Modeling Rail Freight Operations Under Different Operating Strategies

by

Yan Dong

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Abstract

In recent years, there has been an active debate in the rail industry about what kind of operating strategy best fits railroad operating characteristics. The debate focused on degree of (train) schedule-adherence, which reflects fundamental differences in philosophy in terms of how a railroad should be operated. The debate is generally qualitative as opposed to quantitative.

This dissertation aimed to model and evaluate railroad operations under different operating strategies. First, three operating strategies were defined and a framework for evaluating railroad operations under different operating strategies was presented. Second, the major factors that affect adoption of different operating strategies were identified and analyzed by reviewing practice and research in railroads and in other complex systems.

Third, terminal operations were identified as a critical part of railroad operations. Two analytical terminal models, the Intermediate Terminal Model (ITM) and the terminal Processing Sequencing Model system (PSM) were developed applying a methodology that decomposes terminal operations into processes and tasks. The Stochastic Terminal Model (STM) was developed to estimate IB train arrival patterns under different operating strategies. Based on the approach of ITM and PSM and the results of STM, a microscopic Terminal Simulation Model (TSM) was developed and used in a case study in which actual data from a major hump terminal of a Class I railroad was used, and the effects of the identified factors on terminal performance under different operating strategies were estimated.

Fourth, a Network Simulation Model (NSM) was developed and used to evaluate rail network operations, including hump and intermediate terminal operations and line haul movements, under different operating strategies. Two case studies were conducted using the model and two portions of a physical network from a Class I railroad. The results from TSM and NSM are similar and suggest that different operating strategies have different performance on different attributes and choosing an appropriate operating strategy can be a very effective way to improve railroad operations and performance.

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Chapter 1

Introduction

1.1 Background and motivations

In recent years, there has been an active debate in the rail industry about what kind of operating strategy best fits railroad operating characteristics and can achieve satisfactory performance for both shippers and railroads. Among the railroad experts and professionals, there are very different views of and philosophies toward this question.[1] Some experts think that operating a railroad according to some *"schedule"* or *"plan"* is best to provide reliable service to shippers and to maintain a high level of railroad resource utilization. There are other experts who think that operating a railroad according to the principle of *flexibility* is best to take into account such matters as stochastic demand, probabilistic processing times at yards, dynamic availability of road power and crews at different parts of the rail network, extreme weather conditions, and accidents, all of which are inherent in railroad operations. This group of experts argues that a schedule or plan will simply not work due to these factors, and railroad operations should be adjusted continuously and flexibly to accommodate these factors. Yet there is another group of experts who thinks that running a railroad according to some schedule is best but the schedule should be changed and adjusted to accommodate the real situations and the principle of flexibility should be kept in

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[1] See [18, 49] for the discussion.

some degree to reduce part of the operating cost such as the cost of running trains.

The fundamental differences of these groups reflect the different philosophies they hold in terms of how a railroad should be operated. The debate is generally qualitative as opposed to quantitative. There has been very limited research conducted to determine which operating strategy is best for railroads. This is the major question we seek to address in this thesis.

In this chapter, we will first briefly introduce general railroad operations. Then we will define three operating strategies: *schedule-adherence*, *flexible short-run scheduling*, and *flexible operation* in railroad operations, followed by presenting a hierarchical management of railroad operations, which serves as a framework. Our research objective and approach is stated next, followed by the last section of the chapter, in which we outline the organization of this dissertation.

1.2 Railroad operations

Railroad operations involve utilizing rail *cars,* in the form of *trains,* to move shippers' goods from their origins to their destinations. First, a shipper requests a service with a specified service requirement from a railroad.[2] Once the railroad agrees to serve the shipper, a *waybill* is filed between them and at the agreed time, the railroad will send the car(s) to the shipper's site for *loading operation*[3] if the shipper has a siding with the railroad.[4]

After the goods are loaded on a car,[5] the car is picked up by a railroad locomotive and taken to the nearby rail yard (the *pick-up operation*).

After the pick-up operation is finished, the car is then moved to a nearest *classifi-*

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[2] The service requirement includes the amount of goods to transport, the time to start the transport, origin, destination, transit time, and the type of car(s) required.

[3] Usually the loading and unloading operations are not considered as railroad operations, since these operations are conducted on the shipper's or consignee's site and no actions are taken to *move* the traffic.

[4] Otherwise, the goods will be carried to a rail yard of the railroad by some truck(s) from either the shipper, the railroad, or a trucking company.

[5] Sometimes more than one cars are needed to load the goods.

cation terminal[6], where the car is *classified.* It is grouped into a *block* with other cars of similar next or final destination. This operation is usually called the *classification.*

After enough outbound traffic[7] is accumulated or an outbound train's assembly time is reached, the outbound train is assembled. This *assembly operation* involves assembling several blocks together to form an outbound (OB)[8] train using the yard switching crews and engines.

When the assembly operation is finished, the outbound train waits at the departure yard of the terminal for the outbound *inspection operation,* in which the outbound inspector teams check the physical conditions of the running gear and brakes of the cars in the outbound train.

After the outbound inspection is finished, the OB train waits for road power units and crews to be attached and brake tested (the *brake test operation*). After the brake test operation is finished, the outbound train waits for the *departure operation*, in which the system dispatcher gives signal permission for the movement of the outbound train from the terminal to its connected line segment, starting the train's journey via the *line haul movement operation.*[9]

When the outbound train enters another classification terminal on its journey to its destination[10], there are two operations to be conducted: *arrival operation* and *inbound inspection operation*. The arrival operation involves placing the train onto one of the receiving tracks. Then the road power units and the end-of-train (EOT) device[11] are disconnected and removed from the train, and the power units go to the locomotive shop for *preparation and maintenance* and the crew goes to the crew base

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[6] We use the words terminal and yard interchangeably. But the yard with specific names can represent a part of a terminal such as *arrival yard* and *departure yard*.

[7] It is the number of cars from the blocks which can be put together in an outbound train.

[8] We use the railroad convention that "outbound" is sometimes written as "OB" and "inbound" as "IB".

[9] Very often, the train will go through small terminals without stop, or only stops at limited number of small terminals for simplified operations such as setting out or picking up cars. The line segment is referred as the line between two stops.

[10] This train is called an inbound train with respect to the terminal entered.

[11] It is a special powered device, which is placed on the last car of the train to indicate the end of the train.

for *rest* and to prepare for another trip.[12]

When placing the cars onto the receiving tracks, a *double over operation*, which involves breaking the train and placing the cars onto more than one receiving tracks, may be needed if a single receiving track is not long enough to hold all the cars in the train. After the arrival operation is finished, the train waits for inbound inspection operation, which involves inbound inspector teams to check the physical condition of the cars.[13]

If the terminal (the train enters) is the destination of the *train,* this train needs to be classified in this terminal, where the cars from the train either arrive at their destination or need other train(s) to carry them toward their destinations.[14]

If the terminal the train enters is the destination of a *car* on the train, the car is arranged and delivered to its consignee's sidings, which is called *delivery operation.*[15] If the terminal the train enters is not the destination of the car, the car then needs to continue its trip until it reaches its destination.

From the above discussion, we can summarize the major railroad operations as following:

- Local pick-up and delivery operations
- Terminal operations, which include:
    - Inbound train arrival operation
    - Inbound inspection operation
    - Classification operation

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[12] The EOT will be carried to another place for preparation or wait for another usage.

[13] If a car has some mechanical defect (e.g., bad order car) and may not continue its trip without repairs, the inspectors may repair the car at the receiving track if the time is available and the defect is not very serious, otherwise the car needs to go to the car shop for repair. The inbound inspection is not mandated by federal law, while the outbound inspection is mandated under the federal Power Brake Law.

[14] If, on the other hand, the terminal entered is not the destination of the train, the train does not need to be classified in this terminal and only simple operations such as setting out or adding in some cars for the train, some paper work, etc. are conducted.

[15] The goods from the car may also be unloaded to a truck and moved to consignee's site if the consignee has no sidings connected to the terminal.

  - Assembly operation
  - Outbound inspection operation
  - Brake test and departure operation
  - Road power unit preparation and maintenance operation
  - Road crew rest and preparation operation
- Line haul movement operation.

This introduction of railroad operations suggests that terminal operations are a major part of railroad operations. For interested readers, [3] provides more detailed description about railroad operations.

1.3 Railroad operating strategies

1.3.1 Three operating strategies

Railroad operating strategy is based on a general approach or philosophy for conducting daily railroad operations. We categorize the railroad different operating strategies into the following three classes[16]:

- Schedule-adherence (SCH).
- Flexible short-run scheduling (FSS).
- Flexible operation (FLX).

These strategies relate to the railroad *operating plan* which is defined as a set of rules and specifications developed, perhaps monthly or quarterly, to move traffic over the rail network. Train schedules are one part of the railroad operating plan, which specify the times for trains to arrive at and depart from terminals. Railroad operating plans play a significant role in distinguishing between different railroad operating strategies.

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[16] Thereafter in this thesis, we refer to different railroad operating strategies as these three operating strategies

The schedule-adherence approach (SCH) requires that railroad operations are conducted according to the operating plan, with the focus on adhering to train schedules. The major characteristic of this approach is that railroads, like airlines and passenger railroads, create schedules on a regular basis (monthly or quarterly) and then stick to the schedules in their operations, although minor changes are inevitable. The schedule-adherence approach emphasizes the active role of the operating plan, especially train schedules, on the system performance.

The flexible short-run scheduling approach (FSS) requires that a short-run plan is developed at least eight hours (e.g., a shift) ahead of time to accommodate the current situations. Railroad operations are then conducted according to this short-run plan. This approach acknowledges the importance of the operating plan and train schedules for railroad operations, but also recognizes the significant stochasticity and uncertainty in railroad operations resulting from variability in demand, uncertain terminal processing times, weather, track maintenance requirements and other factors. The short-run plan is developed to have a clear and achievable goal for managing trains, crews and locomotives. This short-run schedule will often be different from the schedule given in the operating plan. This approach is flexible in the sense that it responds to actual conditions such as resource availability and predicted traffic volume. It is scheduled in the sense that there is always a clear plan for the near future.

The flexible operation approach (FLX) requires that the railroad operations are conducted according to some rules with no requirement for formal plans such as train schedules or short-run plan being developed and adhered. This approach emphasizes the need to respond to current conditions. The major characteristic of this approach is that railroads establish operations in real-time, or close to real-time, depending on traffic, weather condition, and resource availability. The tonnage based assembly rule, which allows the terminals to assemble and dispatch outbound trains whenever some predefined number of cars are available, is commonly used in practice and is the major flexible operation approach investigated in this research.

The major difference among these three different operating strategies is how strictly the operating plan is adhered to,[17] especially with respect to the train schedules. The schedule-adherence approach requires the most strict adherence to the operating plan. The flexible short-run scheduling approach allows some degree of flexibility in adhering to the operating plan by incorporating current situations. The flexible operation approach, in principle, does not require train schedules.

The planning time frame is another important factor for distinguishing the different approaches. The schedule-adherence approach uses the monthly or quarterly schedule defined by the operating plan to conduct daily operations. The flexible short-run scheduled approach uses a schedule established at least eight hours ahead of time to conduct daily operations. The flexible operating approach uses real-time, or close to real-time, decisions to conduct daily operations.

In essence, the difference involves how to deal with the *global vs. local control*, also referred to as *centralized vs. decentralized control* , in railroad operations. The schedule-adherence approach can be considered as a global or centralized control tool to coordinate the railroad operations among different terminals and other subdivisions, while the flexible operation approach can be considered as a local or decentralized control tool since each terminal could conduct its operations according to its own situation without considering much about network conditions. The flexible short-run scheduling approach can be considered as a control tool which considers both the network and terminal conditions to determine the daily operations.

1.3.2 Definitions of operations under different operating strategies

Railroads' definitions of operations under different operating strategies may be very different and confusing. To our knowledge, the rail industry does not have an agreed-upon meaning of *scheduled* operations, and their approaches in operations may not be the same as the names the railroads use for them. For example, the approach

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[17] Other differences are discussed in the next subsection.

that we have called flexible short-run scheduling is often described by railroads as a "scheduled" approach. The lack of clear definition of operations under different operating strategies reflects an incomplete understanding of these approaches and hinders discussions of their relative merits. In this section, we will therefore offer definitions of operations under different operating strategies.

Definition of schedule-adherence operation

Strictly on-time train arrivals and departures are often impossible because of stochastic demand, extreme weather conditions, unexpected equipment failures, variable terminal processing, etc. Operating completely according to the train schedules is neither possible nor is it the goal of absolute schedule-adherence. The goal of the schedule-adherence strategy to operations is trying to run *most* of the *scheduled* trains *on* or *close to their schedules*.

A scheduled train can be considered to depart on-time if:

$$|t(dept.) - t(sch.dept.)| <= t_0 \tag{1.1}$$

where, $t(dept.)$ is the actual departure time from a terminal and $t(sch.dept.)$ is the scheduled departure time. Equation 1.1 says that the difference between scheduled departure time and the actual departure time at any terminal cannot be greater than a pre-defined time t_0 if it is to be considered an on-time departure. The t_0 may be different for different classes of traffic. For example, for intermodal traffic, t_0 should be smaller than t_0 for coal unit train.

Considering the serious impact of stochasticity on train operations, the definition of *on-time* train movement should also include arrival times at destinations. The on-time train movements can be defined alternatively as:

$$|t(dept.) - t(sch.dept.)| <= t_1 \tag{1.2}$$

$$|t(arr.dest.) - t(sch.dest.)| <= t_2 \tag{1.3}$$

where, t_1 is another threshold time (which may be different from t_0), $t(arr.dest.)$ is the actual arrival time at the destination terminal, and $t(sch.dest.)$ is the scheduled arrival time at the destination terminal. Equations 1.2 and 1.3 say that for on-time train movement, the difference between the scheduled departure time and the actual departure time at any terminal (not including the destination terminal) cannot be greater than t_1 and the difference between the scheduled arrival time and the actual arrival time to the destination terminal cannot be greater than t_2. The purpose of defining the operation under the schedule-adherence strategy in such a way is to allow some limited flexibility in arrival, departure, and therefore in line haul time.

A railroad operation can be considered as a schedule-adherence operation if:

- The schedule-adherence strategy is applied in day-to-day operations;
- There is a schedule for most trains;
- A high proportion of the scheduled trains operate on-time t_{0_i} (or t_{1_i} and t_{2_i}), given t_{0_i} (or t_{1_i} and t_{2_i}) for each class i of trains; and
- The number of unscheduled trains and train cancellations is small and they are avoided whenever it is possible.

Definition of flexible short-run scheduling operation

The definition of the flexible short-run scheduling operation is very similar to the schedule-adherence operation. The major difference is that the flexible short-run scheduling strategy is applied in day-to-day operations, where the scheduled arrival and departure times are from a short-run plan developed at least eight hours (e.g., one shift) ahead of time rather than taken from the operating plan. The time frame for changing the short-run plan can not be too small. Otherwise, this would be a flexible rather than a partially scheduled approach. For example, we cannot say that successfully executing a short-plan that is developed merely one hour ahead of time is an example of a flexible short-run scheduling operation; this would be a flexible operation in effect.

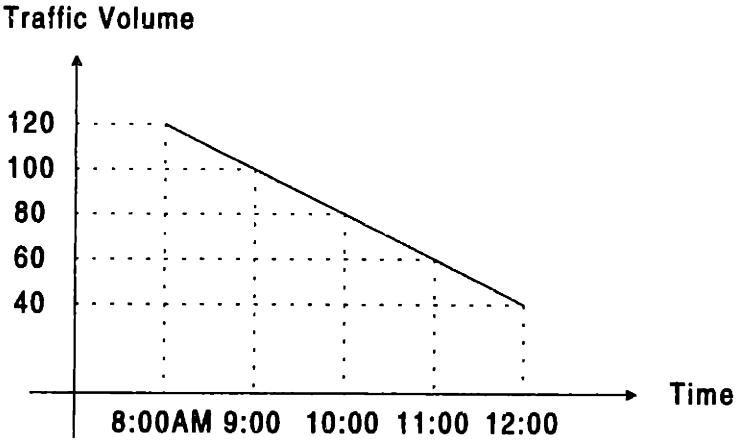

Figure 1-1: A Flexible Dispatching Policy

Definition of flexible operation

If a railroad operation cannot be considered as either schedule-adherence operation or flexible short-run scheduling operation (e.g., the definitions are not satisfied), we say that the railroad operation is a flexible operation. A flexible operation uses rules and procedures in addition to or other than schedules to determine when to run trains. One example of a flexible operation is the traffic-oriented dispatching practice. The simplest case for this policy can be expressed by the following inequality:

$$v(train) >= n \tag{1.4}$$

where, $v(train)$ is the traffic volume of a train at the terminal in consideration. Equation 1.4 says that the traffic volume of a train should not be less than n cars when the train departs the terminal. A more flexible dispatching policy is as shown in Figure 1-1. The scheduled departure time is 8:00 AM. The train will depart the terminal on-time only if there are enough cars to fill out the train, in this case 120 cars. If fewer than 120 cars are available at time 8:00 AM, it can depart at 9:00 AM if at that time 100 cars are available, and so on.

Differences among schedule-adherence, flexible short-run, and flexible operations

Blocks: A railroad's blocking policy determines what cars are assembled into which blocks at each yard. From the operating plan, the blocks at each yard are defined; this can vary by time of day or day of week. Car to block assignments are also defined by the operating plan. For schedule-adherence operation, the blocks at each yard, car-to-block and block-to-train assignments are always the same as in the operating plan. For flexible short-run scheduling and flexible operations, they could vary on a daily basis.

Terminal Operations: Terminal operations usually focus on classifying cars from inbound trains and assembling them to outbound trains. Railroads do not normally schedule terminal operations, although they do schedule resources, e.g., switch crews and carmen working on each shift. They may also schedule train connections, often by use of cutoff times, defined as the latest time that an inbound train can arrive and still have its cars classified in time to make a connection to an outbound train. If trains are scheduled and operated according to schedules, then connections will in effect be scheduled. If train arrivals are unreliable, then cutoffs could give different connection standards based on actual conditions such as the actual arrival times rather than the scheduled times.

Locomotive Distribution: For schedule-adherence and flexible short-run scheduling operations, enough locomotives must be available so that the departure schedule for each outbound train is satisfied. Which locomotive is assigned to which outbound train could be, but usually is not, specified in practice. For flexible operations, the availability of locomotives is a key feature of the current operating environment and therefore an important factor in deciding when to run trains.

Crew Assignment: For schedule-adherence operation, each road crew is usually assigned to a particular outbound train. Every road crew knows which trains they will run. For flexible short-run scheduling and flexible operations, crew assignment could be flexible, meaning that a crew can be assigned to different trains at different time of day or day of week. For yard crews, schedule-adherence, flexible short-run scheduling, and flexible operations are likely to be similar, in that crew assignments are clearly specified (e.g., who will go to which shift) but not their workload.

