|---|---|---|
| 1 | 2 | 2 | 15 | 5% |
| 2 | 2 | 2 | 15 | 25% |
| 3 | 2 | 2 | 15 | 50% |
| 4 | 2 | 2 | 15 | 75% |
| 5 | 2 | 2 | 15 | 95% |
| 6 | 4 | 2 | 15 | 5% |
| 7 | 4 | 2 | 15 | 25% |
| 8 | 4 | 2 | 15 | 50% |
| 9 | 4 | 2 | 15 | 75% |
| 10 | 4 | 2 | 15 | 95% |
| 11 | 4 | 4 | 15 | 5% |
| 12 | 4 | 4 | 15 | 25% |
| 13 | 4 | 4 | 15 | 50% |
| 14 | 4 | 4 | 15 | 75% |
| 15 | 4 | 4 | 15 | 95% |
| 16 | 8 | 2 | 15 | 5% |
| 17 | 8 | 2 | 15 | 25% |
| 18 | 8 | 2 | 15 | 50% |
| 19 | 8 | 2 | 15 | 75% |
| 20 | 8 | 2 | 15 | 95% |
| 21 | 8 | 4 | 15 | 5% |
| 22 | 8 | 4 | 15 | 25% |
| 23 | 8 | 4 | 15 | 50% |
| 24 | 8 | 4 | 15 | 75% |
| 25 | 8 | 4 | 15 | 95% |
| 26 | 8 | 6 | 15 | 5% |
| 27 | 8 | 6 | 15 | 25% |
| 28 | 8 | 6 | 15 | 50% |
| 29 | 8 | 6 | 15 | 75% |
| 30 | 8 | 6 | 15 | 95% |
| 31 | 12 | 2 | 15 | 5% |
| 32 | 12 | 2 | 15 | 25% |
| 33 | 12 | 2 | 15 | 50% |
| 34 | 12 | 2 | 15 | 75% |
| 35 | 12 | 2 | 15 | 95% |
| 36 | 12 | 4 | 15 | 5% |
| 37 | 12 | 4 | 15 | 25% |
| 38 | 12 | 4 | 15 | 50% |
| 39 | 12 | 4 | 15 | 75% |
| 40 | 12 | 4 | 15 | 95% |
| 41 | 12 | 6 | 15 | 5% |
| 42 | 12 | 6 | 15 | 25% |
| 43 | 12 | 6 | 15 | 50% |
| 44 | 12 | 6 | 15 | 75% |
| 45 | 12 | 6 | 15 | 95% |
| 46 | 2 | 2 | 20 | 5% |
| 47 | 2 | 2 | 20 | 25% |
| 48 | 2 | 2 | 20 | 50% |
| 49 | 2 | 2 | 20 | 75% |
| 50 | 2 | 2 | 20 | 95% |
| 51 | 4 | 2 | 20 | 5% |
| 52 | 4 | 2 | 20 | 25% |
| 53 | 4 | 2 | 20 | 50% |
| 54 | 4 | 2 | 20 | 75% |
| 55 | 4 | 2 | 20 | 95% |
| 56 | 4 | 4 | 20 | 5% |
| 57 | 4 | 4 | 20 | 25% |
| 58 | 4 | 4 | 20 | 50% |
| 59 | 4 | 4 | 20 | 75% |
| 60 | 4 | 4 | 20 | 95% |
| 61 | 8 | 2 | 20 | 5% |
| 62 | 8 | 2 | 20 | 25% |
| 63 | 8 | 2 | 20 | 50% |
| 64 | 8 | 2 | 20 | 75% |
| 65 | 8 | 2 | 20 | 95% |
| 66 | 8 | 4 | 20 | 5% |
| 67 | 8 | 4 | 20 | 25% |
| 68 | 8 | 4 | 20 | 50% |
| 69 | 8 | 4 | 20 | 75% |
| 70 | 8 | 4 | 20 | 95% |
| 71 | 8 | 6 | 20 | 5% |
| 72 | 8 | 6 | 20 | 25% |
| 73 | 8 | 6 | 20 | 50% |
| 74 | 8 | 6 | 20 | 75% |
| 75 | 8 | 6 | 20 | 95% |
| 76 | 12 | 2 | 20 | 5% |
| 77 | 12 | 2 | 20 | 25% |
| 78 | 12 | 2 | 20 | 50% |
| 79 | 12 | 2 | 20 | 75% |
| 80 | 12 | 2 | 20 | 95% |
| 81 | 12 | 4 | 20 | 5% |
| 82 | 12 | 4 | 20 | 25% |
| 83 | 12 | 4 | 20 | 50% |
| 84 | 12 | 4 | 20 | 75% |
| 85 | 12 | 4 | 20 | 95% |
| 86 | 12 | 6 | 20 | 5% |
| 87 | 12 | 6 | 20 | 25% |
| 88 | 12 | 6 | 20 | 50% |