Train Schedules: For schedule-adherence operation, the train schedules are fixed from the railroad operating plan. For flexible short-run scheduling operation, the train schedules are given from a short-run plan which is developed at least eight hours ahead of time. For flexible operation, there are no schedules for trains.

Car Schedules: Under schedule-adherence and flexible short-run scheduling operations, cars can have trip plans (or car schedules) that indicate the sequence of trains that will be used to move them to their destinations. For flexible operation, since there are no train schedules, it is impossible to have car schedules.

The major difference between schedule-adherence, flexible short-run scheduling, and flexible operations is the degree of schedule-adherence. In practice, not all trains are scheduled for a railroad, but it is also unlikely that all the trains would be unscheduled. In general, at least some high priority trains such as intermodal trains have schedules, while some low priority trains such as bulk unit trains run when resources are available.

1.4 Hierarchical management for railroad operations

Railroad operations are managed hierarchically. There are several layers in the management of the railroad operations. Based on the studies in [64, 56, 57], we define three management levels in railroad operations: *strategic, tactical,* and *operational.* Some decisions may fit into more than one level of management depending on the scope and time frame of the decisions. Figure 1-2 shows a framework which incorporates the three levels of railroad management, different operating strategies, and railroad performance.

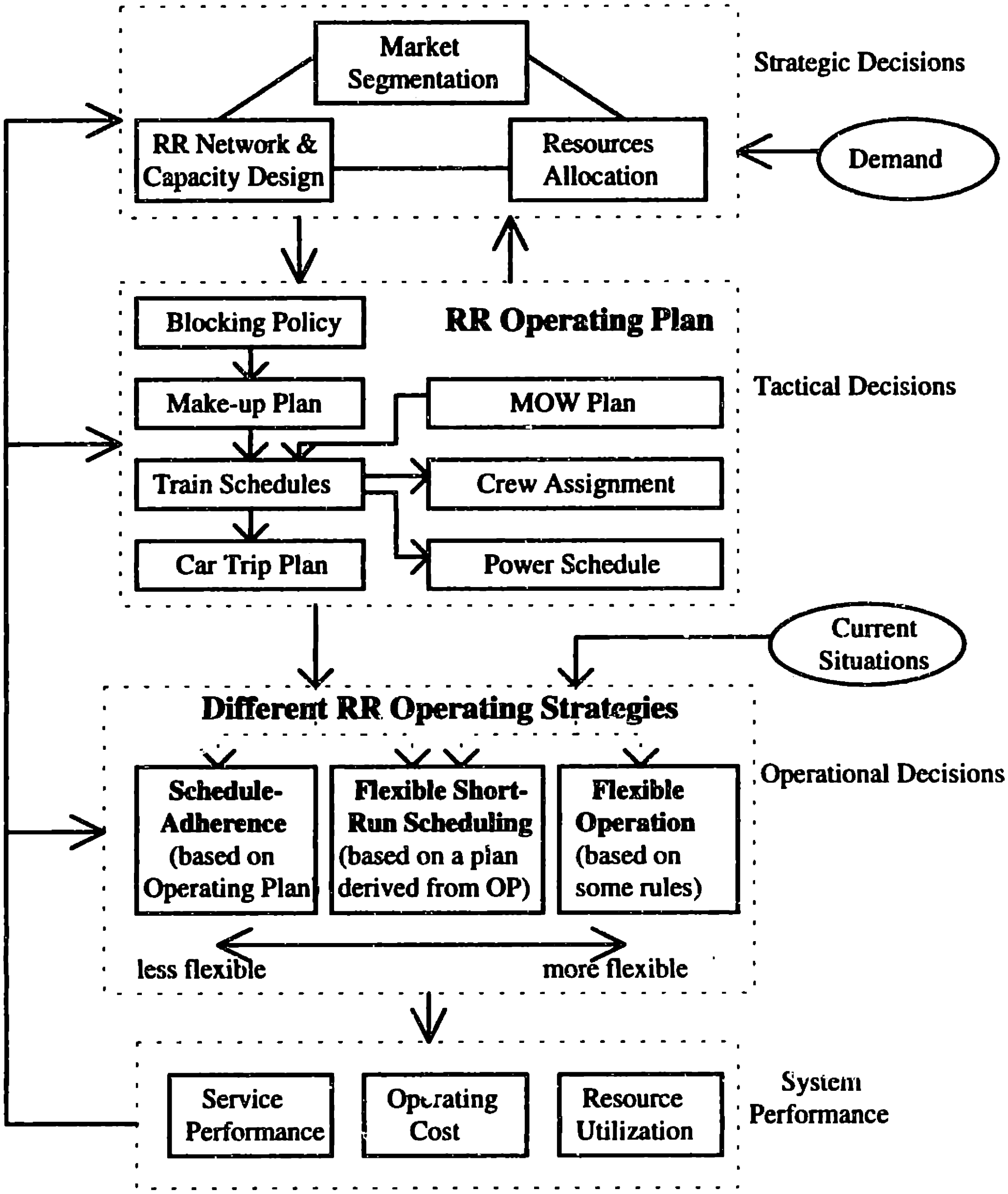

Figure 1-2: Hierarchical Management for Railroad Operations

1.4.1 Strategic management

Strategic management[18] mainly deals with long-term and large capital investment decisions and long-term marketing decisions; these have significant impact on railroad operations. The time frame for this management is long, usually on the order of 1 to 10 years, depending on the nature of the decisions. This level of management also involves acquisition and merger with other railroad(s), or abandonment of unprofitable railroad lines and (or) terminals.

To relate to railroad operations, strategic management involves provision of different services to customers, rail network and capacity design, and resources (such as road power units and crews) allocation over the rail network. Demand[19] is a major factor considered in strategic management, since in essence, what railroads provide is transportation service to customers. The output of strategic management are strategic plans for possible merger and acquisition, expansion of railroad capacity and facilities, marketing, and service differentiation and improvement. The decisions from the strategic management affect lower levels of decision-making, tactical and operational management.

1.4.2 Tactical management

Tactical management has medium-term (e.g., seasonal) horizons due to the effects of changes in factors such as demand and weather. This level of management focuses on effective usage of existing resources, rather than on major investments. The decisions under this management level usually treat demand as given and deterministic and deal with how to move the traffic from their origins to their destinations using the available system resources. The major output of tactical management is an *operating plan* which includes:

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[18] Sometimes it is also called strategic decisions. See [51].

[19] From a broader view, demand also includes the service requirement from customers.

Blocking policy which specifies how to group cars (maybe traveling between different O-D pairs) into different blocks[20] which are taken by outbound trains at each terminal;

Train makeup plan which specifies the blocks each train can carry in a preference order at each terminal;

Maintenance of way (MOW) plan which specifies the plan or schedules to conduct the maintenance of way;

Train schedules which specify each train's routes, and arrival and departure times at each terminal. The blocking policy, train making-up plan, and the MOW plan are the input for developing the train schedules;

Crew assignment which specifies how crews are assigned to trains. The train schedules are input for developing the crew assignment;

Power schedule which specifies how power is assigned to trains. The train schedules are input for developing the power schedule;

Car trip plans which specify the sequence of trains a car will join during its journey from its origin to its destination and intermediate terminals the car will be classified at.

Depending on different operating strategies, the operating plan has significant impact on operational management decisions for at least some aspects if not for all the aspects mentioned above.

1.4.3 Operational management

Operational management deals with the management of day-to-day activities in a detailed and sometimes dynamic environment. The current and short-term predictions

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[20] A block is defined as a group of cars that will be grouped together for movement to their next destination, which could be another terminal or a customer's siding.

are important factors considered in operational management. Operational management requires the greatest level of information regarding local conditions and their relationship to system performance.

One of the major characteristics of operational management is the degree of schedule-adherence[21], which is the major concern we seek to address in this research. The different operating strategies (e.g., SCH, FSS, and FLX) represent different degrees of schedule-adherence. The schedule-adherence strategy provides least flexibility in carrying out the train schedules and the flexible operation strategy has most flexibility in carrying out the train schedules, while the flexible short-run scheduling strategy holds the position between the schedule-adherence and the flexible operation strategies in degree of schedule-adherence.

Some examples of operational management decisions include: *train timetable, empty car distribution, power distribution,* and *extra trains* or *train cancellations.* Depending on different operating strategies, there are different degrees of leeway in operational management. The schedule-adherence strategy requires, for example, that the train timetable is the same as the train schedules and extra trains or train cancellations should be avoided whenever it is possible.

Operational management has direct impact on system performance since it is under this level of management that day-to-day operations are conducted.

Upper level of management may need to get feedback from lower level(s) of management. The system performance often affects all three levels of management, probably in different time frames.

1.5 Research objective and approach

In this research, we focus on modeling and evaluating railroad operations under different operating strategies. We try to understand the characteristics of various types of railroad operations, which should be implemented and what kind of railroad per-

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[21] Other characteristics may include cost minimization, service maximizing, and profit maximizing. The operating strategies under these forms of operational management are not addressed in this research.

formance would be achieved under different operating strategies. Various railroad operating conditions such as stochastic demand, probabilistic processing times at yards, etc. are changed and used in the evaluation to see how these operating conditions would affect the choice among operating strategies. Based on performance achieved under different operating strategies, we try to draw conclusions in terms of which operating strategy is best under what kind of operating conditions.

To achieve the research objective, we first identify and capture the major characteristics of the railroad operations and incorporate them and other realistic considerations into our modeling effort. The discussions of railroad operations (in section 1.2 on page 15) and the major characteristics of different operating strategies (in section 1.3 on page 18) suggest that different operating strategies are mainly implemented in *terminal operations* in that OB trains are assembled and run based on different degrees of schedule-adherence under different operating strategies. For example, the flexible operation strategy requires that OB trains are assembled at terminals whenever the traffic warrants the operation, while the schedule-adherence strategy requires that OB trains are assembled some time ahead of its scheduled departure so that it can depart on-time according to the train schedules. On the other hand, the local pick-up and delivery operations and the line haul movement operation are not much different for different operating strategies.[22] Therefore, we first focus on modeling terminal operations under different operating strategies.

To model terminal operations, we developed a methodology that decomposes terminal operations into processes and tasks and models these tasks in the processes by specifying or determining the processing sequencing for these tasks. Two analytical terminal models, the *intermediate terminal model (ITM)* and the terminal *processing sequencing model (PSM) system,* were developed using the methodology.[23] They

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[22] The differences of these operations under different operating strategies are discussed in section 1.3.2 on page 24.

[23] The methodology and models are also an important tool to address the terminal service performance problems, which were a critical part for improving railroad service performance and not addressed properly in railroad practice and research. See [59, 54, 16, 60] for discussions. The models were used by several Class I railroads in North America as tools to analysis terminal problems. See [19, 5, 38].

serve as a demonstration of the methodology and decision support tools for terminal managers and can be used to estimate terminal performance under different operating strategies by specifying, as a model input, a specific IB arrival pattern and OB departure requirement for a shift or a day.

To analyze the arrival and departure patterns of the trains at terminals under the scheduled and flexible operations, we developed a *stochastic terminal model (STM)*.

Based on the conclusions from the stochastic model[24] and the methodology incorporated in the ITM and the terminal processing sequencing model system, we developed a *microscopic terminal simulation model (TSM)* as a tool to evaluate terminal operations and performance under different operating strategies for a period of time long enough (e.g., one month) to get realistic estimation of terminal performance. A case study using real data from a Class I railroad was conducted and various scenarios were designed and used to evaluate the terminal operations under different operating conditions and under different operating strategies.

After we modeled and evaluated terminal operations under different operating strategies, we then moved to the network level to simulate and evaluate a network's operations under different operating strategies to get realistic estimates of network performance, including terminal performance, train performance within the network, and the system level resource utilization such as the utilization of road crews and power units. The network operations include several terminals' operations, both large hump terminals[25] and intermediate terminals[26] and the line haul movement operations among the terminals.[27] Two case studies using two portions of a real physical network from a Class I railroad were conducted to evaluate the network operations and performance under different operating strategies. In case study one, the model simulates the operations of a *service lane network,* where there are two

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[24] They are used to specify IB train arrival patterns at the terminals under different operating strategies.

[25] A hump terminal is a form of classification terminal, where the major classification facility is a "hump". See [3] for detailed description.

[26] Note the difference of the word "intermediate" used here and the "intermediate" terminal model, where "intermediate" modifies model rather than terminal in ITM.

[27] The local pick-up and delivery operations are treated as inbound and outbound trains, respectively, into and out of the terminals.

large hump terminals and several intermediate terminals between them. In case study two, the model simulates the operations of an *area network*, where there are three large hump terminals and several intermediate terminals.[28] Various scenarios were designed and used to evaluate these networks' operations under different operating conditions and under different operating strategies.

1.6 Thesis outline

The structure of the thesis is shown by Figure 1-3. The thesis is organized as follows:

In Chapter 2, we first review related practice and research in complex systems, including other transportation systems. The review focuses on the factors determining which operating strategy is used in daily operations under the given system characteristics and structure and the operating conditions outside the systems. The review is of interest to the railroad industry in that railroads can obtain insights from other industries dealing with related problems. We also review and analyze the practice and research in rail industry to identify key issues and factors determining which operating strategy is best under what kind of operating conditions.

In Chapter 3, we present terminal analytical models to address terminal operations and performance. These models include intermediate terminal model, terminal processing sequencing model system, and a stochastic terminal model. These models serve as tools for the development of a methodology to model terminal operations and performance and an understanding of the major characteristics of the schedule-adherence and the flexible operations, which are used in the development of the terminal simulation model and network simulation model in Chapter 4 and 5, respectively.

In Chapter 4, we present the terminal simulation model which simulates terminal operations under different operating strategies. Actual data from a major hump terminal of a Class I railroad is used in the simulation for the base case study. The

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[28] The network simulation model and technique developed in this research can, in principle, be applied to simulate the operations of a network with any number of hump terminals under a computer's or computer system's capability.

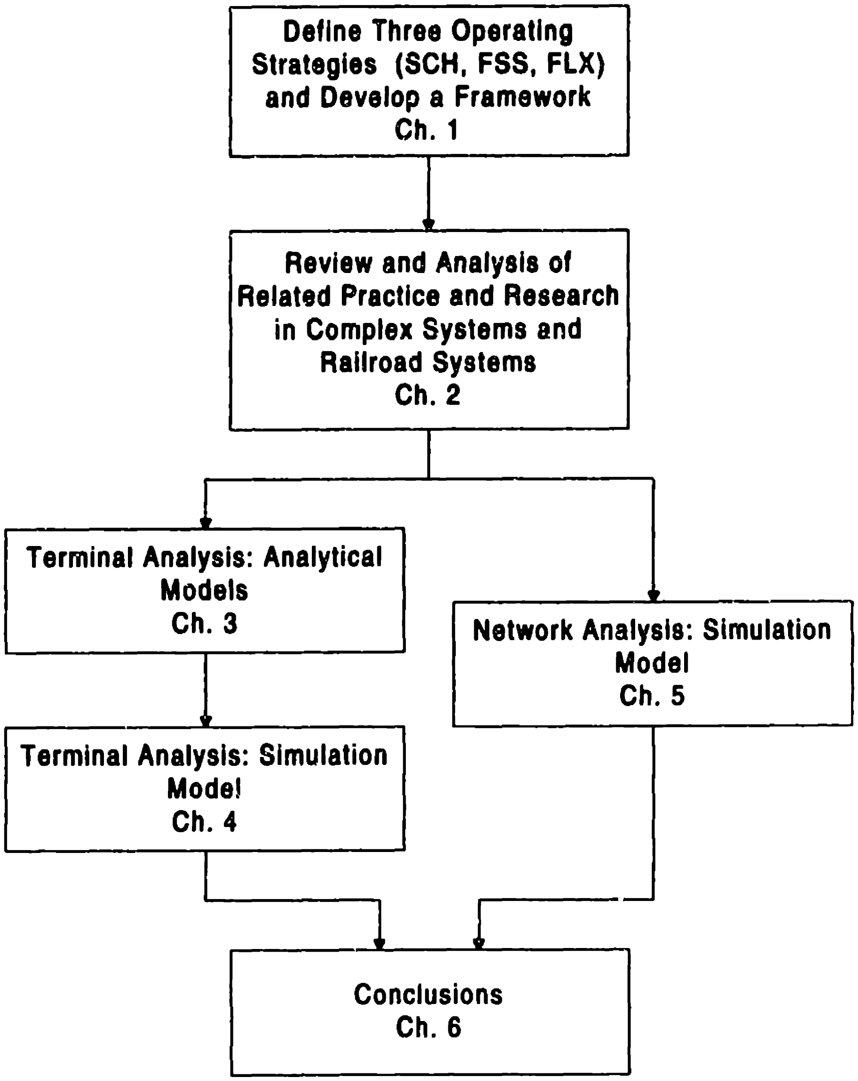

Figure 1-3: Thesis Structure

sensitivity analysis is conducted to estimate the effects of various operating conditions on terminal performance. Various scenarios are designed and used to evaluate terminal operations under different operating strategies.

In Chapter 5, we present the rail network simulation model. Two case studies are conducted using two portions of a Class I railroad. Sensitivity analysis is conducted to evaluate these networks' operations and performance under different operating conditions. Various scenarios are designed and used to evaluate these networks' operations and performance under different operating strategies, with a focus on the utilization of system resources such as road crews and power units, the terminal performance, and the train performance for each origin destination (O-D) pair.

In the last chapter, Chapter 6, we summarize the research and the conclusions from the study followed by the summary of the major contributions of the research and directions for future study in this topic.

Chapter 2

Review and Analysis of Related Practice and Research in Railroads and Other Complex Systems[1]

2.1 Introduction

In Chapter 1, three fundamental operating strategies were defined, their major characteristics were analyzed, and a framework for evaluating these different operating strategies were presented. In this chapter, we will review practice and research in complex systems, including other transportation systems, and railroads, focusing on what kind of operating strategies are used in these complex systems and what are the factors and how they affect the adoption of these operating strategies.

Railroads typically do not run according to a highly disciplined plan [59]. Depending on traffic volumes and operating conditions, trains can be early or late, consolidated or annulled or extra trains can be operated. These decisions are normally made by a centralized operations control center, based upon system policy and

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[1] This chapter is based on a working paper conducted for the Association of American Railroads (AAR) prepared with the guidance of both Prof. Joseph Sussman and Carl Martland. See [17].

input from terminal, line, and power officials.

In recent years, however, there have been discussions about operating a railroad according to a plan, with a focus on running trains according to schedules [78, 11, 37]. In [37], a scheduled approach was suggested for railroad operations. It was said to benefit customers in the form of consistent and reliable service and the railroad in the form of efficient and profitable operations. Car and locomotive utilization would benefit from the ability to plan in advance where and when equipment would be needed and available. With scheduled trains, railroads gain the ability to schedule tight connections at terminals and shorter car dwell time in yards. The positive marketing implications of the ability to better predict service times when running regularly scheduled trains were also mentioned as a benefit of scheduled operations.

Railroad operations are always affected by senior management's understanding of the trade-offs among different attributes of system performance: service, costs, and resource utilization [24]. The service requirements from shippers have also significant impact on railroad operations, since shippers have more choices and play an active role.

Some customers require scheduled operations. They explicitly ask railroads to have trip plans for their cars and provide the schedules of those trains that are used to move the cars to their destinations. Other customers may not care about how their shipments are moved if railroads can provide reliable service or information about when their shipments are going to arrive in advance. For example, some customers want a consistent schedule over a period of months; others just want advance notice about the shipments' arrival times. For the former case, shippers are more concerned with the train performance according to the train schedules and their cars' connections at terminals. For the latter case, train schedules are not necessary to provide satisfactory customer service performance.

To better serve shippers while taking operating costs and resource utilization into consideration, railroads often use both scheduled and flexible approaches to organize their operations. High priority traffic are usually moved by scheduled operation while lower priority traffic are moved by flexible operation. For example, many railroads use tighter schedules[2] for intermodal traffic than for general merchandise traffic, while unit trains operate flexibly without any schedules.

The review and analysis of related practice and research in railroads and other complex systems will provide a better framework for understanding the trade-offs among different operating strategies. There are two sets of results of general use to the rail industry.

First, we review practices and research in other complex systems, both in transportation and other field, that may be of interest to railroads. This review includes the strategies they use in their operations, why they use these strategies, and the major characteristics of these systems that determine the adoption of these strategies.

Second, we review railroad operations' practice and related research and identify key parameters, such as stochasticity, the extent of peaking, and processing variability, which can significantly affect the determination of an appropriate operating strategy under given operating conditions.

2.2 Review of related practice and research in other complex systems and other transportation systems

The issue of determining which operating strategy is best for operations is not unique to the rail industry. It also exists in manufacturing, communications, production, distribution, and other transportation systems. Advanced computer technology, operations management and operations research, engineering technique and knowledge base, control theory, large scale systems' optimization methods, and conventional strategic planning technique are among the approaches that have been used extensively to address this issue. There are many different approaches proposed and used by other complex systems. This may indicate that different approaches can be effective for the same system if properly applied. In the following review, we analyze

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[2] The schedules have tighter connections at terminals.

what strategies are used in these systems, why they use the strategies, and how the major characteristics of these systems affect their adoption of these strategies.

We first summarize the major findings in Table 2.1 and then give detailed analysis. In Table 2.1, the key system characteristics are organized in such a way that the approaches and strategies applied are in increasing order of flexibility.

Key System Characteristics	**Approaches & Strategies Applied**
Highly Related Components	Schedule with Buffered Time, Use Feedback
High Costs of Resources, Fixed Capacity, Easy to Predict Processing Time, Recovery Time Available	Scheduled Operations with Some Level of Buffered Time
Complex Hierarchical Structure	Consistent Planning (PERT & CPM) & Timely Adjusting
Need for Consolidating & Swapping Traffic	Flexible Short-Run Schedule
Multiple Choices Available	Flexibility, Robustness, Decision Tree
Need to Handle Extreme Situations	Contingency Planning
Large Peaks, Unbalanced Demand, & High Frequency	Real-Time Operations Control Strategies, Flexible Operations Dominate Schedule
High Capacity, Fast Speed	No Schedule, Use Alternative Routes, Complete Accessibility
Wait for Customers, Operate on Customers' Schedules	No Schedule, Very Flexible, Provide Service on Demand

Table 2.1: Findings from the Review of Complex Systems

Table 2.1 shows that for systems with highly related components, scheduled operation[3] with buffered times is important to achieve reliable performance. Airline systems have expensive resources, such as crews and airplanes, and fixed airplane capacity. It is relatively easy to predict processing (e.g., flight) time and there is a recovery time (e.g., during the late evening) to catch up when there are delays. They usually use scheduled operations with some level of buffered times.

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[3] The scheduled operation here may be similar to schedule-adherence operation or flexible short-run scheduling operation, since different industries may have different situations. In essence, the approach is a scheduled approach.

For the systems with complex hierarchical structures, consistent planning (which requires low processing variability and low external stochasticity) and timely adjustment are critical. For the less-than-truckload systems (LTL), the need to consolidate various kinds of traffic to the same destinations makes it reasonable to use a scheduled operation. Due to the external stochasticity and processing variability, a flexible short-run scheduling approach is usually applied in the daily operations.

For the systems facing strategic decisions with multiple choices, flexibility and robustness[4] are often significant factors to be considered in the decision making process. For the systems which need to handle extreme situations, contingency planning is usually an inevitable process. The real-time flexible operations control strategies dominate the scheduled approach for public transportation systems during large peak hours, especially with unbalanced demand and high service frequency. For telecommunication systems with very high capacity and fast speed, no schedule is needed in that the users of these systems do not need to specify when and where to use them. For the transportation systems which operate under customers' schedules (e.g., taxi operations), the operations are very flexible.

The detailed analysis is given below. This analysis is based upon examples of the planning processes used in various contexts.

2.2.1 Flexible production scheduling

A study funded by USDOT [75] developed a flexible production scheduling system for a ship building factory. The technique was originally developed in Japan. This technique emphasizes the consistent planning among different departments and tasks. The planning processing is like the application of PERT (Project Evaluation and Review Technique) or CPM (Critical Path Method). A hierarchical structure in the planning process was used (a larger task was divided into smaller tasks). The flexibility comes from the quick response of each department to the problems as they occur. It emphasized better communication among different departments (includ-

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[4] Robustness is defined as the system capability to handle different conditions with acceptable level-of-service.

ing each department's upper leader unit and lower subordinate units) and better decision-making following from communication and coordination. The critical paths for building a ship may often be changed, but the planning process is ongoing, incorporating flexibility and planning into a uniform framework. The purpose of the planning is to consistently perform all the tasks in the ship building.

2.2.2 A flexible manufacturing system with buffers

A flexible manufacturing system is a special manufacturing system that can produce multiple products using the same system. Different combinations of the components of the system will produce different products. There are many approaches used to schedule these systems, including network flow techniques, probabilistic models (including the Markov process), and flow shop modeling. Hitz [44] studied the production scheduling problem for flexible flow shops. The flexibility was shown by a serial arrangement of buffered multipurpose machines connected by a conveyer system which allows fully mechanized parts handling. The buffer is the extra time (besides the normal processing times) that is scheduled to allow for the machine to handle abnormal operations, increase the reliability of the machine and the whole system. Kimemia [46] applied network flow optimization technique in flexible manufacturing systems to get optimal operating strategies which assign each operation to a workstation and specify the sequence of workstation visits. Gershwin [36] adopted stochastic approach (a variation of the Markov process) to similar systems to incorporate feedback into the modeling effort. The purpose of incorporating feedback is to respond to and mitigate the effects of random, potentially disruptive events, thus increasing the flexibility of the system.

2.2.3 Balancing cost and flexibility

Fleischmann et al. [31] developed a decision support system (DSS) for a manufacturer of personal computers to balance the market requirements for a high service level against the cost of flexibility of the production system. The core of the DSS is a linear programming (LP) model which determines the daily variation of the production quantities (the flexibility of the production) and the resulting costs and service level. It is a multi-objective system which combines several objectives in the objective function, each with a specified weight.

2.2.4 Contingency plans

In order to improve the flexibility of a complex system, contingency plans can be developed. These plans deal with the extreme situations which can happen in the future, even through they may be unlikely. For example, during the energy crisis of the early 1970s, Massachusetts [68] developed an energy and fuel contingency plan to handle possible fuel shortages. The plan specified what procedures and decisions should be applied under various conditions. The plan included three levels of possible actions:

- allocate available supplies under some priorities and rules of procedure;
- increase available supplies temporarily by drawing down inventories; and
- restrict demand for consumption of fuel.

Berman [9] discussed how to test contingency plans for improving the ability of the system to respond to emergency situations. The US Coast Guard [39] developed "Alaska Coastal Sub-Region Oil and Hazardous Substances Pollution Contingency Plan" to handle extreme situations where the decision-makers, the related countries, organizations and their roles, the related treaties and international conventions, detailed handling procedures are all clearly listed.

2.2.5 Robust plans

Gupta et al. [41] studied the strategic problem of "robust" plans. Strategic choices depend in part upon the ability to handle variability. A "robust" plan is more effective in handling possible situations in the future. Plant selection was chosen as a case study. If only the current situation were considered, the best place for the plant (in terms of minimum cost) may be at A. But if possible future development were considered, then B may be better for most situations. So, the best place to build the plant may be at B, even though the cost for building the plant at B is not the minimum one.

2.2.6 Transit scheduled planning and flexible operational control

Wilson [77] gave a comprehensive review of bus operations planning and operational problems. The strategic planning deals with the transit network and service design. The tactical planning focuses on how to allocate available resources (e.g., buses and drivers) to provide the best possible service at the least cost. The operational planning deals with how to develop schedules for service (timetables), vehicles, and crews. This level of planning also schedules spare drivers who are required to be available to fill in for absent regular drivers and to provide unscheduled extra service which is required from time to time.

From the planning point of view, transit operations are scheduled. For the daily transit operations, however, different strategies may be applied. For example, with an automatic vehicle location and control system (AVLC), the dispatcher now has several strategies for dealing with a vehicle that is delayed: take measures to help the vehicle catch up with the schedule, or delay the following vehicles in order to insure an even frequency by preventing bunching. For transit systems without very serious congestion, daily operations control may focus on adherence to schedules while for heavily congested systems, real-time scheduling of buses is usually applied. For the latter case, which stops will be served or skipped is decided for each departure of a bus.

Eberlein [26] studied real-time control strategies in transit operations, which include station control, interstation control, and others. Transit systems usually have very large peaks. They use very short headways during the peak and the capacity of buses or trains could be very large during the peak hours since many standees can be added. Most of the strategies are examples of flexible operations in transit operations. Station control contains two main classes of strategies: holding trains to equalize headways and station skipping, which includes deadheading, expressing, and short-turning. Interstation control includes speed control, traffic signal preemption, etc. Other strategies includes adding vehicles and splitting trains.

2.2.7 Frequent, unscheduled operations

Winner [78] pointed out that many subways and transit systems do not adhere to schedules. The service is so frequent that riders just arrive, expecting a train to arrive within a few minutes. Customers' perceptions of service performance (such as reliability) are based upon the frequency of the service. Air shuttle services work the same way; the high frequency of service and ease of getting a seat usually make the schedule unimportant. Another business where service reliability is normally very good but not scheduled is in taxi and paratransit services. Such services run on customers' schedules, not published ones. Many over-the-road trucking services operate this way. Service is not scheduled, it is provided on demand. So schedules are not important to service reliability where service frequencies are high or where service is so individualized that customers determine the schedule.

Larson and Odoni [53] applied geometric probability, queuing theory, and network theory to urban service systems (including transportation services) problems. The problem settings are simple. For example, a fire truck needs to reach the fire or a salesman needs to visit each city at least once in the area or region. The problems are how to perform the activities efficiently by taking advantage of flexibility when performing these activities and how to predict the long-term behavior of the systems, such as the travel times.

For urban transportation systems, commuters usually have fixed home-to-work schedules (based upon their work schedule), but they have the flexibility of mode and route choice [15, 70, 7].

For telecommunication networks, the service is not scheduled; customers make their own calls and access the network when they want. Advanced technology has created high capacity telecommunication systems, and service reliability depends upon having sufficient capacity in the network to provide the service customers need. Since telecommunications are very fast, it makes no difference if alternative routes rather than the shortest routes are used. The telecommunication center switches and routes calls.

2.2.8 Flexibility in scheduled airline operations

For the airline industry, there are many approaches used to increase the flexibility of the airline operations. Unlike the transit systems, airlines do not take extra people in an airplane. The airlines must spread the demand. To handle stochastic demand, Belobaba [6] proposed the application of booking limits on the number of seats available at different prices on the same flight. The seat inventory control problem, which is one of the important areas for yield or revenue management, is to determine the number of seats to make available to each fare class from a common or shared inventory so as to maximize total expected revenues for a scheduled future flight departure. Berge et al. [8] proposed demand driven dispatch approach to handle stochastic demand. The assignment of airplane capacity to flight schedules to meet fluctuating market needs by this approach was proposed as follows: utilizing a demand forecast which improves as the flight departure approaches, aircraft are dynamically assigned to flights to better match the predicted final demand. Flexible assignment of aircraft allows scheduled flights to handle more or fewer people.

Since the fuel on any airplane is limited and it is relatively easy to predict flight time, it is possible to increase the flexibility of the airline operations to improve the system performance. Terrab and Odoni [72] proposed using a ground-holding approach to handle the congestion at some airports. They analyzed the fundamental case in which flights from many origins must be scheduled for arrival at a single, congested airport. The purpose of the analysis was to determine the assignment of ground-holding times to flights, i.e., the determination of whether and by how much the take-off of a particular aircraft headed for the congested airport should be postponed to reduce the likelihood and extent of airborne delays. Usually, since there are buffers in the schedules, the service is still reliable.

2.2.9 Optimization of schedules

Due to the high costs of resources such as crew and airplane, and since it is relatively easy to predict flight times, airlines usually schedule resources and flights. The schedule for flights allows complex optimization techniques to be used to schedule expensive crews and airplanes. The crew scheduling problem deals with how to assign crews optimally (in terms of cost) to different flight legs to cover all flights while various crew, airplane maintenance, and other constraints are satisfied [27]. The aircraft rotation problem deals with how to assign different kinds of aircraft to cover all flights to satisfy demand while using minimum number of aircraft and satisfying various maintenance and operational constraints [27]. The air flow scheduling problem deals with how to develop a tactical plan for moving flights over the network [63, 10].

At some level, time buffers are added in the schedule that allow considerable operating flexibility. This operating flexibility is required to handle stochastic and uncertain situations such as unfavorable weather conditions and peak-hour demand.

Like public transportation systems, airlines have clear off-peak hours (e.g., at night), which provide much potential to recover from the deviations of schedules and to maintain their equipment such as aircraft. This recovery time is naturally available for airlines by the demand pattern. The travel demand in late evening and early morning is limited so that airlines can maintain their aircraft and let the crews rest.

For trucking and less-than-truckload (LTL) industry, Powell and Sheffi [65] proposed using an interactive optimization system for network design problem. This problem is to route freight over a less-than-truckload motor carrier network. The output of the problem can be regarded as schedules for a period of months. The operational schedules are usually obtained by modifying the model results by taking actual available traffic, current network situations, and available resources into consideration. Braklow et al. [32] discussed a model, named SYSNET, which was used by Yellow Freight System. In addition to be applied in long-range network design problems, SYSNET was mainly used in tactical load planning, which involves monthly planning and revision of the set of instructions that govern handling and consolidation of shipments through the network. The load plan is static, with contingency provisions to handle daily fluctuations in the freight. The application of the strategies reported a significant improvement in both travel time and travel time reliability. These are examples of flexible short-run schedules guided by a fixed schedule.

Table 2.2 (on next page) summarizes the major findings from these examples, showing the approaches used, research strategies followed, and the key characteristics of the systems.

2.3 Review of railroad practice and research

2.3.1 Railroad practice in operations

Winner [78] discussed whether freight railroads should maintain schedules, like airlines. He concluded that schedules per se were not necessarily important. But it is important that railroads meet customer requirements and expectations. He reported that railroads generally agreed with the premise of his opinion while shippers did not. He pointed out that some railroads thought they should schedule some trains but that they should charge more for scheduled services.

The railroads who participated the RASIG Annual Meeting at New Orleans in 1995 [18] generally supported a scheduled approach, but one that allowed considerable flexibility in implementation. A senior representative of Norfolk Southern said that for service reliability, scheduled operation is a great idea because this approach facilitates fulfilling service commitments. But even under the scheduled operations, the railroad should allow running second sections,[5] consolidating traffic, and canceling trains, when economics dictate and when their own equipment needs and customer delivery schedules can be met. The railroad favors scheduled operations while emphasizing the importance of increasing flexibility.

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[5] Due to the capacity limitation of a scheduled train, the train can be assembled second time to carry the traffic left by the first train. This train is called a second section train.

Systems	Sys Characteristics	Strategies Applied
Flexible Manufacturing Systems	Multi-Machine Systems	Buffered Time, Use Feedback Optimization & Prob Models
Large Production Systems	Hierarchical Structure	Better Communication Quick Response Consistent Planning (PERT) Continuously Adjusting Plan
Small Manufacturing Company	Focus on Market & Costs	Multi-Objective Management
Facility Location	Multi-Choices	Flexibility, Robustness Decision Tree, Prob Models
Energy Supply	Extreme Situations	Contingency Plan
Telecom Networks	High Capacity Fast Speed	No Schedule, Accessible
General Public Transit	Large Peaks Unbalanced Demand Short Headways Add More People	Real-Time Control Strategies
Some Subways Air Shuttle	High Frequency	Flexible Operations
Taxi	on Customer's Schedule	Very Flexible
Urban Systems	Peak Home-to-Work Schedules	Flexible Choices & Analysis
Airlines	High Resource Costs Fixed Capacity Limited Fuel Predictable Flight Time Recovery Time	Scheduling Crew Scheduling Aircraft Air Flow Optimization Seat Inventory Control Yield Management Demand Driven Dispatching Ground Holding
Trucking (LTL) Systems	Hierarchical Structure Consolidating Demand	Flexible Short-Run Schedules with Real-Time or Close to Real-Time Implementation

Table 2.2: Review Summary for Complex Systems

During the meeting, a senior representative from Conrail said that Conrail used a fixed schedule for train operations. The results of the fixed schedule were better service, lower cost, and more locomotives. He reported in detail how the railroad developed an operating plan and implemented the plan. During the first half of 1994, Conrail forecast traffic, developed the operating plan, and estimated capacity (under different conditions such as snow). Executing the plan resulted in frequent extra sections and asset imbalance. Now Conrail is developing an operating plan with the participation of marketing, financial planning, system transportation planning, and all related divisions. Their goal is to design an operating plan that improves transit reliability while maintaining costs and equipment utilization.

The representative of Santa Fe thought that the scheduled operations were important to achieve better service. He also thought that the equipment cycle was very important. Burke [11] reported that besides Santa Fe, Norfolk Southern, and Conrail, Union Pacific, CSXT, Southern Pacific, and Burlington Northern are all moving toward scheduled service. CSXT is developing a flexible short-run schedule which is used in daily operations.

For many railroads, the concept of a scheduled railroad encompasses not only the schedule, but also a network or system plan implemented, run and directed from a central point. By doing this, it allows for some flexibility and aims at maximizing resource utilization across the whole railroad while meeting the customers' schedules. Railroads have been centralizing decisions concerning how much flexibility to allow in operations. For example, CSXT, UP and other major railroads have established centralized systems for operations control, power management, crew management, and customer service. The purpose of these control systems is to achieve better communications among the different functions of the system, provide better service to customers, and respond more quickly to possible problems.

2.3.2 Related research and approaches for railroad operations

The review in this section focuses on the research which shows how different approaches or strategies can be applied to different components of the rail system. We will not conduct extensive review of studies for different components of the rail system. We first present the major approaches and ideas of related research in applying different operating strategies in various components of the rail system in Table 2.3. A detailed literature review follows.