| | | | | |
|---|---|---|---|---|
| 89 | 12 | 6 | 20 | 75% |
| 90 | 12 | 6 | 20 | 95% |
| 91 | 2 | 2 | 25 | 5% |
| 92 | 2 | 2 | 25 | 25% |
| 93 | 2 | 2 | 25 | 50% |
| 94 | 2 | 2 | 25 | 75% |
| 95 | 2 | 2 | 25 | 95% |
| 96 | 4 | 2 | 25 | 5% |
| 97 | 4 | 2 | 25 | 25% |
| 98 | 4 | 2 | 25 | 50% |
| 99 | 4 | 2 | 25 | 75% |
| 100 | 4 | 2 | 25 | 95% |
| 101 | 4 | 4 | 25 | 5% |
| 102 | 4 | 4 | 25 | 25% |
| 103 | 4 | 4 | 25 | 50% |
| 104 | 4 | 4 | 25 | 75% |
| 105 | 4 | 4 | 25 | 95% |
| 106 | 8 | 2 | 25 | 5% |
| 107 | 8 | 2 | 25 | 25% |
| 108 | 8 | 2 | 25 | 50% |
| 109 | 8 | 2 | 25 | 75% |
| 110 | 8 | 2 | 25 | 95% |
| 111 | 8 | 4 | 25 | 5% |
| 112 | 8 | 4 | 25 | 25% |
| 113 | 8 | 4 | 25 | 50% |
| 114 | 8 | 4 | 25 | 75% |
| 115 | 8 | 4 | 25 | 95% |
| 116 | 8 | 6 | 25 | 5% |
| 117 | 8 | 6 | 25 | 25% |
| 118 | 8 | 6 | 25 | 50% |
| 119 | 8 | 6 | 25 | 75% |
| 120 | 8 | 6 | 25 | 95% |
| 121 | 12 | 2 | 25 | 5% |
| 122 | 12 | 2 | 25 | 25% |
| 123 | 12 | 2 | 25 | 50% |
| 124 | 12 | 2 | 25 | 75% |
| 125 | 12 | 2 | 25 | 95% |
| 126 | 12 | 4 | 25 | 5% |
| 127 | 12 | 4 | 25 | 25% |
| 128 | 12 | 4 | 25 | 50% |
| 129 | 12 | 4 | 25 | 75% |
| 130 | 12 | 4 | 25 | 95% |
| 131 | 12 | 6 | 25 | 5% |
| 132 | 12 | 6 | 25 | 25% |
| 133 | 12 | 6 | 25 | 50% |
| 134 | 12 | 6 | 25 | 75% |
| 135 | 12 | 6 | 25 | 95% |
| 136 | 12 | 2 | 30 | 75% |
| 137 | 12 | 2 | 30 | 95% |
| 138 | 12 | 4 | 30 | 5% |
| 139 | 12 | 4 | 30 | 25% |
| 140 | 12 | 4 | 30 | 50% |
| 141 | 12 | 4 | 30 | 75% |
| 142 | 12 | 4 | 30 | 95% |
| 143 | 12 | 6 | 30 | 5% |
| 144 | 12 | 6 | 30 | 25% |
| 145 | 12 | 6 | 30 | 50% |
| 146 | 12 | 6 | 30 | 75% |
| 147 | 12 | 6 | 30 | 95% |
| 148 | 2 | 2 | 35 | 5% |
| 149 | 2 | 2 | 35 | 25% |
| 150 | 2 | 2 | 35 | 50% |
| 151 | 2 | 2 | 35 | 75% |
| 152 | 2 | 2 | 35 | 95% |
| 153 | 4 | 2 | 35 | 5% |
| 154 | 4 | 2 | 35 | 25% |
| 155 | 4 | 2 | 35 | 50% |
| 156 | 4 | 2 | 35 | 75% |
| 157 | 4 | 2 | 35 | 95% |
| 158 | 4 | 4 | 35 | 5% |
| 159 | 4 | 4 | 35 | 25% |
| 160 | 4 | 4 | 35 | 50% |
| 161 | 4 | 4 | 35 | 75% |
| 162 | 4 | 4 | 35 | 95% |
| 163 | 8 | 2 | 35 | 5% |
| 164 | 8 | 2 | 35 | 25% |
| 165 | 8 | 2 | 35 | 50% |
| 166 | 8 | 2 | 35 | 75% |
| 167 | 8 | 2 | 35 | 95% |
| 168 | 8 | 4 | 35 | 5% |
| 169 | 8 | 4 | 35 | 25% |
| 170 | 8 | 4 | 35 | 50% |
| 171 | 8 | 4 | 35 | 75% |
| 172 | 8 | 4 | 35 | 95% |
| 173 | 8 | 6 | 35 | 5% |
| 174 | 8 | 6 | 35 | 25% |
| 175 | 8 | 6 | 35 | 50% |
| 176 | 8 | 6 | 35 | 75% |
| 177 | 8 | 6 | 35 | 95% |
| 178 | 12 | 2 | 35 | 5% |
| 179 | 12 | 2 | 35 | 25% |
| 180 | 12 | 2 | 35 | 50% |
| 181 | 12 | 2 | 35 | 75% |
| 182 | 12 | 2 | 35 | 95% |
| 183 | 12 | 4 | 35 | 5% |
| 184 | 12 | 4 | 35 | 25% |
| 185 | 12 | 4 | 35 | 50% |
| 186 | 12 | 4 | 35 | 75% |
| 187 | 12 | 4 | 35 | 95% |
| 188 | 12 | 6 | 35 | 5% |

| 189 | 12 | 6 | 35 | 25% |
|---|---|---|---|---|
| 190 | 12 | 6 | 35 | 50% |
| 191 | 12 | 6 | 35 | 75% |
| 192 | 12 | 6 | 35 | 95% |