Problems	Approaches and Strategies
Stochastic Demand	Reservation & Booking Systems (SCH Approach)
Terminal Performance Problems	Probabilistic Connection Standard (Allow Some Flexibility) Hump Sequencing (FSS Approach) Hump Sequencing & Classification Track Assignment (SCH Approach) Hump & Assembly Sequencing (FSS Approach) Statistical Process Control (SPC) (SCH Approach) Terminal Operating Plan (TOP) (FSS Approach)
Line Haul Movement Problems	Master Scheduling & Real-Time Scheduling (SCH & FSS Approaches) Real-Time Meet/Pass (FLX or FSS Approaches)
Crew & Power Requirements	Power Scheduling (FSS and SCH Approaches) Crew Scheduling (SCH and FSS Approaches)
Unreliable Train Movement	Train Scheduling (SCH Approach) Short-Run Schedule (FSS Approach)
Unreliability of Car Trip Times	Dynamic Car Scheduling (FSS Approach)
Unreliability of Rail Network	Consistent Scheduling (SCH Approach)
Service Design	Service Differentiation (SCH Approach)
Bad Weather	Contingency Planning (SCH Approach)

Table 2.3: Summary of Approaches in Rail Freight Transportation

Table 2.3 shows that to deal with stochastic demand and better utilize available capacity, railroads can use reservation and booking system to smooth high priority demand such as intermodal traffic. To achieve better terminal performance, the following approaches were proposed: using probabilistic connection standards; developing hump sequencing, hump and assembly sequencing, and hump sequencing and classification track assignment; applying statistical process control techniques; and using a formal terminal operating plan. To handle the variability of line haul movement, railroads can develop master schedules or real-time schedules and real-time meet/pass plans. To reduce dynamic variations in the demand for crews and power, the scheduled approach usually dominates the flexible approach. To improve train reliability, both scheduled and flexible short-run scheduling approaches were proposed. To improve car trip time reliability, a dynamic car scheduling, which was a flexible short-run scheduling approach, was proposed. To improve network reliability, consistent scheduling and service differentiation were proposed, both being scheduled approaches in nature. To handle extreme weather conditions, contingency plans were developed.

The detailed literature review is given below.

Kwon and Martland [52] simulated the effects of traffic variability, line haul reliability, and controls on dispatching trains from terminals on rail network reliability. This work was based upon earlier work of Folk and Sussman [35]. Both studies simulated train operations over a small network under a variety of assumptions concerning demand variability and train makeup policy. The simulation results showed that in the base case, which was characterized by tightly scheduled connections, the main causes of unreliability were missed connections and delays related to late arrivals of inbound trains. O-D traffic variation affected network reliability, but less significantly than line haul time variation affected network reliability. The simulation results also showed that network reliability can be significantly improved by implementing policies that allow a moderate degree of flexibility in deciding when to originate trains and that require trains to run even if they are substantially shorter than desired. The effects of train cancellations were found to be very strong, in two ways. If train makeup policy required a high minimum train length, then the average train length could be pushed very close to the train length limits, with corresponding improvements in capacity utilization and reductions in crew and locomotive costs. On the other hand, such policies resulted in more delays than any other situation studied.

Harker et al. [43] studied the management and information systems required for a successful Advanced Train Control Systems (ATCS). They proposed two extreme cases of scheduling strategy: a master scheduling strategy and a real-time scheduling strategy. A master scheduling strategy was defined to be the periodic establishment of timetables that govern arrival and departure times based on a periodic review of demand levels and resource availability. Once established, the schedule would be in effect until the next scheduling period, subject only to minor revisions in the interim. This strategy is analogous to airline scheduling strategies. Real-time scheduling operates over a considerably shorter planning interval. Under this strategy, timetables are continually revised as capacity on the network and demand in the market place change. Real-time scheduling strategies are analogous to trucking schedules, which are determined daily according to demand and resource availability. They said that in practice, scheduling strategies incorporate characteristics of each extreme, and therefore hybrid designs are warranted. Harker [42] and Jovanovic and Harker [45] discussed the scheduling of rail operations and developed models and algorithms to establish real-time schedules. The purpose of the real-time scheduling system was to attempt to achieve the times stated in the tactical schedules with a high degree of certainty.

There are many optimization models that address crew and locomotive assignment problems. These models commonly assume fixed demand pattern. For a given schedule, these models try to optimize assignment of crews or locomotives to get better resource utilization. They are usually used as tactical tools. There was one exception by Smith and Sheffi [71]. They studied locomotive scheduling under uncertain demand. Recognizing that power requirements for each train are sometimes not known with certainty, and the fleet of locomotives may not be homogeneous, they dealt with both of these complications by formulating a multicommodity flow problem with convex objective function on a time-space network. The convex objective was used to minimize expected cost under uncertainty by penalizing trip arcs likely to have too little power. This example shows how it is possible to optimize resource utilization under uncertain demand if train operations are scheduled.

Terminal operations are shown by many researchers as an important area for the rail system [58, 59, 16]. Yagar et al. [79] presented an algorithm for sequencing the hump process. They modeled yard activities using simulation methods, while the hump sequencing decision relied on dynamic programming. The effort of this research was to try to develop a flexible short-run hump sequencing schedule to improve terminal performance. Guignard and Kraft [40] presented a mixed integer programming model that determined the hump sequence and classification track assignments. The objective was to improve the effectiveness (i.e., meeting the time constraints) and efficiency (i.e., doing so at minimum cost) of the yard operations. This model solves the hump sequencing and classification track assignment simultaneously by modeling the combined problem as a multicommodity flow across a time-space network. The drawback of this optimization approach is that, as the size of the planing horizon and number of variables increase, the problem becomes difficult or impossible to solve. Ferguson [33] connected the field of machine scheduling with the yard sequencing problem using a mathematical model that represents the yard problem as a two-machine sequencing problem. The objective in this formulation was to minimize the maximum tardiness of outbound trains. The model results gave the classification and assembly sequences. These approaches clearly were examples of flexible operational planning.

Martland [58] presented the PMAKE model as a means to describe the probability of a car making its connection given its scheduled yard time. PMAKE analysis has proven to be more effective than car scheduling in predicting both yard and O-D performance (e.g., Case Studies of Boston & Maine in [28] and Santa Fe in [29], and terminal control systems [30]). These studies showed that terminal connections were not reliable, which made it difficult to schedule train connections at terminals.

Duffy [22] focused on how to reduce processing time variability in terminals. Terminal processing times were shown by him to be highly variable, which was an important reason for missed connections. Processing time variability was also an important factor in making terminal scheduling difficult. He draw a parallel between the processing functions of the yard and the production line in a general manufacturing setting. Using data gathered at CSXT's Radnor Yard in Nashville, he determined the mean and variance for each of the major yard processes. Standard methods of statistical process control (SPC) were used, with time-series plots proving easy identification of activities gone abnormally. The causal analysis for the points identified as "out-of-control" was conducted. The purpose of the analysis was to identify when the system was out of control, determine the cause, bring the processing under control, and influence the variables that can bring the yard processing rates closer to their desired values.

MIT's research on service reliability indicated a need to provide better support for managing task level operations in terminals [59]. Dong [16] proposed using a formal terminal operating plan (TOP) as a tool to improve terminal operations, trying to make terminal operations more scheduled by developing a flexible short-run schedule. The notion of achievability of a TOP was developed, which is the likelihood that a set of tasks that are assigned by the terminal managers will be accomplished within the time allotted for completing the tasks. It can be used at the system level to assess the overall likelihood that the terminal will complete its set of tasks, at the terminal level to determine which processes are most in need of careful supervision, and at the task level to ensure that work assignments are reasonable.

For other aspects of the rail operations, there are also many interesting ideas and approaches. To balance stochastic demand, Kraft [50] proposed using a reservation and booking system for rail freight transportation, which is like passenger transportation. This approach is based on service rather than price differentiation. Kwon [51] presented a method to differentiate service among different customers according to their different service requirements. He kept scheduled train service but assigned cars flexibly to blocks. Martland et al. [59] discussed how to link terminal control systems to advanced line control systems to get more reliable service. Christodouleas [14] presented an approach to planning terminal and line operations together to form a consistent network plan, in which each component is connected with each other. For example, the output of a line segment in terms of leaving time of the line segment to its adjacent terminal is the input of the terminal. The emphasis of this research was to optimize all the components of the network simultaneously.

Kraft [49] proposed a concept of flexible scheduling in freight railroad operations. The main points of the concept were to have a scheduled network and precision adherence to schedule, no annulments, extra sections operated as needed, and a traffic priority system that improves train capacity utilization and reduces the need to run unplanned extras. CSXT is said to have applied similar but not identical approaches in its daily operations [24]. CSXT determines train schedules 12 to 18 hours ahead of time and adhere to the schedules.

To handle extreme situations, a Chicago operating and winter contingency plan [13] was developed by a major railroad. This plan illustrated some aspects of a robust plan. The winter provided some challenging problems for rail operations in Chicago area such as reduced train size, crew and power shortage, and increased congestion over the network. Under this situation, some approaches were proposed to handle these problems such as: some traffic flows were given alternative routes for use if the scheduled route was highly congested; some block changes were defined if the weather was extremely bad; terminal operations could be changed in unfavorable situations; some candidate connections were given if scheduled connections could not be made; key telephone numbers of foreign railroads were prepared to exchange information and to facilitate traffic interchanges.

We summarize the research reviewed in Table 2.4.

2.4 Investigation of factors affecting use of different operating strategies

Based on the review of the practice and research in railroads and other complex systems in the previous two sections, we analyze what factors or parameters affect and how they affect the use of different operating strategies.

System Components	**Research Conducted**
Demand	Reservation & Booking Systems [Kraft 95]
Terminal Operations	Connection Reliability [Martland 82] Hump Sequencing (HS) [Yagar et al. 83] Hump Sequencing & Classification Track Assignment [Guigard et al. 93] HS & Assembly Sequencing [Ferguson 93] Statistical Process Control (SPC) [Duffy 94] Terminal Operating Plan (TOP) [Dong 94]
Line Haul Operations	Master Scheduling & Real-Time Scheduling [Harker et al. 92] Real-Time Meet/Pass Models and Algorithms [Jovanovic & Harker 91, Harker 92]
Crew & Power Scheduling	Power Scheduling under Uncertainty [Smith & Sheffi 92]
Train Scheduling	Flexible Scheduling [Kraft 94] Short-Run Flexible Scheduling [CSXT 95]
Car Scheduling	Dynamic Car Scheduling [Kwon 94]
Network Reliability	Effects of Traffic Variability Line Haul Reliability & Train Dispatching Policy on Network Reliability [Folk & Sussman 72, Kwon & Martland 92]
Network Level Scheduling	Consistent Scheduling [Christodouleas 95]
Service Design	Service Differentiation [Kwon 94]
Extreme Situations	Chicago Winter Contingency Plan [94] Robust Plan Development [Dong 95]

Table 2.4: Summary of Related Research in Rail Freight Transportation

From the practice and literature review of complex systems, including other transportation systems, and railroad operations, we identify the following key system parameters: processing variability, system operational structure, cost of resources, capacity, service frequency, available recovery time, the need to handle extreme situations, stochastic demand, customer service requirement, and uncertain events such as accidents, weather, unscheduled maintenance, labor disputes and strikes, and sabotage, which are important in choosing different operating strategies in operations. We use Figure 2-1 to compare how these parameters affect the adoption of different operating strategies.

Values Favoring Flexible Approach	Key System Parameters	Values Favoring Scheduled Approach
	Internal Conditions:	
High	Processing Variability	Low
Less Related	System Components	Highly Related
Low	Cost of Resources	High
Large	Capacity	Small
High	Service Frequency	Low
Not Available	Recovery Time	Available
Need	Handle Extreme Situations	Not Needed
	External Conditions:	
High	Stochastic Demand	Low
Low	Customer Service Requirement	High
More Likely	Uncertain Events	Less Likely

Figure 2-1: Key Parameters Affecting Use of Different Operating Strategies

In Figure 2-1, internal conditions are factors under system control, while external conditions are factors out of system control. Figure 2-1 shows that a complex system with low processing variability, highly related components, high cost of system resources, small system capacity, low service frequency, available recovery time, no need to handle extreme situations, low stochastic demand, high customer service requirement, and less likely of uncertain events tends to use scheduled approach, while a system with factor values in the opposite tends to use flexible approach.

Figure 2-2 shows that when internal and external factors have values favoring flex-

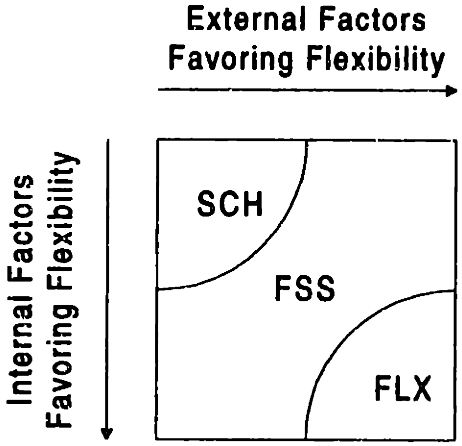

Figure 2-2: Effects of Internal and External Conditions on Use of Different Operating Strategies

ible operation, the flexible operation strategy is a good strategy for the given operating condition and the scheduled approach may not be a good choice. On the other hand, when internal and external factors have values favoring scheduled approach, the schedule-adherence strategy is a good strategy for the given operating condition and the flexible operation strategy may not be a good choice. The area between the schedule-adherence and the flexible operation strategies is the place where either internal conditions or external conditions or both do not fit well into the schedule-adherence and the flexible operation strategies. Under this operating condition, the flexible short-run scheduling strategy may be a good approach. The flexible operation and the schedule-adherence strategies can also be used depending on the values of internal and external factors.

Figure 2-3 shows some examples mainly from different transportation modes in this analysis. The large processing variability (e.g., variable time for serving a customer), high capacity, and the high stochastic demand of the telecommunication systems and the large processing variability and the high stochastic demand of the taxi operations make them use a very flexible approach. They can be grouped to the lower-right corner of Figure 2-3. For airlines, the relatively low processing variability, fixed capacity, easy to predict flying time, and smoothed demand make the schedule-adherence strategy a reasonable choice. They are at the upper-left corner of

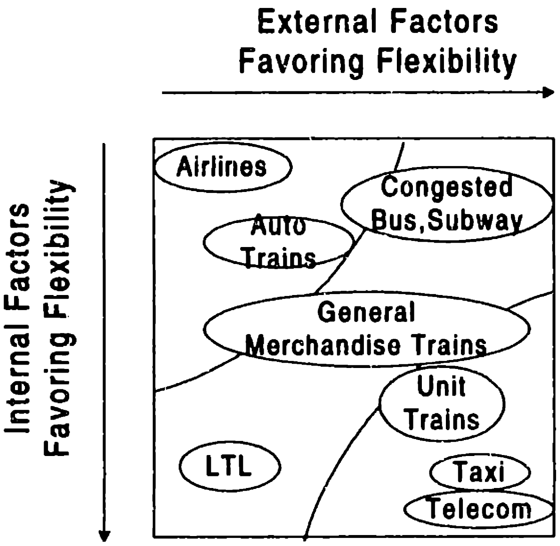

Figure 2-3: Effects of Internal and External Conditions on Use of Different Operating Strategies for Different Systems

Figure 2-3.

For LTL systems, running directs to bypass a breakbulk makes some traffic at consolidation terminals wait for and be delayed by other traffic, which significantly increases processing variability. On the other hand, the number of shippers requiring less-than-truckload service is very large. Even though the demand from each shipper is stochastic, the total demand at each terminal is very stable.[6] These conditions make it reasonable for LTL systems to use a flexible short-run scheduling approach, which develops a loading plan by incorporating current demand information. This approach corresponds to somewhere close to the lower-left corner of Figure 2-3. For heavily congested transit systems, the very high stochastic demand delays buses and trains at terminals and expands to the whole systems even though the processing variability such as running time between stations are relatively small. To deal with this situation, they often apply real-time control strategies. This flexible approach corresponds to somewhere close to the upper-right corner of Figure 2-3.

For rail systems, the processing variability and demand stochasticity for high priority traffic such as intermodal and auto trains are small and the service requirement

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[6] See, for example, [32] for discussions.

is high, so the schedule-adherence strategy seems appropriate. On the other hand, the coal unit trains can be operated at any time of the day and they are generally low priority trains that will incur many meet/pass delays, which means that the schedule-adherence operations may be unachievable. So flexible operation strategy seems appropriate for this traffic. General merchandise traffic includes various classes of traffic with different priorities between those of intermodal and unit trains. The demand stochasticity, processing variability, and service requirement may be quite different for those goods. These situations make various general merchandise traffic locate at somewhere between the upper-right to the lower-left corner of Figure 2-3. So, they could operate under the flexible short-run scheduling approach, the schedule-adherence approach, or the flexible approach. In later part of the thesis (e.g., Chapter 4 and 5), models incorporating parameters and variables representing internal conditions (such as processing variability) and external conditions (such as stochastic demand) will be developed and used to evaluate terminal and network operations under different operating strategies.

2.5 Summary and conclusions

In this chapter, we reviewed related research and practice in railroads and other complex systems including other transportation systems. We identified the following key characteristics or parameters, which affect the choice of different approaches: processing variability, system operational structure, cost of resources, capacity, service frequency, available recovery time, the need to handle extreme situations, stochastic demand, customer service requirement, and uncertain events such as accidents, weather, unscheduled maintenance, etc. These factors can be grouped into internal conditions which are under the system control and external conditions which are out of system control. How these factors affect the use of different approaches is discussed.

The low processing variability, highly related components, high cost of system resources, small system capacity, low service frequency, available recovery time, no need to handle extreme situations, low stochastic demand, high customer service requirement, and less likely of uncertain events favor scheduled approach (e.g., need schedules or short-run schedules as means to achieve better service performance and resource utilization, and to reduce operating cost). The high processing variability, not highly related components, low cost of system resources, high system capacity, high service frequency, not available recovery time, need to handle extreme situations, high stochastic demand, low customer service requirement, and more likely of uncertain events favor flexible approach. For other operating conditions, the flexible short-run scheduling strategy may be a good choice.

The review of railroad practice suggested that the railroads are, based on our definition of different operating strategies, using both the flexible operation strategy and the flexible short-run scheduling strategy in their operations, while the schedule-adherence strategy has not been fully applied in practice.

The review of other complex systems and railroad operations provide us an understanding and a better framework in terms of what factors and how they affect which operating strategy is best in operations. They are the parameters that we will use to evaluate different operating strategies. Before evaluating different operating strategies at terminal level, however, we will address the issue of how to model terminal operations in the next chapter, Chapter 3.

Chapter 3

Modeling Rail Terminal Operations: Analytic Models

3.1 Methodology

The discussions of railroad operations in Chapter 1 and 2 show that terminal operations are a major part of railroad operations. In order to evaluate railroad operations under different operating strategies, we need to understand how terminals will behave under these operating strategies. To study terminal operations under different operating strategies, we need to first develop terminal models. The terminal models developed can also be used to improve terminal operations and performance. Studies (see [59, 54, 16, 60] for example) show that terminal operations are a critical part for rail freight operations improvement. Major service problems often occur at terminals. A typical car spends most of its cycle time (e.g., around 60%) at terminals (see [16]), indicating great potential of terminal operations improvement on system performance.

As discussed in Chapter 1, the major terminal operations include:

- IB arrival;
- IB inspection;
- Classification (or hump for hump yard);

- OB assembly;

- OB inspection;

- Brake test and departure.

- Road power preparation and maintenance;

- Road crew rest and preparation.

In this research, a methodology is developed in that each terminal operation is treated as a process as in a production line of a general manufacturing setting;[1] each IB, OB train, road crew and power unit is part of the process as a task waiting to be performed. The terminal operations can then be decomposed into processes and tasks. Terminal operations and performance are a function of performing these tasks in the processes.

The major terminal performance measures include:

- Connection reliability, which measures the percentage of cars at the terminal that make their scheduled connection;

- Average yard time, which measures the average time cars spend in the terminal;

- Processing time, which measures the average time each car spends in the processes from its arrival at the terminal until its departure from the terminal;

- Operating cost, which measures the total cost of terminal operations.

This methodology is applied in developing models as tools to evaluate different operating strategies throughout this research. This methodology is also very useful to address terminal operations and performance, since it assumes that the terminal operations and performance are a function of these processes and tasks.[2]

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[1] That is, an operation in rail terminal is equivalent to a process in a general manufacturing setting.

[2] In Dong [16], how this methodology can be applied to improve terminal operations and performance is discussed in great detail.

In the next two sections, we will develop two terminal models to study the terminal operations using the methodology just described. These models can be used to estimate terminal performance under different operating strategies for a short period of time such as a shift or a day by specifying, as the model input, specific IB arrival pattern and OB departure requirement. They cannot be used, however, to estimate terminal performance under different operating strategies for a long period of time such as a month or a quarter.

The inbound arrival and outbound departure are conducted by road engines and crews; these two operations are not the major concern of terminal manager. So these two models do not explicitly model these two operations. Also the road crew and power rest and preparation operations are not under the control of terminal manager and hence not modeled in these two models.

3.2 Intermediate terminal model[3]

3.2.1 Introduction

One of the key findings of the reliability studies conducted in recent years by the MIT Rail Group is that reliability is very much related to terminal management, which is essentially the ordering and controlling of various tasks within the processes performed by the yard. The ability to model terminal operations relies on the ability to model these tasks within the processes. The ability to coordinate these tasks in order to accomplish the overall processing requirements is one of the most difficult challenges faced by the terminal manager. In practice, the terminal manager often uses a simple "rule of thumb" to organize the terminal operations. These rules take forms such as "First In/First Out", particularly among the inbound processes in the terminal (arrival, IB inspection, and classification). On the OB end of the terminal,

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[3] The model was developed under the guidance of Carl Martland, Patrick Little, and Prof. Joseph Sussman. It is actually only one part of the intermediate terminal model developed at MIT. See [55]. It is called the terminal operating plan (TOP) evaluation module. The other part of the model was developed by Carl Martland, which is called the terminal capacity module.

similarly simple rules (such as "never delay the departure of Train 111") govern the task assignments. The result of these simple rules is that the terminal is operated under a *de facto* terminal operating plan (TOP), which may or may not be adequate to achieve a high level of service. In many cases, the yard manager may not even consider the activities as being conducted under an explicit TOP, although conversations with yard managers suggest that there is something of an expected ordering of events.

These informal TOP's have several potential problems and weaknesses. First, they often do not specify which activities are to be completed in which order, leaving these decisions to the discretion of the yardmaster. This is because of the high variance in inbound train arrival times, leading to the need for flexibility. Secondly, the TOP's do not usually specify the time allotment for performing specific tasks by crews or workers. The yardmaster may indicate that the hump engine is to classify track 3 next, but rarely does he also indicate that the work should be completed by a particular time. Finally, because of the informal nature of the TOP, the lower level managers often fail to coordinate activities across the yard. If, for example, the yardmaster supervising assembly activities, the Bowl Yardmaster, considers departure of particular trains on time as the primary measure of success, he may order the assembly of trains in a manner which "runs away" from the traffic being ordered for classification by his counterpart, the Hump Yardmaster [22].

To address these concerns, the author suggested that railroads should begin the development of formal and explicit TOP's to assist terminal managers in controlling the tasks and processes in their yards. These TOP's should include the intended sequencing of tasks within each process, and an estimate of the time required to accomplish the tasks. To support the development and evaluation of the TOP, the author proposed the use of ***achievability***, which measures the probability of successfully completing the tasks and processes, and measures of the expected performance consequences of the TOP [16]. To further assist in the process of developing, evaluating, and selecting TOP's, the Intermediate Terminal Model, which we now describe, was developed.

3.2.2 The model

The Intermediate Terminal Model (ITM) is a spreadsheet model, which used the methodology introduced in section 3.1. The model estimates the connection reliability, average yard time, PMAKE parameters,[4] achievability of the TOP,[5] and the costs of the TOP. The model is organized as a series of sheets, named *Standard Plan, Revised Plan, Tasks, IB Plan,* and *OB Plan.* Each of these is discussed below, using an example with data from a Class I railroad.

Standard Plan

This sheet, shown in Figure 3-1, gives the schedule of IB and OB trains,[6] train connections, basic performance characteristics of the yard processes, and available terminal resources. The IB train schedule and expected train connections can be derived from the operating plan or analysis of historical data.

Consider in Figure 3-1, the characteristics of IB train $I1$ (the first record). This train is scheduled to arrive at 5:00 AM (on Sept. 15, 1994 in Figure 3-1), with 100 cars, and is usually yarded onto track $A1$ in the receiving yard. The composition of this train's traffic is that 5% of the cars should depart on OB train $O1$, 12% on OB train $O2$, etc. The characteristics of the OB trains are also given, again as derived from the operating plan or analysis of historical data. The first OB train, $O1$, is scheduled to depart at 23:35 PM, carrying 100 cars comprising 5 blocks and usually using departure track $D2$.

This sheet also includes a set of processing time inputs, consisting of the mean processing times (in hours) and standard deviation of processing times (in hours). We assume that the processing times in each process are normally distributed in this

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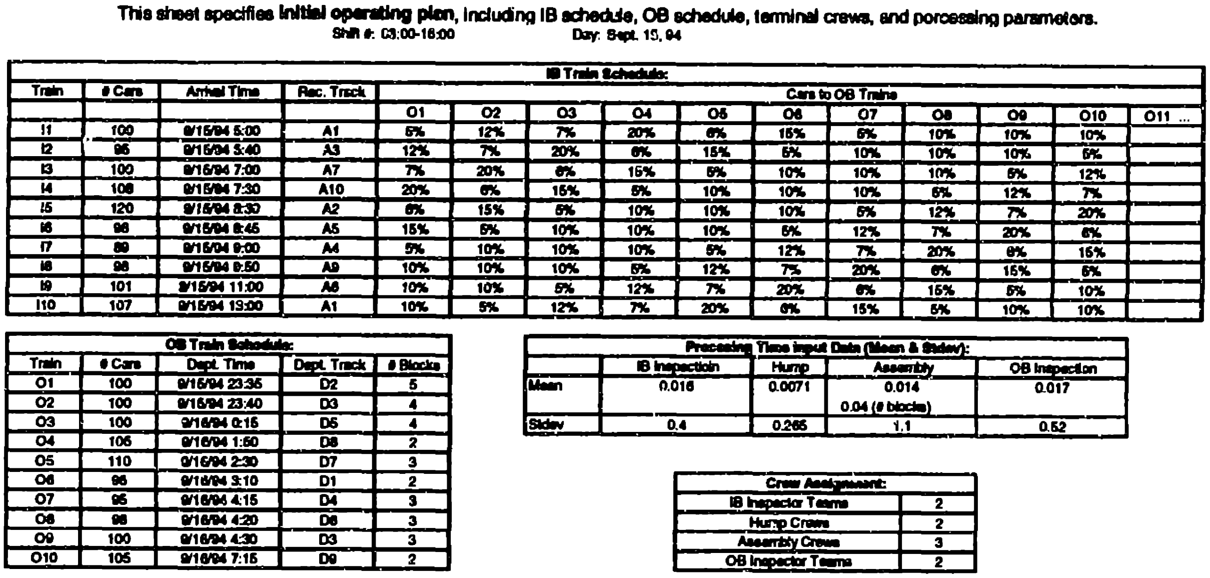
[4] They are the terminal measures of average processing time and additional time needed to achieve maximizing connection reliability. See [58] for detailed discussions.

[5] The probability of successfully carrying out the TOP. See [16] for detailed discussions.

[6] The schedule could be the train schedules from the operating plan under schedule-adherence strategy, short-run schedule under flexible short-run scheduling strategy, or predicted arrival times of IB trains and OB departure requirements from system managers under flexible operation strategy.



This sheet specifies initial operating plan, including IB schedule, OB schedule, terminal crews, and porcessing parameters.
Shift #: 03:00-16:00 Day: Sept. 15, 94

IB Train Schedule:

Train	# Cars	Arrival Time	Rec. Track	Cars to OB Trains										
				O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11 ...
I1	100	9/15/94 5:00	A1	5%	12%	7%	20%	6%	15%	5%	10%	10%	10%	
I2	95	9/15/94 5:40	A3	12%	7%	20%	6%	15%	5%	10%	10%	10%	5%	
I3	100	9/15/94 7:00	A7	7%	20%	6%	15%	5%	10%	10%	10%	5%	12%	
I4	108	9/15/94 7:30	A10	20%	6%	15%	5%	10%	10%	10%	5%	12%	7%	
I5	120	9/15/94 8:30	A2	6%	15%	5%	10%	10%	10%	5%	12%	7%	20%	
I6	96	9/15/94 8:45	A5	15%	5%	10%	10%	10%	5%	12%	7%	20%	6%	
I7	89	9/15/94 9:00	A4	5%	10%	10%	10%	5%	12%	7%	20%	6%	15%	
I8	98	9/15/94 9:50	A9	10%	10%	10%	5%	12%	7%	20%	6%	15%	5%	
I9	101	9/15/94 11:00	A6	10%	10%	5%	12%	7%	20%	6%	15%	5%	10%	
I10	107	9/15/94 13:00	A1	10%	5%	12%	7%	20%	6%	15%	5%	10%	10%	

OB Train Schedule:

Train	# Cars	Dept. Time	Dept. Track	# Blocks
O1	100	9/15/94 23:35	D2	5
O2	100	9/15/94 23:40	D3	4
O3	100	9/16/94 0:15	D5	4
O4	106	9/16/94 1:50	D8	2
O5	110	9/16/94 2:30	D7	3
O6	96	9/16/94 3:10	D1	2
O7	95	9/16/94 4:15	D4	3
O8	98	9/16/94 4:20	D6	3
O9	100	9/16/94 4:30	D3	3
O10	105	9/16/94 7:15	D9	2

Processing Time Input Data (Mean & Stdev):

	IB Inspectioin	Hump	Assembly	OB Inspection
Mean	0.016	0.0071	0.014 0.04 (# blocks)	0.017
Stdev	0.4	0.265	1.1	0.52

Crew Assignment:

IB Inspector Teams	2
Hump Crews	2
Assembly Crews	3
OB Inspector Teams	2

Figure 3-1: Standard Plan

model as:

$$\begin{aligned} \textit{Mean IB inspection time} &= 0.016 * (\#\ \textit{cars in IB train}) && (3.1)\\ \textit{Mean hump time} &= 0.0071 * (\#\ \textit{cars in IB train}) && (3.2)\\ \textit{Mean Assembly time} &= 0.014 * (\#\ \textit{cars in OB train}) + \\ & \quad 0.04 * (\#\ \textit{blocks in OB train}) && (3.3)\\ \textit{Mean OB inspection time} &= 0.017 * (\#\ \textit{cars in OB train}) && (3.4) \end{aligned}$$

These inputs are used in calculating the achievability of the tasks assigned. For example, using the inputs in Figure 3-1, we would expect that to inspect a 100 car train would take 1.6 hours on average.[7] If the terminal manager allowed this amount of time for a 100 car train, he could expect to succeed in accomplishing this task only

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[7] See 0.016 in the column labeled as *IB inspection* in *Processing Time Input Data* table.

50% of the time,[8] since the average IB inspection time for a 100 car train is 1.6 hours. The values to be input can be derived in a number of different ways. For example, if the yard has a detailed set of yard reports (either manual or computerized), the values can be estimated from these. If an extensive industrial engineering type yard study has been performed this can also support the estimates. Finally, if no other data is available, it is possible to use parameters from other similar yards as a starting point, although clearly the values will not be as accurate as ones deriving specifically for the terminal.

The final section of the Standard Plan Sheet is the section known as *Crew Assignment.* This section is used to indicate the number of inspector teams (both IB and OB) and engine crews (hump and assembly). This data is used in the calculation of costs and to validate the work assignments in the Task Sheet.

Revised Plan

It is rare that the operations described in the operating plan are carried out without any deviation. The Revised Plan in Fig. 3-2 allows the user to adjust the inbound and outbound train times and cars to correspond to the estimated times of arrival and departure (ETA/ETD) and most recent consist information. In the example given, only the times (not the composition) are changed a little bit from the operating plan. For example, consider IB train *I*1; its arrival time is changed from 5:00 to 5:10, ten minutes late compared to the time from the train schedules. This sheet, rather than the Standard Plan sheet, is used in the calculation of connections reliability, PMAKE, achievability, etc. If the model is being used to establish alternative TOP's for the operating plan, the user would set the Revised Plan to be the same as the Standard Plan (e.g., first sheet). If, on the other hand, a user wants to see the effects of adding trains or significantly altering schedules from the operating plan, he would change the IB and OB train information on this sheet.

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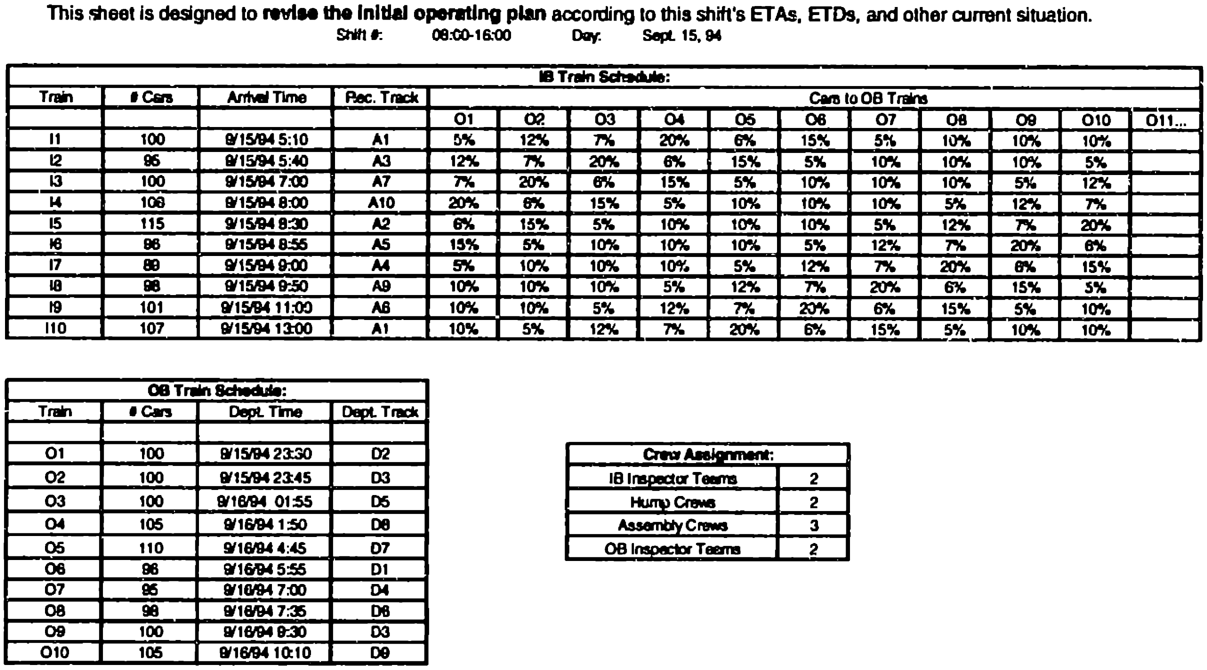
[8] We assume that processing time at each process has a Normal distribution, which is symmetric.



This sheet is designed to **revise the initial operating plan** according to this shift's ETAs, ETDs, and other current situation.

Shift #: 08:00-16:00 Day: Sept. 15, 94

IB Train Schedule:														
Train	# Cars	Arrival Time	Rec. Track	Cars to OB Trains										
				O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11...
I1	100	9/15/94 5:10	A1	5%	12%	7%	20%	6%	15%	5%	10%	10%	10%	
I2	96	9/15/94 5:40	A3	12%	7%	20%	6%	15%	5%	10%	10%	10%	5%	
I3	100	9/15/94 7:00	A7	7%	20%	6%	15%	5%	10%	10%	10%	5%	12%	
I4	108	9/15/94 8:00	A10	20%	6%	15%	5%	10%	10%	10%	5%	12%	7%	
I5	115	9/15/94 8:30	A2	6%	15%	5%	10%	10%	10%	5%	12%	7%	20%	
I6	96	9/15/94 8:55	A5	15%	5%	10%	10%	10%	5%	12%	7%	20%	6%	
I7	89	9/15/94 9:00	A4	5%	10%	10%	10%	5%	12%	7%	20%	6%	15%	
I8	98	9/15/94 9:50	A9	10%	10%	10%	5%	12%	7%	20%	6%	15%	5%	
I9	101	9/15/94 11:00	A6	10%	10%	5%	12%	7%	20%	6%	15%	5%	10%	
I10	107	9/15/94 13:00	A1	10%	5%	12%	7%	20%	6%	15%	5%	10%	10%	

OB Train Schedule:			
Train	# Cars	Dept. Time	Dept. Track
O1	100	9/15/94 23:30	D2
O2	100	9/15/94 23:45	D3
O3	100	9/16/94 01:55	D5
O4	105	9/16/94 1:50	D8
O5	110	9/16/94 4:45	D7
O6	96	9/16/94 5:55	D1
O7	95	9/16/94 7:00	D4
O8	98	9/16/94 7:35	D6
O9	100	9/16/94 8:30	D3
O10	105	9/16/94 10:10	D9

Crew Assignment:	
IB Inspector Teams	2
Hump Crews	2
Assembly Crews	3
OB Inspector Teams	2

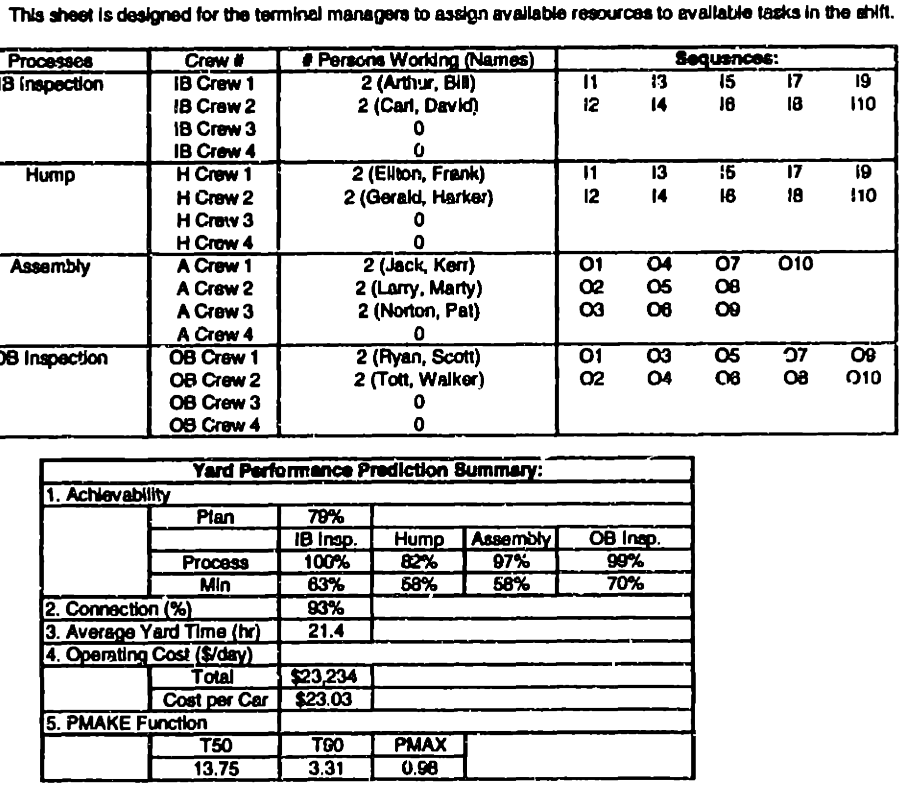
Figure 3-2: Revised Plan

Task Sheet

One of the most important functions the terminal managers undertake is to assign workers to perform a variety of tasks in a particular sequence. The Task Sheet allows the model user to do this for inbound and outbound inspection crews and for hump and assembly engines. In addition, this sheet presents a summary of the results of the model.