Data set #2:

| Run# | B | D | K | S | P |
|---|---|---|---|---|---|
| 1 | 2 | 4 | 2 | 20 | 5% |
| 2 | 2 | 4 | 2 | 20 | 25% |
| 3 | 2 | 4 | 2 | 20 | 50% |
| 4 | 2 | 4 | 2 | 20 | 75% |
| 5 | 2 | 4 | 2 | 20 | 95% |
| 6 | 2 | 4 | 2 | 25 | 5% |
| 7 | 2 | 4 | 2 | 25 | 25% |
| 8 | 2 | 4 | 2 | 25 | 50% |
| 9 | 2 | 4 | 2 | 25 | 75% |
| 10 | 2 | 4 | 2 | 25 | 95% |
| 11 | 2 | 4 | 2 | 35 | 5% |
| 12 | 2 | 4 | 2 | 35 | 25% |
| 13 | 2 | 4 | 2 | 35 | 50% |
| 14 | 2 | 4 | 2 | 35 | 75% |
| 15 | 2 | 4 | 2 | 35 | 95% |
| 16 | 2 | 4 | 2 | 40 | 5% |
| 17 | 2 | 4 | 2 | 40 | 25% |
| 18 | 2 | 4 | 2 | 40 | 50% |
| 19 | 2 | 4 | 2 | 40 | 75% |
| 20 | 2 | 4 | 2 | 40 | 95% |
| 21 | 2 | 8 | 2 | 20 | 5% |
| 22 | 2 | 8 | 2 | 20 | 25% |
| 23 | 2 | 8 | 2 | 20 | 50% |
| 24 | 2 | 8 | 2 | 20 | 75% |
| 25 | 2 | 8 | 2 | 20 | 95% |
| 26 | 2 | 8 | 2 | 25 | 5% |
| 27 | 2 | 8 | 2 | 25 | 25% |
| 28 | 2 | 8 | 2 | 25 | 50% |
| 29 | 2 | 8 | 2 | 25 | 75% |
| 30 | 2 | 8 | 2 | 25 | 95% |
| 31 | 2 | 8 | 2 | 35 | 5% |
| 32 | 2 | 8 | 2 | 35 | 25% |
| 33 | 2 | 8 | 2 | 35 | 50% |
| 34 | 2 | 8 | 2 | 35 | 75% |
| 35 | 2 | 8 | 2 | 35 | 95% |
| 36 | 2 | 8 | 2 | 40 | 5% |
| 37 | 2 | 8 | 2 | 40 | 25% |
| 38 | 2 | 8 | 2 | 40 | 50% |
| 39 | 2 | 8 | 2 | 40 | 75% |
| 40 | 2 | 8 | 2 | 40 | 95% |
| 41 | 2 | 8 | 4 | 20 | 5% |
| 42 | 2 | 8 | 4 | 20 | 25% |
| 43 | 2 | 8 | 4 | 20 | 50% |
| 44 | 2 | 8 | 4 | 20 | 75% |
| 45 | 2 | 8 | 4 | 20 | 95% |
| 46 | 2 | 8 | 4 | 25 | 5% |
| 47 | 2 | 8 | 4 | 25 | 25% |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 48 | 2 | 8 | 4 | 25 | 50% | 98 | 2 | 12 | 2 | 40 | 50% |
| 49 | 2 | 8 | 4 | 25 | 75% | 99 | 2 | 12 | 2 | 40 | 75% |
| 50 | 2 | 8 | 4 | 25 | 95% | 100 | 2 | 12 | 2 | 40 | 95% |
| 51 | 2 | 8 | 4 | 35 | 5% | 101 | 2 | 12 | 4 | 20 | 5% |
| 52 | 2 | 8 | 4 | 35 | 25% | 102 | 2 | 12 | 4 | 20 | 25% |
| 53 | 2 | 8 | 4 | 35 | 50% | 103 | 2 | 12 | 4 | 20 | 50% |
| 54 | 2 | 8 | 4 | 35 | 75% | 104 | 2 | 12 | 4 | 20 | 75% |
| 55 | 2 | 8 | 4 | 35 | 95% | 105 | 2 | 12 | 4 | 20 | 95% |
| 56 | 2 | 8 | 4 | 40 | 5% | 106 | 2 | 12 | 4 | 25 | 5% |
| 57 | 2 | 8 | 4 | 40 | 25% | 107 | 2 | 12 | 4 | 25 | 25% |
| 58 | 2 | 8 | 4 | 40 | 50% | 108 | 2 | 12 | 4 | 25 | 50% |
| 59 | 2 | 8 | 4 | 40 | 75% | 109 | 2 | 12 | 4 | 25 | 75% |
| 60 | 2 | 8 | 4 | 40 | 95% | 110 | 2 | 12 | 4 | 25 | 95% |
| 61 | 2 | 8 | 6 | 20 | 5% | 111 | 2 | 12 | 4 | 30 | 5% |
| 62 | 2 | 8 | 6 | 20 | 25% | 112 | 2 | 12 | 4 | 30 | 25% |
| 63 | 2 | 8 | 6 | 20 | 50% | 113 | 2 | 12 | 4 | 30 | 50% |
| 64 | 2 | 8 | 6 | 20 | 75% | 114 | 2 | 12 | 4 | 30 | 75% |
| 65 | 2 | 8 | 6 | 20 | 95% | 115 | 2 | 12 | 4 | 30 | 95% |
| 66 | 2 | 8 | 6 | 25 | 5% | 116 | 2 | 12 | 4 | 35 | 5% |
| 67 | 2 | 8 | 6 | 25 | 25% | 117 | 2 | 12 | 4 | 35 | 25% |
| 68 | 2 | 8 | 6 | 25 | 50% | 118 | 2 | 12 | 4 | 35 | 50% |
| 69 | 2 | 8 | 6 | 25 | 75% | 119 | 2 | 12 | 4 | 35 | 75% |
| 70 | 2 | 8 | 6 | 25 | 95% | 120 | 2 | 12 | 4 | 35 | 95% |
| 71 | 2 | 8 | 6 | 35 | 5% | 121 | 2 | 12 | 4 | 40 | 5% |
| 72 | 2 | 8 | 6 | 35 | 25% | 122 | 2 | 12 | 4 | 40 | 25% |
| 73 | 2 | 8 | 6 | 35 | 50% | 123 | 2 | 12 | 4 | 40 | 50% |
| 74 | 2 | 8 | 6 | 35 | 75% | 124 | 2 | 12 | 4 | 40 | 75% |
| 75 | 2 | 8 | 6 | 35 | 95% | 125 | 2 | 12 | 4 | 40 | 95% |
| 76 | 2 | 8 | 6 | 40 | 5% | 126 | 2 | 12 | 6 | 20 | 5% |
| 77 | 2 | 8 | 6 | 40 | 25% | 127 | 2 | 12 | 6 | 20 | 25% |
| 78 | 2 | 8 | 6 | 40 | 50% | 128 | 2 | 12 | 6 | 20 | 50% |
| 79 | 2 | 8 | 6 | 40 | 75% | 129 | 2 | 12 | 6 | 20 | 75% |
| 80 | 2 | 8 | 6 | 40 | 95% | 130 | 2 | 12 | 6 | 20 | 95% |
| 81 | 2 | 12 | 2 | 20 | 5% | 131 | 2 | 12 | 6 | 25 | 5% |
| 82 | 2 | 12 | 2 | 20 | 25% | 132 | 2 | 12 | 6 | 25 | 25% |
| 83 | 2 | 12 | 2 | 20 | 50% | 133 | 2 | 12 | 6 | 25 | 50% |
| 84 | 2 | 12 | 2 | 20 | 75% | 134 | 2 | 12 | 6 | 25 | 75% |
| 85 | 2 | 12 | 2 | 20 | 95% | 135 | 2 | 12 | 6 | 25 | 95% |
| 86 | 2 | 12 | 2 | 25 | 5% | 136 | 2 | 12 | 6 | 30 | 5% |
| 87 | 2 | 12 | 2 | 25 | 25% | 137 | 2 | 12 | 6 | 30 | 25% |
| 88 | 2 | 12 | 2 | 25 | 50% | 138 | 2 | 12 | 6 | 30 | 50% |
| 89 | 2 | 12 | 2 | 25 | 75% | 139 | 2 | 12 | 6 | 30 | 75% |
| 90 | 2 | 12 | 2 | 25 | 95% | 140 | 2 | 12 | 6 | 30 | 95% |
| 91 | 2 | 12 | 2 | 35 | 5% | 141 | 2 | 12 | 6 | 35 | 5% |
| 92 | 2 | 12 | 2 | 35 | 25% | 142 | 2 | 12 | 6 | 35 | 25% |
| 93 | 2 | 12 | 2 | 35 | 50% | 143 | 2 | 12 | 6 | 35 | 50% |
| 94 | 2 | 12 | 2 | 35 | 75% | 144 | 2 | 12 | 6 | 35 | 75% |
| 95 | 2 | 12 | 2 | 35 | 95% | 145 | 2 | 12 | 6 | 35 | 95% |
| 96 | 2 | 12 | 2 | 40 | 5% | 146 | 2 | 12 | 6 | 40 | 5% |
| 97 | 2 | 12 | 2 | 40 | 25% | 147 | 2 | 12 | 6 | 40 | 25% |