In the example shown in Fig. 3-3, each of the tasks has been assigned using a First In/First Out (FIFO) schedule. For example, inbound inspection crew #1 has been assigned to inspect train $I1$, crew #2 inspects $I2$, crew #3 inspects $I3$, and so on. A similar routine has been followed in assigning the sequences to the hump engines, assembly engines, and outbound inspectors. This sequence of tasks is used by the subsequent sheets to determine the train connections and achievability of the tasks and processes in the TOP.

The Task Sheet also presents a summary of the various results of the model. The



This sheet is designed for the terminal managers to assign available resources to available tasks in the shift.

Processes	Crew #	# Persons Working (Names)	Sequences:				
IB Inspection	IB Crew 1	2 (Arthur, Bill)	I1	I3	I5	I7	I9
	IB Crew 2	2 (Carl, David)	I2	I4	I6	I8	I10
	IB Crew 3	0					
	IB Crew 4	0					
Hump	H Crew 1	2 (Elton, Frank)	I1	I3	I5	I7	I9
	H Crew 2	2 (Gerald, Harker)	I2	I4	I6	I8	I10
	H Crew 3	0					
	H Crew 4	0					
Assembly	A Crew 1	2 (Jack, Kerr)	O1	O4	O7	O10	
	A Crew 2	2 (Larry, Marty)	O2	O5	O8		
	A Crew 3	2 (Norton, Pat)	O3	O6	O9		
	A Crew 4	0					
OB Inspection	OB Crew 1	2 (Ryan, Scott)	O1	O3	O5	O7	O9
	OB Crew 2	2 (Tott, Walker)	O2	O4	O6	O8	O10
	OB Crew 3	0					
	OB Crew 4	0					

Yard Performance Prediction Summary:					
1. Achievability					
	Plan	79%			
		IB Insp.	Hump	Assembly	OB Insp.
	Process	100%	82%	97%	99%
	Min	63%	58%	58%	70%
2. Connection (%)		93%			
3. Average Yard Time (hr)		21.4			
4. Operating Cost ($/day)					
	Total	$23,234			
	Cost per Car	$23.03			
5. PMAKE Function					
	T50	T90	PMAX		
	13.75	3.31	0.98		

Figure 3-3: Task Sheet

summary is organized in terms of the achievability measures, connection reliability, predicted average yard time, costs, and PMAKE function. Because these results may not be clear until the later sheets are presented, discussion of this part is deferred to subsection 3.2.2.

Inbound Plan

The Inbound Plan sheet in Fig. 3-4 is comprised of the IB inspection and hump or classification processes. The presentation is slightly different for the two, since the inbound inspection process can be organized in terms of the particular tasks for the crew, while the hump engines are constrained by the availability of the hump lead. In both cases, however, the key issue is the assignment of times to perform the tasks specified in the Task Sheet. Each is discussed below.

The first four columns represent basic information regarding the trains to be inspected: the IB train number (e.g., the third column), number of cars (e.g., the second column), the receiving track to receiving the IB train (e.g., the fourth column), and the work order for each IB inspector (e.g., the first column). For *Inbound Inspection Plan* at upper part of Figure 3-4, the model user specifies a start time for the first task of each crew (8:20 in this case), a pure processing time[9] for each track to be inspected, and a minimum slack, or idle time, between tasks. (This is an extension beyond the usual practice in yards and terminals, where only the sequence of tasks is generally supplied). The model then determines the start and end times for each of the tasks, and calculates the achievability for each task and for the overall process.

For task level achievability, the formula is:

$$Ach(task) = \Phi(\frac{pure\ proc. - mean}{stdev}) \tag{3.5}$$

where, *pure proc.* is the pure processing time specified for the task by the model user, and *mean* and *stdev* are the mean and standard deviation of the task (see

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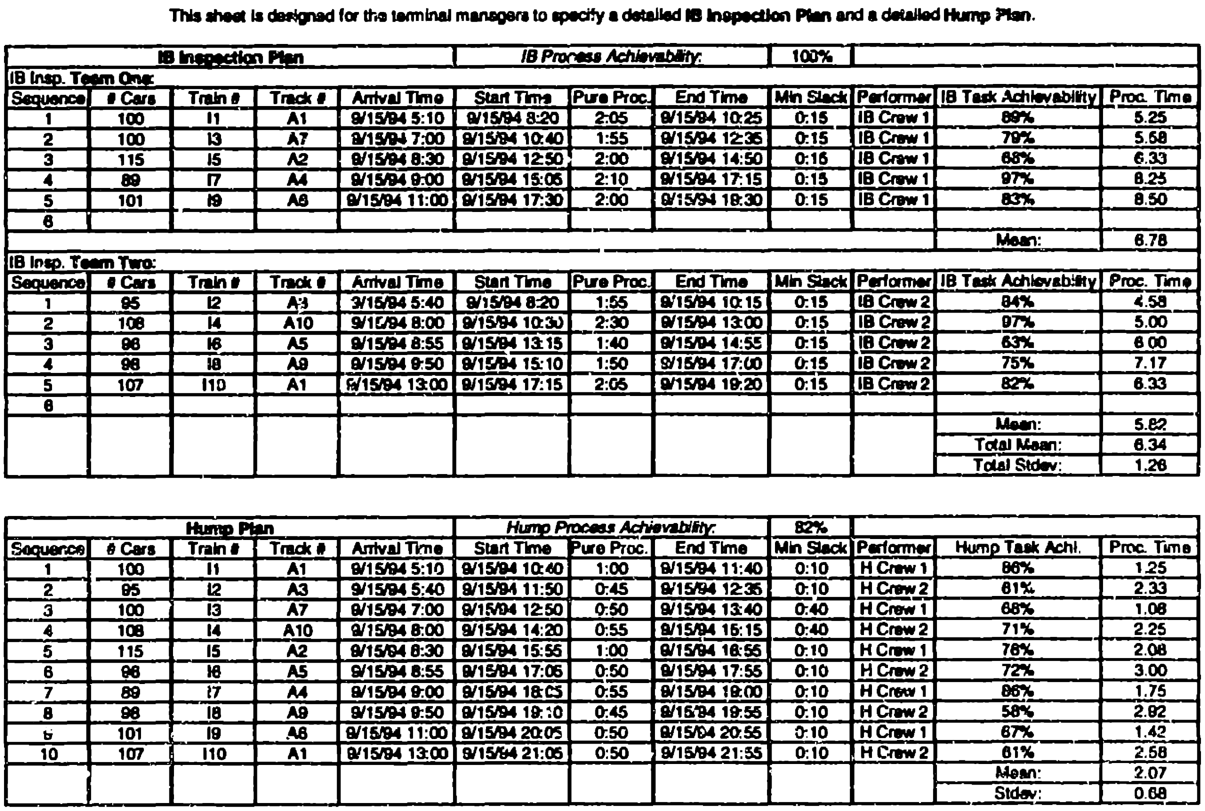
[9] Which is defined as the time to perform the task without waiting time or slack time. See [16] for detailed discussions.



This sheet is designed for the terminal managers to specify a detailed IB Inspection Plan and a detailed Hump Plan.

IB Inspection Plan					*IB Process Achievability:*			100%			
IB Insp. Team One:											
Sequence	# Cars	Train #	Track #	Arrival Time	Start Time	Pure Proc.	End Time	Min Slack	Performer	IB Task Achievability	Proc. Time
1	100	I1	A1	9/15/94 5:10	9/15/94 8:20	2:05	9/15/94 10:25	0:15	IB Crew 1	89%	5.25
2	100	I3	A7	9/15/94 7:00	9/15/94 10:40	1:55	9/15/94 12:35	0:15	IB Crew 1	79%	5.58
3	115	I5	A2	9/15/94 8:30	9/15/94 12:50	2:00	9/15/94 14:50	0:16	IB Crew 1	68%	6.33
4	89	I7	A4	9/15/94 9:00	9/15/94 15:05	2:10	9/15/94 17:15	0:15	IB Crew 1	97%	8.25
5	101	I9	A6	9/15/94 11:00	9/15/94 17:30	2:00	9/15/94 18:30	0:15	IB Crew 1	83%	8.50
6											
										Mean:	6.78
IB Insp. Team Two:											
Sequence	# Cars	Train #	Track #	Arrival Time	Start Time	Pure Proc.	End Time	Min Slack	Performer	IB Task Achievability	Proc. Time
1	95	I2	A3	9/15/94 5:40	9/15/94 8:20	1:55	9/15/94 10:15	0:15	IB Crew 2	84%	4.58
2	108	I4	A10	9/15/94 8:00	9/15/94 10:30	2:30	9/15/94 13:00	0:15	IB Crew 2	97%	5.00
3	98	I6	A5	9/15/94 8:55	9/15/94 13:15	1:40	9/15/94 14:55	0:15	IB Crew 2	63%	6.00
4	98	I8	A9	9/15/94 9:50	9/15/94 15:10	1:50	9/15/94 17:00	0:15	IB Crew 2	75%	7.17
5	107	I10	A1	9/15/94 13:00	9/15/94 17:15	2:05	9/15/94 19:20	0:15	IB Crew 2	82%	6.33
6											
										Mean:	5.82
										Total Mean:	6.34
										Total Stdev:	1.26

Hump Plan					*Hump Process Achievability:*			82%			
Sequence	# Cars	Train #	Track #	Arrival Time	Start Time	Pure Proc.	End Time	Min Slack	Performer	Hump Task Achl.	Proc. Time
1	100	I1	A1	9/15/94 5:10	9/15/94 10:40	1:00	9/15/94 11:40	0:10	H Crew 1	86%	1.25
2	95	I2	A3	9/15/94 5:40	9/15/94 11:50	0:45	9/15/94 12:35	0:10	H Crew 2	81%	2.33
3	100	I3	A7	9/15/94 7:00	9/15/94 12:50	0:50	9/15/94 13:40	0:40	H Crew 1	68%	1.08
4	108	I4	A10	9/15/94 8:00	9/15/94 14:20	0:55	9/15/94 15:15	0:40	H Crew 2	71%	2.25
5	115	I5	A2	9/15/94 8:30	9/15/94 15:55	1:00	9/15/94 16:55	0:10	H Crew 1	76%	2.08
6	98	I6	A5	9/15/94 8:55	9/15/94 17:05	0:50	9/15/94 17:55	0:10	H Crew 2	72%	3.00
7	89	I7	A4	9/15/94 9:00	9/15/94 18:05	0:55	9/15/94 19:00	0:10	H Crew 1	86%	1.75
8	98	I8	A9	9/15/94 9:50	9/15/94 19:10	0:45	9/15/94 19:55	0:10	H Crew 2	58%	2.92
9	101	I9	A6	9/15/94 11:00	9/15/94 20:05	0:50	9/15/94 20:55	0:10	H Crew 1	67%	1.42
10	107	I10	A1	9/15/94 13:00	9/15/94 21:05	0:50	9/15/94 21:55	0:10	H Crew 2	61%	2.58
										Mean:	2.07
										Stdev:	0.68

Figure 3-4: Inbound Plan

Formulas 3.1 to 3.4 on page 66 for means and Figure 3-1 on page 66 for standard deviations for the processes).

For process level achievability, the formula is:

$$Ach(process) = \Phi(\frac{\sum_{i=1}^{n} pure\ proc._i - \sum_{i=1}^{n} mean_i}{\sqrt{n * (\sum_{i=1}^{n} stdev_i^2)}}) \tag{3.6}$$

where, i is an individual task and n is the number of tasks in the process.

In this case, the process achievability is very close to 100%, meaning that the probability that the two inspection crews will complete all the inspections by the final end time (19:30) is almost 100%. The individual task achievabilities are much lower. For example, the probability that crew #1 will inspect Track $A2$ (inbound train $I5$) in the 2 hours allowed is about 66%. This may seem counterintuitive at first, until one considers that in the overall process time, any free time gained by one task can be, in effect, allocated to other tasks, while this cannot be done at the individual task level. In addition to calculating the task and process level achievability, the model calculates the mean and standard deviation of the time to complete each of the processes. For the inbound inspection, this time is the complete time from the inbound train's arrival until the completion of the inspection. This time is used in the calculation of the PMAKE and the average yard time.

The lower part of Figure 3-4 is the *Hump Plan* which is also specified in terms of the start time for the use of the hump and the pure processing time for each track to be humped. Once again, the model calculates the task and the process achievability and the processing times. In this case the mean time includes the time from the completion of the inbound inspection until the cars are classified. Consider the hump processing time for IB train $I6$, for example, it is equal to 3 hours, the end time of the hump (17:55) minus the end time of its IB inspection (14:55).

Outbound Plan

Once the cars are classified into outbound blocks, it still remains to assemble the blocks into the outbound trains, and to inspect those trains. Figure 3-5 and 3-6 present the elements of the Outbound Plan sheet.

Figure 3-5 (on next page) is a set of matrices used in the calculation of train connections and the *Assembly Plan*. The upper matrix simply calculates the number of cars for each inbound train to each outbound train. The lower matrix rearranges the outbound trains in terms of the order for assembly given in the Task Sheet, and depending on the subsequent times of assembly, the connection reliability is estimated. The connection condition is:

$$If\ t(end\_hump_i) \leq t(start\_assembly_j) \Rightarrow cars_{i \rightarrow j}\ make\ their\ connection \quad (3.7)$$

where, $t(end\_hump_i)$ is the end hump time for IB train i, $t(start\_assembly_j)$ is the start assembly time for OB train j, and $cars_{i \rightarrow j}$ are the cars from IB train i, which are to make the connections to OB train j.

In this example, the predicted connection reliability is about 93%. The lowest part of Figure 3-5 is the assembly plan for the assembly engines. As in the inbound sheets, the user specifies the initial start time, the pure processing time allowed for building the outbound train, and the minimum slack time. The model calculates the start and end time for all the other tasks, the number of cars which connect to the train, and the associated achievabilities and mean and standard deviation of the processing times.

The Figure 3-6 is an estimate of the bowl time for each of the inbound/outbound connections,[10] *OB Inspection Plan,* and the calculations of the overall connection performance, plan level achievability, PMAKE function parameters, average yard time, and the operating costs. The mean and standard deviation of the bowl time is used in the generation of the PMAKE and the average yard times. As in the inbound inspection, the achievabilities and mean and standard deviation of the OB inspection processing times are calculated. In addition, the time that the train will wait from the completion of the inspection until the scheduled departure is calculated.

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[10] If IB arrival time minus OB departure time is negative, 24 hours are added to the bowl time, meaning the IB train has to make the connection of the same OB train next day.

This sheet is designed for the terminal managers to specify a detailed Assembly Plan and a detailed OB Inspection Plan.

				Cars to OB Trains									
Train	# Cars	End Hump	Rec. Track	O1	O2	O3	O4	O5	O6	O7	O8	O9	O10
I1	100	9/15/94 11:40	A1	5	12	7	20	6	15	5	10	10	10
I2	95	9/15/94 12:35	A3	11	7	19	6	14	5	10	10	10	5
I3	100	9/15/94 13:40	A7	7	20	6	15	5	10	10	10	5	12
I4	108	9/15/94 15:15	A10	22	6	16	5	11	11	11	5	13	8
I5	115	9/15/94 16:55	A2	7	17	6	12	12	12	6	14	8	23
I6	96	9/15/94 17:55	A5	14	5	10	10	10	5	12	7	19	6
I7	89	9/15/94 19:00	A4	4	9	9	9	4	11	6	18	5	13
I8	98	9/15/94 19:55	A9	10	10	10	5	12	7	20	6	15	5
I9	101	9/15/94 20:55	A6	10	10	5	12	7	20	6	15	5	10
I10	107	9/15/94 21:55	A1	11	5	13	7	21	6	16	5	11	11
			Sum:	101	101	101	101	102	102	102	100	101	103

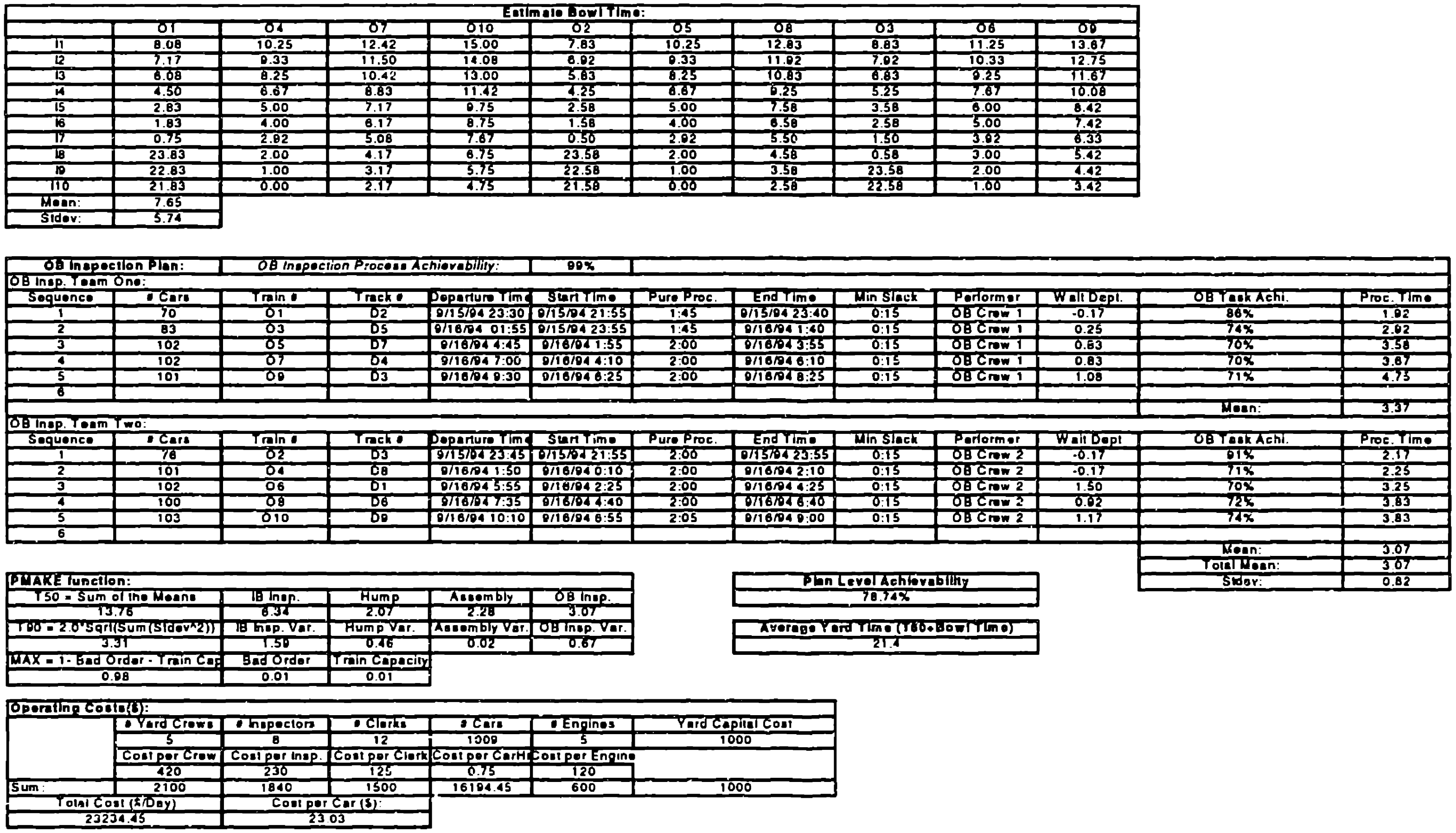
Connection Matrix Calculation Form:

	O1	O4	O7	O10	O2	O5	O8	O3	O6	O9		
I1	5	20	5	10	12	6	10	7	15	10		
I2	11	6	10	5	7	14	10	19	5	10		
I3	7	15	10	12	20	5	10	6	10	5		
I4	22	5	11	8	6	11	5	16	11	13		
I5	7	12	6	23	17	12	14	6	12	8		
I6	14	10	12	6	5	10	7	10	5	19		
I7	4	9	6	13	9	4	18	9	11	5		
I8	0	5	20	5	0	12	6	10	7	15		
I9	0	12	6	10	0	7	15	0	20	5		
I10	0	7	16	11	0	21	5	0	6	11	Sum:	*Connection Performance*
Sum Make:	70	101	102	103	76	102	100	83	102	101	940	92.70%
Total:	101	101	102	103	101	102	100	101	102	101	1014	

Initial and Revised Assembly Plan (you can revise the assembly start time and processing time to get satisfactory OB volume. You can also cancel OB trains.)

					Assembly Process Achievability:			97%			
Train #	Dept. Time	Dept. Track	Start Time	Pure Proc.	End Time	Min Slack	Performer	# of Cars	# Missed	Ass. Task Achi.	Proc. Time
O1	9/15/94 23:30	D2	9/15/94 19:45	2:00	9/15/94 21:45	0:10	A Crew 1	70	31	72%	2.00
O4	9/16/94 1:50	D8	9/15/94 21:55	2:00	9/15/94 23:55	0:10	A Crew 1	101	0	58%	2.00
O7	9/16/94 7:00	D4	9/16/94 0:05	2:25	9/16/94 2:30	0:10	A Crew 1	102	0	70%	2.42
O10	9/16/94 10:10	D9	9/16/94 2:40	2:30	9/16/94 5:10	0:10	A Crew 1	103	0	72%	2.50
										Mean:	2.23
O2	9/15/94 23:45	D3	9/15/94 19:30	2:15	9/15/94 21:45	0:10	A Crew 2	76	25	76%	2.25
O5	9/16/94 4:45	D7	9/15/94 21:55	2:25	9/16/94 0:20	0:10	A Crew 2	102	0	70%	2.42
O8	9/16/94 7:35	D6	9/16/94 0:30	2:20	9/16/94 2:50	0:10	A Crew 2	100	0	69%	2.33
										Mean:	2.33
O3	9/16/94 01:55	D5	9/15/94 20:30	2:15	9/15/94 22:45	0:10	A Crew 3	83	18	74%	2.25
O6	9/16/94 5:55	D1	9/15/94 22:55	2:15	9/16/94 1:10	0:10	A Crew 3	102	0	65%	2.25
O9	9/16/94 9:30	D3	9/16/94 1:20	2:20	9/16/94 3:40	0:10	A Crew 3	101	0	68%	2.33
										Mean:	2.28
										Total Mean:	2.28
										Stdev:	0.14

Figure 3-5: Outbound Plan, part 1



Estimate Bowl Time:										
	O1	O4	O7	O10	O2	O5	O8	O3	O6	O9
I1	8.08	10.25	12.42	15.00	7.83	10.25	12.83	8.83	11.25	13.67
I2	7.17	9.33	11.50	14.08	6.92	9.33	11.92	7.92	10.33	12.75
I3	6.08	8.25	10.42	13.00	5.83	8.25	10.83	6.83	9.25	11.67
I4	4.50	6.67	8.83	11.42	4.25	6.67	9.25	5.25	7.67	10.08
I5	2.83	5.00	7.17	9.75	2.58	5.00	7.58	3.58	6.00	8.42
I6	1.83	4.00	6.17	8.75	1.58	4.00	6.58	2.58	5.00	7.42
I7	0.75	2.92	5.08	7.67	0.50	2.92	5.50	1.50	3.92	6.33
I8	23.83	2.00	4.17	6.75	23.58	2.00	4.58	0.58	3.00	5.42
I9	22.83	1.00	3.17	5.75	22.58	1.00	3.58	23.58	2.00	4.42
I10	21.83	0.00	2.17	4.75	21.58	0.00	2.58	22.58	1.00	3.42
Mean:	7.65									
Stdev:	5.74									

OB Inspection Plan:		*OB Inspection Process Achievability:*			99%							
OB Insp. Team One:												
Sequence	# Cars	Train #	Track #	Departure Time	Start Time	Pure Proc.	End Time	Min Slack	Performer	Wait Dept.	OB Task Achi.	Proc. Time
1	70	O1	D2	9/15/94 23:30	9/15/94 21:55	1:45	9/15/94 23:40	0:15	OB Crew 1	-0.17	86%	1.92
2	83	O3	D5	9/16/94 01:55	9/15/94 23:55	1:45	9/16/94 1:40	0:15	OB Crew 1	0.25	74%	2.92
3	102	O5	D7	9/16/94 4:45	9/16/94 1:55	2:00	9/16/94 3:55	0:15	OB Crew 1	0.83	70%	3.58
4	102	O7	D4	9/16/94 7:00	9/16/94 4:10	2:00	9/16/94 6:10	0:15	OB Crew 1	0.83	70%	3.67
5	101	O9	D3	9/16/94 9:30	9/16/94 6:25	2:00	9/16/94 8:25	0:15	OB Crew 1	1.08	71%	4.75
6												
											Mean:	3.37
OB Insp. Team Two:												
Sequence	# Cars	Train #	Track #	Departure Time	Start Time	Pure Proc.	End Time	Min Slack	Performer	Wait Dept.	OB Task Achi.	Proc. Time
1	76	O2	D3	9/15/94 23:45	9/15/94 21:55	2:00	9/15/94 23:55	0:15	OB Crew 2	-0.17	91%	2.17
2	101	O4	D8	9/16/94 1:50	9/16/94 0:10	2:00	9/16/94 2:10	0:15	OB Crew 2	-0.17	71%	2.25
3	102	O6	D1	9/16/94 5:55	9/16/94 2:25	2:00	9/16/94 4:25	0:15	OB Crew 2	1.50	70%	3.25
4	100	O8	D6	9/16/94 7:35	9/16/94 4:40	2:00	9/16/94 6:40	0:15	OB Crew 2	0.92	72%	3.83
5	103	O10	D9	9/16/94 10:10	9/16/94 6:55	2:05	9/16/94 9:00	0:15	OB Crew 2	1.17	74%	3.83
6												
											Mean:	3.07
											Total Mean:	3.07
											Stdev:	0.82

PMAKE function:				
T50 = Sum of the Means	IB Insp.	Hump	Assembly	OB Insp.
13.76	6.34	2.07	2.28	3.07
T90 = 2.0*Sqrt(Sum(Stdev^2))	IB Insp. Var.	Hump Var.	Assembly Var.	OB Insp. Var.
3.31	1.59	0.46	0.02	0.67
MAX = 1- Bad Order - Train Cap	Bad Order	Train Capacity		
0.98	0.01	0.01		

Plan Level Achievability
78.74%

Average Yard Time (T50+Bowl Time)
21.4

Operating Costs($):						
	# Yard Crews	# Inspectors	# Clerks	# Cars	# Engines	Yard Capital Cost
	5	8	12	1009	5	1000
	Cost per Crew	Cost per Insp.	Cost per Clerk	Cost per CarH	Cost per Engine	
	420	230	125	0.75	120	
Sum:	2100	1840	1500	16194.45	600	1000
Total Cost ($/Day)	Cost per Car ($):					
23234.45	23.03					

Figure 3-6: Outbound Plan, part 2

If the number is negative, the TOP anticipates that the train will not be ready until after the scheduled departure time. For example, outbound train $O1$ is scheduled to depart at 23:30, but will not be ready to depart until 23:40. In this case, the terminal management will have to closely watch the operation.

The summary of various performance indices in Figure 3-6 are the same measures given in the Task Sheet. First, the *Plan Level Achievability* is given. This is the probability that all the processes will be accomplished in the times allocated for them.

The formula for calculating plan level achievability is:

$$Ach(plan) = \prod_{i}^{m} Ach(process_i) \tag{3.8}$$

where, i is individual process, $Ach(process_i)$ the achievability of process i, and m is the total number of processes modeled (e.g., four in this model).

In this example, the Plan Level Achievability is approximately 79%. This means that if the yard follows this plan, it should expect that it will not be able to carry out the set of tasks more than one day out of five. This may or may not be acceptable to management. If it is not, managers have the option of allowing more time for various tasks, or adding resources to assist in completing them. Another alternative is to identify certain critical tasks and to monitor them closely. In the Task Sheet, the minimum achievability task values are given, so that managers can determine which tasks are most likely to require careful monitoring or adjustment.

If the plan is not achieved, some tasks will be performed using longer time than the time allotted, and possibly they will cause other tasks to be delayed. Under this circumstance, the terminal performance will be expected to worse and cannot be estimated using the current TOP. To estimate the terminal performance, the delayed tasks with the delayed time will be the changed information to the model and a new TOP can be generated based on the changed information, which can be used to estimate the terminal performance under changed situations.

The second set of performance measures is the estimation of the shift-level process

PMAKE. $T50$, the necessary time to expect that 50% of the cars can make their first connection, is simply the sum of the mean times for each of the required processes (including necessary waiting time). In this case, $T50$ is 13.76 hours. $T90$, the additional time for there to be a 90 percent probability that a car will make the first connection is calculated using the standard deviations for the processing times, and the formula is:

$$T90 = 1.96 * \sqrt{\sum_{i}^{n} stdev_i^2} \tag{3.9}$$

$$\approx 2.0 * \sqrt{\sum_{i}^{n} stdev_i^2} \tag{3.10}$$

In this case, the value is 3.31 hours. Finally, MAX, the maximum percentage of cars that make their connection even if all goes well in processing, is determined to be subject to bad orders or left behind for train capacities.

Using $T50$ and the average bowl time from Figure 3-6, the *Average Yard Time* is calculated. In this example, an average car can expect to spend slightly over 21 hours in the yard.

The final set of measures are a series of car and resource costs for the terminal, using service unit costing methods. For example, the cost per train crew, inspector, clerk, and per car hour are input by the user. These are then rallied for the entire set of resources and car hours generated, and the total cost per day and per car are calculated.

It should be noted that connection reliability measures assume that the plan will be achieved, that is, be carried out within the times allocated. As such, the yard manager must seek out TOP's which are able to generate high connection performance and high achievability. Clearly, it does little good to have a "great" plan which cannot be accomplished on a regular basis.

Examples Using the ITM

In this section, several examples of how the ITM might be used are given. In each case, the base case as given in the previous sections has been used as a starting point.

Example 1 and 2: disruptions in system operations It often happens that events beyond the control of the terminal manager will cause the yard to be disrupted. In this example, the base case described in section 3.2.2 was changed so that trains *I*2, *I*4, and *I*6 all arrived 8 hours late (due, for example, to a line blockage).

First, we estimate the terminal performance if no change is made to the TOP in response to these events. All the task assignments have been left unchanged, and the yard continues as though nothing has happened. The effects on the yard are extremely great. Train connection performance falls from its previous 93% to only 63%, average yard time climbs to 26.2 hours, and the costs per car increase from $23.03 to $30.64, all due to increased car hire charges. The PMAKE values increase accordingly as T50 increases from 13.75 to 15.07 and T90 increases from 3.31 to 8.77. The achievability measure increases modestly, since there is now much more time to carry out the tasks, while awaiting the late arrivals.

Second, a simple adjustment is made to deal with this disruption. The delayed trains are not planned in the TOP (e.g., as if they were not coming) until they are expected to arrive, and the crews are assigned to other tasks in the meantime. The predicted connection reliability stays over 90%, the average yard time actually drops from the base case value to 19.0 hours (since many cars on the late arrivals still make connections), and the cost per car drops sharply to $18.73/carhour. The achievability returns to approximately its previous level. In essence, the line delays to the trains do not have significantly impact on the yard, since managers can determine alternative TOP's.

This example also highlights an interesting phenomenon of the model in terms of optimal solutions. In this example, the managers can develop plans in response to disruption which appear to outperform the base case. This clearly suggests that either the base case operation was not optimal, or the train schedule is not very coordinated with the yard's operations. The model will not seek out optimal solutions, in part because it is not clear what an optimal solution is, and in part because of resource limits. It is likely that skilled users will, with practice, begin to find solutions which are high in both achievability and connection performance.

3.2.3 Summary and conclusions

Terminals are critical elements of effective and reliable railroad operations. In spite of their importance, however, managers and planners are often faced with tools which treat the yard as a black box, or which fail to consider the complex nature of terminal operations. At the heart of improved terminal performance are the issues of providing adequate resources and using those resources effectively. The Intermediate Terminal Model demonstrates that it is possible to develop tools which model terminal operations using the methodology developed in section 3.1 (on page 61) and measure and support terminal management and planning. It allows the user to predict the consequences of a terminal operating plan not only in terms of system objectives (such as train connections and costs), but also in terms of the likelihood that the plan can be accomplished on a repeated basis. This plan, process and task level achievability is particularly important for managers and planners, since it allows them to determine which activities must be closely monitored if the system operating plan objectives are to be realized. It also allows managers and planners to consider the consequences of changes in the operating plan, and be alerted to the changes in the operating plan, which are likely to require significant adjustments to the TOP.

3.3 Terminal processing sequencing model system

3.3.1 Introduction

The Intermediate Terminal Model discussed in section 3.2 takes the processing sequencing at each process as input. The model user, either the terminal manager or the system level manager, needs to explicitly specify the sequence of the available tasks for each process. The model then estimates the terminal performance such as average yard time, connection performance, PMAKE values, and achievability of TOP based on the available terminal resources and processing capability. In this section, we will develop a model system that can determine the "optimal"[11] sequences of available tasks for each process by using an optimization technique. The methodology used in this model system is the same as that used in ITM.

We assume, in the model system, that inbound train arrival time and outbound train departure time are given (e.g., from the operating plan, short-run plan, or predicted times of arrival and departure). The overall objective of the model system is to maximize the total number of cars making their first connections.

The terminal processing sequencing model system is comprised of four major optimization models; each of them solves the processing sequencing for one process of the terminal operations, IB inspection, hump, assembly, and OB inspection. This model system uses a sequential optimization technique based upon the characteristics of the terminal operations. It first optimizes the hump or classification sequence based on a concept of "*potential car hours avoided*". Then the model system treats the optimal hump sequence as given and optimizes the inbound inspection sequence and assembly sequence. After an optimal assembly sequence is determined, the model system then optimizes the outbound inspection sequence.

3.3.2 Model concept

In this subsection, we will present the model concept in the hump sequencing context. We assume that the terminal is a hump terminal and we will use hump operation as the general classification operation.

The goal of the hump sequencing model is to determine inbound train hump sequence and the hump time for each inbound train. The model will determine the hump sequence for all the inbound trains for a day (or shift) and the start and end

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[11] The model system applies a heuristic sequentially to get the solution. The solution is not optimal from a mathematical modeling view.

IB TRAIN	SCH ARR	1st OB TRAIN	SCH DEPT	BLK	2nd OB TRAIN	SCH DEPT	CARS	PCH AVD
Q555	15.50	A002	29.00	BBH	A002	53.00	1.3	31.2
				SSR	A002	53.00	1.2	28.8
		A001	24.02	TTO	A001	48.02	2.2	52.8
		Q001	25.00	AAB	Q001	49.00	3.9	93.6
				JJX	Q001	49.00	2.5	60.0
				OOL	Q001	49.00	4.3	103.2
		Q007	44.00	BBL	Q007	68.00	3.1	74.4
		Q004	42.00	NNS	Q004	66.00	1.0	24.0
		Q003	38.00	SSV	Q003	62.00	1.9	45.6
		R002	26.50	MTG	R002	50.50	2.8	67.2
				TTM	R008	38.00	2.8	32.2
				WWN	R002	50.50	2.2	52.8
		R008	38.00	MMA	R008	62.00	3.2	76.8
				SSR	R008	62.00	1.4	33.6
				TTM	R002	50.50	4.3	53.7
		R007	37.50	JJM	Q001	49.00	2.1	24.1
				OOL	R007	61.50	3.2	76.8
		R003	29.00	CCG	R003	53.00	1.1	26.4
				SSI	R003	53.00	2.8	67.2
TOTAL IB TRAIN Q555							47.3	1024.4

Table 3.1: Potential Car Hours Avoided Example

time of the hump operation for each inbound train.