| 148 | 2 | 12 | 6 | 40 | 50% | 198 | 4 | 8 | 4 | 25 | 50% |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 149 | 2 | 12 | 6 | 40 | 75% | 199 | 4 | 8 | 4 | 25 | 75% |
| 150 | 2 | 12 | 6 | 40 | 95% | 200 | 4 | 8 | 4 | 25 | 95% |
| 151 | 4 | 4 | 2 | 20 | 5% | 201 | 4 | 8 | 4 | 35 | 5% |
| 152 | 4 | 4 | 2 | 20 | 25% | 202 | 4 | 8 | 4 | 35 | 25% |
| 153 | 4 | 4 | 2 | 20 | 50% | 203 | 4 | 8 | 4 | 35 | 50% |
| 154 | 4 | 4 | 2 | 20 | 75% | 204 | 4 | 8 | 4 | 35 | 75% |
| 155 | 4 | 4 | 2 | 20 | 95% | 205 | 4 | 8 | 4 | 35 | 95% |
| 156 | 4 | 4 | 2 | 25 | 5% | 206 | 4 | 8 | 4 | 40 | 5% |
| 157 | 4 | 4 | 2 | 25 | 25% | 207 | 4 | 8 | 4 | 40 | 25% |
| 158 | 4 | 4 | 2 | 25 | 50% | 208 | 4 | 8 | 4 | 40 | 50% |
| 159 | 4 | 4 | 2 | 25 | 75% | 209 | 4 | 8 | 4 | 40 | 75% |
| 160 | 4 | 4 | 2 | 25 | 95% | 210 | 4 | 8 | 4 | 40 | 95% |
| 161 | 4 | 4 | 2 | 35 | 5% | 211 | 4 | 8 | 6 | 20 | 5% |
| 162 | 4 | 4 | 2 | 35 | 25% | 212 | 4 | 8 | 6 | 20 | 25% |
| 163 | 4 | 4 | 2 | 35 | 50% | 213 | 4 | 8 | 6 | 20 | 50% |
| 164 | 4 | 4 | 2 | 35 | 75% | 214 | 4 | 8 | 6 | 20 | 75% |
| 165 | 4 | 4 | 2 | 35 | 95% | 215 | 4 | 8 | 6 | 20 | 95% |
| 166 | 4 | 4 | 2 | 40 | 5% | 216 | 4 | 8 | 6 | 25 | 5% |
| 167 | 4 | 4 | 2 | 40 | 25% | 217 | 4 | 8 | 6 | 25 | 25% |
| 168 | 4 | 4 | 2 | 40 | 50% | 218 | 4 | 8 | 6 | 25 | 50% |
| 169 | 4 | 4 | 2 | 40 | 75% | 219 | 4 | 8 | 6 | 25 | 75% |
| 170 | 4 | 4 | 2 | 40 | 95% | 220 | 4 | 8 | 6 | 25 | 95% |
| 171 | 4 | 8 | 2 | 20 | 5% | 221 | 4 | 8 | 6 | 35 | 5% |
| 172 | 4 | 8 | 2 | 20 | 25% | 222 | 4 | 8 | 6 | 35 | 25% |
| 173 | 4 | 8 | 2 | 20 | 50% | 223 | 4 | 8 | 6 | 35 | 50% |
| 174 | 4 | 8 | 2 | 20 | 75% | 224 | 4 | 8 | 6 | 35 | 75% |
| 175 | 4 | 8 | 2 | 20 | 95% | 225 | 4 | 8 | 6 | 35 | 95% |
| 176 | 4 | 8 | 2 | 25 | 5% | 226 | 4 | 8 | 6 | 40 | 5% |
| 177 | 4 | 8 | 2 | 25 | 25% | 227 | 4 | 8 | 6 | 40 | 25% |
| 178 | 4 | 8 | 2 | 25 | 50% | 228 | 4 | 8 | 6 | 40 | 50% |
| 179 | 4 | 8 | 2 | 25 | 75% | 229 | 4 | 8 | 6 | 40 | 75% |
| 180 | 4 | 8 | 2 | 25 | 95% | 230 | 4 | 8 | 6 | 40 | 95% |
| 181 | 4 | 8 | 2 | 35 | 5% | 231 | 4 | 12 | 2 | 20 | 5% |
| 182 | 4 | 8 | 2 | 35 | 25% | 232 | 4 | 12 | 2 | 20 | 25% |
| 183 | 4 | 8 | 2 | 35 | 50% | 233 | 4 | 12 | 2 | 20 | 50% |
| 184 | 4 | 8 | 2 | 35 | 75% | 234 | 4 | 12 | 2 | 20 | 75% |
| 185 | 4 | 8 | 2 | 35 | 95% | 235 | 4 | 12 | 2 | 20 | 95% |
| 186 | 4 | 8 | 2 | 40 | 5% | 236 | 4 | 12 | 2 | 25 | 5% |
| 187 | 4 | 8 | 2 | 40 | 25% | 237 | 4 | 12 | 2 | 25 | 25% |
| 188 | 4 | 8 | 2 | 40 | 50% | 238 | 4 | 12 | 2 | 25 | 50% |
| 189 | 4 | 8 | 2 | 40 | 75% | 239 | 4 | 12 | 2 | 25 | 75% |
| 190 | 4 | 8 | 2 | 40 | 95% | 240 | 4 | 12 | 2 | 25 | 95% |
| 191 | 4 | 8 | 4 | 20 | 5% | 241 | 4 | 12 | 2 | 35 | 5% |
| 192 | 4 | 8 | 4 | 20 | 25% | 242 | 4 | 12 | 2 | 35 | 25% |
| 193 | 4 | 8 | 4 | 20 | 50% | 243 | 4 | 12 | 2 | 35 | 50% |
| 194 | 4 | 8 | 4 | 20 | 75% | 244 | 4 | 12 | 2 | 35 | 75% |
| 195 | 4 | 8 | 4 | 20 | 95% | 245 | 4 | 12 | 2 | 35 | 95% |
| 196 | 4 | 8 | 4 | 25 | 5% | 246 | 4 | 12 | 2 | 40 | 5% |
| 197 | 4 | 8 | 4 | 25 | 25% | 247 | 4 | 12 | 2 | 40 | 25% |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 248 | 4 | 12 | 2 | 40 | 50% | 298 | 4 | 12 | 6 | 40 | 50% |
| 249 | 4 | 12 | 2 | 40 | 75% | 299 | 4 | 12 | 6 | 40 | 75% |
| 250 | 4 | 12 | 2 | 40 | 95% | 300 | 4 | 12 | 6 | 40 | 95% |
| 251 | 4 | 12 | 4 | 20 | 5% | 301 | 6 | 4 | 2 | 20 | 5% |
| 252 | 4 | 12 | 4 | 20 | 25% | 302 | 6 | 4 | 2 | 20 | 25% |
| 253 | 4 | 12 | 4 | 20 | 50% | 303 | 6 | 4 | 2 | 20 | 50% |
| 254 | 4 | 12 | 4 | 20 | 75% | 304 | 6 | 4 | 2 | 20 | 75% |
| 255 | 4 | 12 | 4 | 20 | 95% | 305 | 6 | 4 | 2 | 20 | 95% |
| 256 | 4 | 12 | 4 | 25 | 5% | 306 | 6 | 4 | 2 | 25 | 5% |
| 257 | 4 | 12 | 4 | 25 | 25% | 307 | 6 | 4 | 2 | 25 | 25% |
| 258 | 4 | 12 | 4 | 25 | 50% | 308 | 6 | 4 | 2 | 25 | 50% |
| 259 | 4 | 12 | 4 | 25 | 75% | 309 | 6 | 4 | 2 | 25 | 75% |
| 260 | 4 | 12 | 4 | 25 | 95% | 310 | 6 | 4 | 2 | 25 | 95% |
| 261 | 4 | 12 | 4 | 30 | 5% | 311 | 6 | 4 | 2 | 35 | 5% |
| 262 | 4 | 12 | 4 | 30 | 25% | 312 | 6 | 4 | 2 | 35 | 25% |
| 263 | 4 | 12 | 4 | 30 | 50% | 313 | 6 | 4 | 2 | 35 | 50% |
| 264 | 4 | 12 | 4 | 30 | 75% | 314 | 6 | 4 | 2 | 35 | 75% |
| 265 | 4 | 12 | 4 | 30 | 95% | 315 | 6 | 4 | 2 | 35 | 95% |
| 266 | 4 | 12 | 4 | 35 | 5% | 316 | 6 | 4 | 2 | 40 | 5% |
| 267 | 4 | 12 | 4 | 35 | 25% | 317 | 6 | 4 | 2 | 40 | 25% |
| 268 | 4 | 12 | 4 | 35 | 50% | 318 | 6 | 4 | 2 | 40 | 50% |
| 269 | 4 | 12 | 4 | 35 | 75% | 319 | 6 | 4 | 2 | 40 | 75% |
| 270 | 4 | 12 | 4 | 35 | 95% | 320 | 6 | 4 | 2 | 40 | 95% |
| 271 | 4 | 12 | 4 | 40 | 5% | 321 | 6 | 8 | 2 | 20 | 5% |
| 272 | 4 | 12 | 4 | 40 | 25% | 322 | 6 | 8 | 2 | 20 | 25% |
| 273 | 4 | 12 | 4 | 40 | 50% | 323 | 6 | 8 | 2 | 20 | 50% |
| 274 | 4 | 12 | 4 | 40 | 75% | 324 | 6 | 8 | 2 | 20 | 75% |
| 275 | 4 | 12 | 4 | 40 | 95% | 325 | 6 | 8 | 2 | 20 | 95% |
| 276 | 4 | 12 | 6 | 20 | 5% | 326 | 6 | 8 | 2 | 25 | 5% |
| 277 | 4 | 12 | 6 | 20 | 25% | 327 | 6 | 8 | 2 | 25 | 25% |
| 278 | 4 | 12 | 6 | 20 | 50% | 328 | 6 | 8 | 2 | 25 | 50% |
| 279 | 4 | 12 | 6 | 20 | 75% | 329 | 6 | 8 | 2 | 25 | 75% |
| 280 | 4 | 12 | 6 | 20 | 95% | 330 | 6 | 8 | 2 | 25 | 95% |
| 281 | 4 | 12 | 6 | 25 | 5% | 331 | 6 | 8 | 2 | 35 | 5% |
| 282 | 4 | 12 | 6 | 25 | 25% | 332 | 6 | 8 | 2 | 35 | 25% |
| 283 | 4 | 12 | 6 | 25 | 50% | 333 | 6 | 8 | 2 | 35 | 50% |
| 284 | 4 | 12 | 6 | 25 | 75% | 334 | 6 | 8 | 2 | 35 | 75% |
| 285 | 4 | 12 | 6 | 25 | 95% | 335 | 6 | 8 | 2 | 35 | 95% |
| 286 | 4 | 12 | 6 | 30 | 5% | 336 | 6 | 8 | 2 | 40 | 5% |
| 287 | 4 | 12 | 6 | 30 | 25% | 337 | 6 | 8 | 2 | 40 | 25% |
| 288 | 4 | 12 | 6 | 30 | 50% | 338 | 6 | 8 | 2 | 40 | 50% |
| 289 | 4 | 12 | 6 | 30 | 75% | 339 | 6 | 8 | 2 | 40 | 75% |
| 290 | 4 | 12 | 6 | 30 | 95% | 340 | 6 | 8 | 2 | 40 | 95% |
| 291 | 4 | 12 | 6 | 35 | 5% | 341 | 6 | 8 | 4 | 20 | 5% |
| 292 | 4 | 12 | 6 | 35 | 25% | 342 | 6 | 8 | 4 | 20 | 25% |
| 293 | 4 | 12 | 6 | 35 | 50% | 343 | 6 | 8 | 4 | 20 | 50% |
| 294 | 4 | 12 | 6 | 35 | 75% | 344 | 6 | 8 | 4 | 20 | 75% |
| 295 | 4 | 12 | 6 | 35 | 95% | 345 | 6 | 8 | 4 | 20 | 95% |
| 296 | 4 | 12 | 6 | 40 | 5% | 346 | 6 | 8 | 4 | 25 | 5% |
| 297 | 4 | 12 | 6 | 40 | 25% | 347 | 6 | 8 | 4 | 25 | 25% |

| | | | | | | | | | | |
|-----|---|----|---|----|-----|-----|---|----|---|----|-----|
| 348 | 6 | 8  | 4 | 25 | 50% | 398 | 6 | 12 | 2 | 40 | 50% |
| 349 | 6 | 8  | 4 | 25 | 75% | 399 | 6 | 12 | 2 | 40 | 75% |
| 350 | 6 | 8  | 4 | 25 | 95% | 400 | 6 | 12 | 2 | 40 | 95% |
| 351 | 6 | 8  | 4 | 35 | 5%  | 401 | 6 | 12 | 4 | 20 | 5%  |
| 352 | 6 | 8  | 4 | 35 | 25% | 402 | 6 | 12 | 4 | 20 | 25% |
| 353 | 6 | 8  | 4 | 35 | 50% | 403 | 6 | 12 | 4 | 20 | 50% |
| 354 | 6 | 8  | 4 | 35 | 75% | 404 | 6 | 12 | 4 | 20 | 75% |
| 355 | 6 | 8  | 4 | 35 | 95% | 405 | 6 | 12 | 4 | 20 | 95% |
| 356 | 6 | 8  | 4 | 40 | 5%  | 406 | 6 | 12 | 4 | 25 | 5%  |
| 357 | 6 | 8  | 4 | 40 | 25% | 407 | 6 | 12 | 4 | 25 | 25% |
| 358 | 6 | 8  | 4 | 40 | 50% | 408 | 6 | 12 | 4 | 25 | 50% |
| 359 | 6 | 8  | 4 | 40 | 75% | 409 | 6 | 12 | 4 | 25 | 75% |
| 360 | 6 | 8  | 4 | 40 | 95% | 410 | 6 | 12 | 4 | 25 | 95% |
| 361 | 6 | 8  | 6 | 20 | 5%  | 411 | 6 | 12 | 4 | 30 | 5%  |
| 362 | 6 | 8  | 6 | 20 | 25% | 412 | 6 | 12 | 4 | 30 | 25% |
| 363 | 6 | 8  | 6 | 20 | 50% | 413 | 6 | 12 | 4 | 30 | 50% |
| 364 | 6 | 8  | 6 | 20 | 75% | 414 | 6 | 12 | 4 | 30 | 75% |
| 365 | 6 | 8  | 6 | 20 | 95% | 415 | 6 | 12 | 4 | 30 | 95% |
| 366 | 6 | 8  | 6 | 25 | 5%  | 416 | 6 | 12 | 4 | 35 | 5%  |
| 367 | 6 | 8  | 6 | 25 | 25% | 417 | 6 | 12 | 4 | 35 | 25% |
| 368 | 6 | 8  | 6 | 25 | 50% | 418 | 6 | 12 | 4 | 35 | 50% |
| 369 | 6 | 8  | 6 | 25 | 75% | 419 | 6 | 12 | 4 | 35 | 75% |
| 370 | 6 | 8  | 6 | 25 | 95% | 420 | 6 | 12 | 4 | 35 | 95% |
| 371 | 6 | 8  | 6 | 35 | 5%  | 421 | 6 | 12 | 4 | 40 | 5%  |
| 372 | 6 | 8  | 6 | 35 | 25% | 422 | 6 | 12 | 4 | 40 | 25% |
| 373 | 6 | 8  | 6 | 35 | 50% | 423 | 6 | 12 | 4 | 40 | 50% |
| 374 | 6 | 8  | 6 | 35 | 75% | 424 | 6 | 12 | 4 | 40 | 75% |
| 375 | 6 | 8  | 6 | 35 | 95% | 425 | 6 | 12 | 4 | 40 | 95% |
| 376 | 6 | 8  | 6 | 40 | 5%  | 426 | 6 | 12 | 6 | 20 | 5%  |
| 377 | 6 | 8  | 6 | 40 | 25% | 427 | 6 | 12 | 6 | 20 | 25% |
| 378 | 6 | 8  | 6 | 40 | 50% | 428 | 6 | 12 | 6 | 20 | 50% |
| 379 | 6 | 8  | 6 | 40 | 75% | 429 | 6 | 12 | 6 | 20 | 75% |
| 380 | 6 | 8  | 6 | 40 | 95% | 430 | 6 | 12 | 6 | 20 | 95% |
| 381 | 6 | 12 | 2 | 20 | 5%  | 431 | 6 | 12 | 6 | 25 | 5%  |
| 382 | 6 | 12 | 2 | 20 | 25% | 432 | 6 | 12 | 6 | 25 | 25% |
| 383 | 6 | 12 | 2 | 20 | 50% | 433 | 6 | 12 | 6 | 25 | 50% |
| 384 | 6 | 12 | 2 | 20 | 75% | 434 | 6 | 12 | 6 | 25 | 75% |
| 385 | 6 | 12 | 2 | 20 | 95% | 435 | 6 | 12 | 6 | 25 | 95% |
| 386 | 6 | 12 | 2 | 25 | 5%  | 436 | 6 | 12 | 6 | 30 | 5%  |
| 387 | 6 | 12 | 2 | 25 | 25% | 437 | 6 | 12 | 6 | 30 | 25% |
| 388 | 6 | 12 | 2 | 25 | 50% | 438 | 6 | 12 | 6 | 30 | 50% |
| 389 | 6 | 12 | 2 | 25 | 75% | 439 | 6 | 12 | 6 | 30 | 75% |
| 390 | 6 | 12 | 2 | 25 | 95% | 440 | 6 | 12 | 6 | 30 | 95% |
| 391 | 6 | 12 | 2 | 35 | 5%  | 441 | 6 | 12 | 6 | 35 | 5%  |
| 392 | 6 | 12 | 2 | 35 | 25% | 442 | 6 | 12 | 6 | 35 | 25% |
| 393 | 6 | 12 | 2 | 35 | 50% | 443 | 6 | 12 | 6 | 35 | 50% |
| 394 | 6 | 12 | 2 | 35 | 75% | 444 | 6 | 12 | 6 | 35 | 75% |
| 395 | 6 | 12 | 2 | 35 | 95% | 445 | 6 | 12 | 6 | 35 | 95% |
| 396 | 6 | 12 | 2 | 40 | 5%  | 446 | 6 | 12 | 6 | 40 | 5%  |
| 397 | 6 | 12 | 2 | 40 | 25% | 447 | 6 | 12 | 6 | 40 | 25% |

| 448 | 6 | 12 | 6 | 40 | 50% |
| 449 | 6 | 12 | 6 | 40 | 75% |
| 450 | 6 | 12 | 6 | 40 | 95% |

# Appendix V - Economic Comparison Spreadsheet

Economic Comparison

---

1 Global Parameters

| | | |
|---|---|---|
| i | 0.15 | discount rate |
| u | 2300 | utilization work-hours/year |
| L | 20 | dist. fro mterminal to rail yard (mi) |
| V | 40 | truck speed (mph) |
| Vt | 30 | train speed (mph) |
| Cl | 40 | labor cost ($/hour) |
| A | 600 | boxes to be unloaded |
| I | 0.5 | intermodal fraction |
| H | 2 | ship headway (days) |
| n | 5 | headways to unload domestic |
| n' | 0.5 | headways to unload intermodal |
| ks | 2.5 | intermodal vs regular strad move |
| kt | 0.5 | train vs truck transportation cost |
| K | 2 | number of tracks under crane |
| S | 20 | number of railcars in a string |
| D | 6 | number of intermodal destinations |
| P | 0.5 | ship sorting level |
| B | 2 | buffer size |
| Ds | 150 | strad storage density (FEU/acre) |
| Dt | 36 | double-stack train stg. dens. (FEU/acre) |
| LV | 1,000,000 | land value ($/acre) |
| Nc | 3 | number of cranes |
| Ci | 1 | holding cost for loaded box ($/hour) |
| Cr | 0.75 | holding cost for railcar ($/hour) |
| Cv | 2000 | holding cost for loaded vessel ($/hour) |
| Ck | 20 | cost per cut (from Keaton) |
| tu | 1 | time per cut (min) |
| Hoist | 2 | single or double (for indirect and semi only) |

Global derived parameters

| | | |
|---|---|---|
| throughput | 109,500 | one-way moves/year |
| E[C] | 0.15 | number of cuts per railcar |

| buffer effect | short | long | interm |
|---|---|---|---|
| Px | 0.67 | 0.17 | 0.17 |
| E[Tx] | 40.00 | 138.81 | |
| E[T] | 59.06 | | |
| E[T2] | 5148.16 | 21111.18 | |
| rho | 0.66 | | |
| gamma | 0.69 | | |
| alpha' | 0.02 | | |
| phi | 0.99 | crane productivity coefficient | |

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## 2 Equipment Costs

|  | SINGLE-HOIST DOCK CRANE | DBL-HOIST DOCK CRANE | PUSHER TRACTORS | STRADDLE CARRIER | TRUCK |
|---|---|---|---|---|---|
| capital | 7,000,000 | 9,500,000 | 1,300,000 | 650,000 | 150,000 |
| life | 20 | 20 | 12 | 12 | 12 |
| hourly capital | 486.23 | 659.88 | 104.27 | 52.14 | 12.03 |
| hourly labor | 80.00 | 160.00 | 80.00 | 40.00 | 40.00 |
| hourly maint | 25.00 | 35.00 | 40.00 | 20.00 | 10.00 |
| productivity | 35.00 | 40.00 | 40.00 | 11.67 | 0.67 |
|  | Cc | Cc' | Cp | Cs | Cd |
| cost per move | 16.89 | 21.37 | 5.61 | 9.61 | 93.05 |
| notes: | 2 operators | 4 operators | 1/track |  | 1h @terminal |

## 3 Handling Costs

|  | INDIRECT | SEMI | DIRECT |
|---|---|---|---|
| crn->dock | 21.37 |  |  |
| strad->stg | 9.61 |  |  |
| strad->trk | 9.61 |  |  |
| trk->yard(i) | 93.05 |  |  |
| ystg->trn(i) | 9.61 |  |  |
| crn->dock |  | 21.37 |  |
| strad->stg(d) |  | 9.61 |  |
| strad->trk(d) |  | 9.61 |  |
| strad->trn(i) |  | 24.03 |  |
| trn->yard(i) |  | 46.52 |  |
| crn->dock |  |  | 27.30 |
| strad->stg(d) |  |  | 9.73 |
| strad->trk(d) |  |  | 9.73 |
| trn->yard(i) |  |  | 46.52 |
| extra cuts(i) |  |  | 2.96 |
| $/move | CIh | CSh | CDh |
| TOTAL | 91.92 | 66.26 | 61.77 |

## 4 Rent Costs

Accumulation

900 domestic
300 intermodal

|          | INDIRECT  | SEMI       | DIRECT     |         |
|----------|-----------|------------|------------|---------|
| area(d)  | 6.00      | 6.00       | 6.00       | acres   |
| area(i)  | 2.00      | 8.33       | 8.33       | acres   |
| cost     | 8,000,000 | 14,333,333 | 14,333,333 | $       |
| cost/year| 1,200,000 | 2,150,000  | 2,150,000  | $/year  |
|          |           |            |            |         |
| $/move   | CIr       | CSr        | CDr        |         |
| TOTAL    | 10.96     | 19.63      | 19.63      | $/move  |

## 5 Inventory Costs

|           | INDIRECT | SEMI   | DIRECT |             |
|-----------|----------|--------|--------|-------------|
| Pc        | 40.00    | 40.00  | 39.53  |             |
| ship      | 16.67    | 16.67  | 16.87  |             |
| time(d)   | 130.00   | 130.00 | 130.12 |             |
| time(i)   | 37.00    | 13.17  | 13.32  |             |
| cuts(i)   |          |        | 0.74   |             |
| total box | 83.50    | 71.58  | 72.09  | hours/move  |
| total car |          | 6.58   | 6.66   | hours/move  |
|           |          |        |        |             |
| $/move    | CIi      | CSi    | CDi    |             |
| TOTAL     | 100.17   | 93.19  | 93.95  | $/move      |

## 6 Total Overall Costs

| $/move     | Indirect | Semi-Direct | Direct |
|------------|----------|-------------|--------|
| handling   | 92       | 66          | 62     |
| rent       | 11       | 20          | 20     |
| inventory  | 100      | 93          | 94     |
| TOTAL      | 203      | 179         | 175    |
|            |          |             |        |
| difference |          | 24          | 28     |
| % difference |        | 0.88        | 0.86   |