The operating plan, a short-run plan, or estimated time of arrival and departure determines the first, second, etc. scheduled connections of outbound trains for a car from an inbound train. This train connection information is given as the model input. The *potential car hours (PCH) avoided* is the car hours avoided if the cars from the inbound trains make their first connections rather than their second ones. The formula for calculating PCH avoided is:

$$PCH\ AVD = (t(sec\_dept) - t(fir\_dept)) * cars \tag{3.11}$$

where, $PCH\ AVD$ is the potential car hours avoided, $t(sec\_dept)$ is the second OB train's departure time, and $t(fir\_dept)$ is the first OB train's departure time.

Table 3.1 demonstrates the concept and how to calculate the potential car hours avoided for an inbound train.

In Table 3.1, the first column is the inbound train name ($Q555$ in this case). The inbound train's scheduled arrival time is 15.50 hours in second column. The third column lists the first connected OB trains for the cars from the IB train, followed by their scheduled departure times in column four and their block names in column five. Column six and seven list the second connected OB trains and their scheduled departure times, respectively. Column eight lists the average number of cars for the connections and the last column, column nine, is the potential car hours avoided.

The last row of the example lists the total number of cars from the inbound train and the maximum PCH which can be avoided if all the cars make their first connections.

In practice, not all cars make their first connections due to:

- yard congestion (e.g., queues at the processes);
- scheduled tight connection time;
- minimum processing time required being greater than the scheduled connection time.

If cars make their first connections, we say that the PCH are avoided. The objective function of the hump sequencing model is to maximize *all* the potential car hours that can be avoided.

Since different cars from an inbound train usually make different outbound connections, different hump times may have different PCH avoided for the same inbound train. The following procedure is used to calculate PCH avoided for the model.

Step 1. Estimate average yard processing time (T)

- average inbound train arrival time ($t1$);
- average inbound inspection time ($t2$);
- average hump time ($t3$);
- average outbound train assembly time ($t4$);
- average outbound inspection time ($t5$);
- average brake test and departure time ($t6$)

$$T = t1 + t2 + t3 + t4 + t5 + t6 \tag{3.12}$$

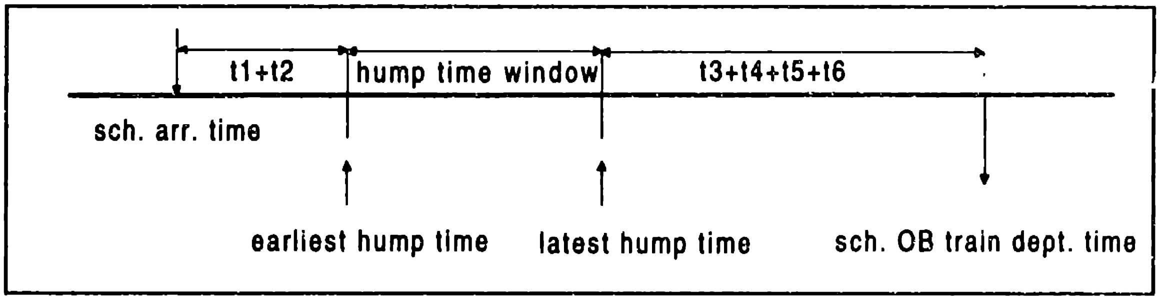

Figure 3-7: Hump Time Window

Step 2. Determine possible (start) hump time window

Figure 3-7 shows how to calculate the hump time window. If there is at least one car from an inbound train I_i whose scheduled *first* connection is the outbound train O_j, the inbound train I_i and outbound train O_j constitute a *possible IB/OB connection train pair*. For each possible IB/OB train pair, the scheduled arrival time of the IB train plus time $(t1 + t2)$ is the *earliest hump time* for the IB train and the scheduled departure time of the OB train minus time $(t3+t4+t5+t6)$ is the *latest hump time* for the IB train to make this connection. The hump time window is the time duration from the earliest hump time to the latest hump time.

Step 3. For a given (start) hump time, determine if connection condition is satisfied for each possible IB/OB connection train pair as follows:

The scheduled OB train departure time minus the time $(t4+t5+t6)$ is the latest OB train assembly time, $t(a)$, in order to make the connection (see Figure 3-8). For each possible IB/OB train connection pair, if the IB train's start hump time is $t(h)$ and

$$t(h) + t3 <= t(a) \tag{3.13}$$

then the PCH will be avoided.[12]

We use the notation of a_{ij} as the potential car hours avoided, if the ith IB train

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[12] It is the same idea as in ITM, where the connection condition is expressed as the end hump time of IB train is less than or equal to the start assembly time of OB train. See expression 3.7 on page 73.

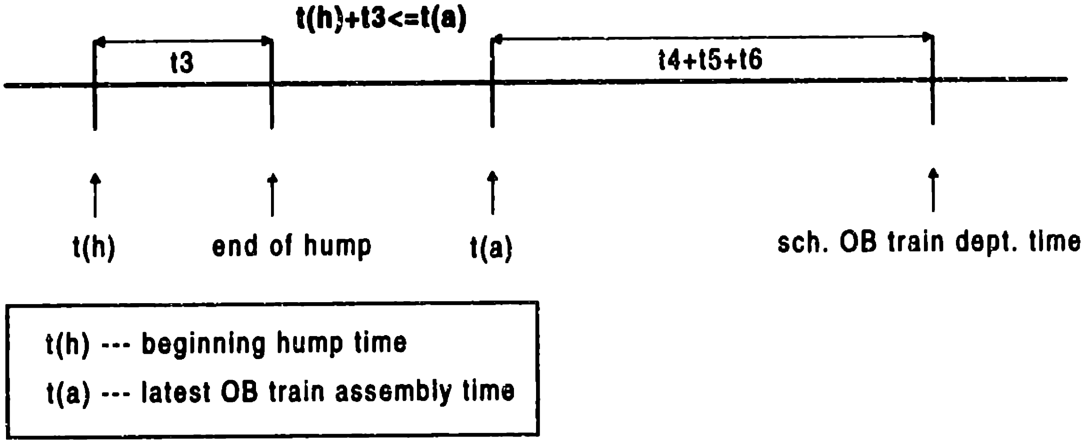

Figure 3-8: Connection Condition

starts to hump at time j. Using this procedure, we can estimate the values of all the a_{ij}.

3.3.3 Model formulations

The hump sequencing model can be stated as follows:

- Decision variables are X_{ij}

  If *ith* IB train starts hump at time j, $X_{ij} = 1$, otherwise $X_{ij} = 0$.

- Coefficients of X_{ij} in the objective function is a_{ij}.

- Model formulation:

$$max \quad \sum_{i=1}^{n} \sum_{j=1}^{m} a_{ij} X_{ij} \tag{3.14}$$

$$s.t. \quad \sum_{j=1}^{m} X_{ij} = 1 \quad \text{for all i;} \tag{3.15}$$

$$\sum_{i=1}^{n} X_{ij} <= 1 \quad \text{for all j;} \tag{3.16}$$

$$X_{ij} \in \{0, 1\} \tag{3.17}$$

Constraint 3.16 says that any IB train must be humped sometime[13] and constraint 3.17 says that at any time period, at most one IB train can be humped assuming that

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[13] The number of time periods m is very large so that all the IB trains can be humped in the time specified.

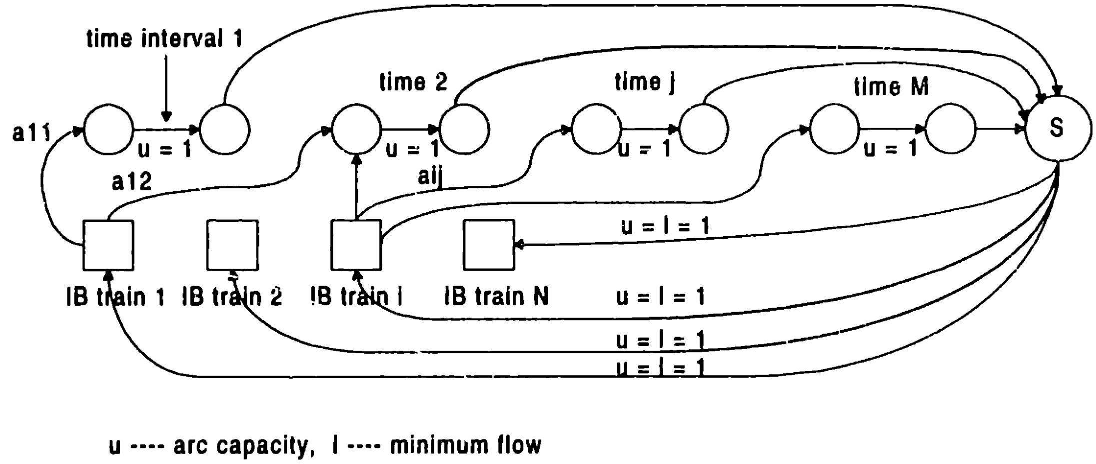

Figure 3-9: The Network Flow Problem

only one hump lead is available.

The output of the hump sequencing model gives the hump start times for all the IB trains. Sorting the IB trains by the hump start times gives the hump sequence.

One useful property of the formulation is that it is a standard *assignment problem,* a special case of the *network flow problems.* As a result, we can ignore the constraints 3.17 and still get the integer solution for the integer problem (e.g., solving the linear programming (LP) without 3.17 is equivalent to solving the integer programming (IP) with 3.17).

Figure 3-9 shows the network flow problem of the formulation. Each square node represents an IB train and each circle node represents either start or end time of a time interval. The last circle note is a dummy node, meaning that all the unprocessed humps will be left to next day or shift. The cost of the link from *ith* IB train to the start-time node of interval j is a_{ij}, the coefficient of the objective function. The capacity of each time interval link is 1, meaning that at most one hump can be processed at any time interval. The cost of the time interval link is 0. The capacity and cost of the link from each end-time node to the dummy node are unlimited and 0, respectively. The link from the dummy node to each IB train has both capacity and minimum flow of 1, meaning that all the IB trains will eventually be processed either at this modeling horizon or the later ones.

The formulation of assembly sequencing model is very similar to that of the hump sequencing model. The differences are: First, for assembly sequencing model, the *possible assembly time window* for each IB/OB connection train pair is from the IB train's end hump time to the OB train's latest assembly time. The potential car hours avoided is calculated according to this time window for each *OB train*. Second, the right hand side (RHS) of the constraints 3.17 is equal to the number of assembly switching engines available to the terminal for the day or shift assuming parallel assembly operations can be conducted.

For IB and OB inspection sequencing models, the possible time windows are from each IB train's arrival time to the latest IB inspection time and from each OB train's end assembly to the latest OB inspection time, respectively. Similarly, the RHS of constraints 3.17, for inspection sequencing models, is equal to the number of inspection teams used. Another difference of these models from the hump sequencing model is that the coefficients of the objective functions. If an inspection (either IB or OB) is to be processed at the *earliest time interval* in the possible time window, the coefficient (e.g., a_{ij}) is 1. If it is to be processed at the second earliest time interval, the coefficient is 2, and so on. Since we take hump time as input for these two models, the objective function can be $max\ \ a_{ij}X_{ij}$ or $min\ \ a_{ij}X_{ij}$, meaning to conduct the inspections *as late as possible (ALAP)* or *as soon as possible (ASAP)*, respectively.

The assembly and IB and OB inspection sequencing models all are network flow problems.

3.3.4 Model implementation

The model system used actual data from a major hump terminal of a Class I railroad. A 60 hours modeling horizon is used to make sure that all the cars from all the IB trains of one day (24 hours) will connect to all the OB trains. The implementation procedure can be summarized as the following steps:

Step 1. The IB arrival and OB departure times are obtained from the operating plan,[14] which was stored in the database system. Then the number of cars for each IB train is estimated by averaging one month real data, which is also stored in the database system.

Step 2. The original data is modified that a car record in an IB train without complete information such as arrival time, block, origin and destination, etc. is deleted. The car record with the volume of less than one car per day is treated as irregular traffic and is also deleted. After the modification, the final IB/OB train information is available as an input file. (See Table 3.1 on page 81 for an example). The processing time is available based on the estimate by terminal manager and the railroad processing standards.

This input file is used for IB inspection and hump sequencing models. The input file is sorted according to OB trains to generate another input file, which is used for assembly and OB inspection sequencing models.

Step 3. The potential car hours avoided are calculated using the concept introduced in section 3.3.2 (on page 80) for each IB train.[15]

Step 4. A programming code in C is written to transform the PCHs calculated in step 3 and other constraints into a standard form for the MPSX, an optimization tool developed by IBM (an early version of the optimization subroutine library (OSL)).

Step 5. Invoking MPSX using the file generated from step 4 as input to get the solution for the hump sequencing model.

Step 6. Using the hump sequence generated from step 5 as input to calculate PCH for assembly process. Repeat step 3 to 5 (for each process) to get assembly and IB and OB inspection sequences.

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[14] The times could also be from a short-run plan or from the estimated time of arrival and departure.

[15] The detailed calculation is done using the database tool under the mainframe environment.

Table 3.2 and 3.3 give two examples of the results generated by the model system. In Table 3.2, all the times are processes' start times in hours. The arrival processing time (e.g., from the time of arrival until the IB train sits at the receiving yard) used is 1 hour. For scenario 1 with IB processing time of 2 hours (e.g., 1 hour's IB inspection), the hump sequencing is given at the fifth column. For scenario 2 with IB processing time of 4 hours (e.g., 3 hours' IB inspection), the hump sequencing is given at the last column.

Table 3.2 shows that the hump and IB inspection sequence is not the IB arrival sequence. The First In/First Out (FIFO) processing rule is not the optimal one for IB operations for the terminal, from which the data are used in the model.

Table 3.3 is one of the OB processing sequence results from the model. The assembly time and OB inspection time used are both 2 hours. The fourth column give the OB inspection sequence and time using the objective function of inspecting OB trains as soon as possible, while the fifth column is the result using the objective function of inspecting OB trains as late as possible. Again, from the results, it clearly shows that the departure sequence is not the sequence of assembly.

The following simple procedure can be used to determine the working order for each team when more than one teams are work for the day (such as assembly crews and IB and OB inspection teams). The OB inspection working order is used in the procedure.

Step 1. Sort the OB trains according to OB inspection times;

Step 2. Assign OB trains with the same start times to different OB inspection teams;

Step 3. Assign other OB trains starting from the top of the OB inspection list sequentially to different OB inspection teams.

The model system gives detailed train and car connection performance information. Table 3.4 gives an example of the results. In the table, "HUMP" and "[illegible]" are the start times for hump and assembly, respectively. "BLK" is the block name of the connection. "CARS", "PCH AVD", "CARS MISS", "CARS MAKE", and "PCH

IB Train	# Cars	Arr. Time	Insp. Time	Hump Time 1*	Hump Time 2*
R111	63	1.00	2.00	3.00	5.00
R222	59	1.50	3.00	4.00	6.00
R333	27	7.00	8.00	9.00	11.00
Q222	92	8.75	10.00	11.00	13.00
Q333	30	10.00	11.00	12.00	14.00
Q444	11	10.25	12.00	13.00	15.00
R444	63	10.00	13.00	14.00	16.00
A111	52	13.00	14.00	15.00	17.00
R555	59	13.00	15.00	16.00	18.00
A222	5	15.00	16.00	17.00	19.00
Q555	47	15.50	17.00	18.00	20.00
Q666	47	21.00	22.00	23.00	25.00
A333	76	22.00	23.00	24.00	26.00
Q888	73	22.00	24.00	25.00	27.00
Q777	59	21.50	25.00	26.00	31.00
R777	50	22.00	28.00	29.00	28.00
R888	56	23.50	29.00	30.00	33.00
R666	58	21.50	30.00	31.00	32.00
A444	22	22.00	31.00	32.00	34.00

* Scenario 1: IB 2 hours and OB 5 hours; Scenario 2: IB 4 hours and OB 4 hours

Table 3.2: IB Processing Sequence Result

OB Train	# Cars	Assm. Time	OB Insp. Time	OB Insp. Late	Dept. Time
A001	45	18.00	20.00	22.00	24.02
Q001	60	20.00	22.00	23.00	25.00
R001	27	18.00	20.00	24.00	26.00
R002	89	20.00	22.00	24.00	26.50
R004	33	22.00	24.00	27.00	29.00
A002	46	24.00	26.00	27.00	29.00
R003	48	24.00	26.00	26.00	29.00
A003	6	26.00	28.00	29.00	31.00
S002	6	16.00	18.00	30.00	32.50
Q002	44	26.00	28.00	30.00	32.50
R005	21	28.00	30.00	31.00	33.00
R006	35	30.00	32.00	33.00	35.00
R007	53	32.00	34.00	35.00	37.50
R008	63	30.00	32.00	36.00	38.00
A004	29	28.00	30.00	35.00	38.00
Q003	65	32.00	34.00	36.00	38.00
Q004	55	34.50	36.00	40.00	42.00
Q005	49	36.50	38.00	40.00	42.50
Q006	50	38.00	40.00	41.00	43.50
Q007	89	36.00	38.00	42.00	44.00
R009	40	40.00	42.00	45.00	47.00

Table 3.3: OB Processing Sequence Result

IB TRAIN	SCH ARR	HUMP	1st OB TRAIN	ASSM	SCH DEPT	BLK	2nd OB TRAIN	SCH DEPT	CARS	PCH AVD	CARS MISS	CARS MAKE	PCH MAKE	1st CNN Car Hours	2nd CNN Car Hours
Q555	15.50	18.00	A002	24.00	29.00	BBH	A002	53.00	1.3	31.2	0.0	1.3	31.2	17.5	48.7
						SSR	A002	53.00	1.2	28.8	0.0	1.2	28.8	16.2	45.0
			A001	18.00	24.02	TTO	A001	46.02	2.2	52.8	2.2	0.0	0.0	18.7	71.5
			Q001	20.00	25.00	AAB	Q001	49.00	3.9	93.6	0.0	3.9	93.6	37.0	130.6
						JJX	Q001	49.00	2.5	60.0	0.0	2.5	60.0	23.8	83.8
						OOL	Q001	49.00	4.3	103.2	0.0	4.3	103.2	40.8	144.0
			Q007	36.00	44.00	BBL	Q007	68.00	3.1	74.4	0.0	3.1	74.4	88.3	162.7
			Q004	34.00	42.00	NNS	Q004	66.00	1.0	24.0	0.0	1.0	24.0	26.5	50.5
			Q003	32.00	38.00	SSV	Q003	62.00	1.9	45.6	0.0	1.9	45.6	42.7	88.3
			R002	20.00	26.50	MTG	R002	50.50	2.8	67.2	0.0	2.8	67.2	30.8	98.0
						TTM	R008	30.00	2.8	32.2	0.0	2.8	32.2	30.8	63.0
						WWN	R002	50.50	2.2	52.8	0.0	2.2	52.8	24.2	77.0
			R008	30.00	38.00	MMA	R008	62.00	3.2	76.8	0.0	3.2	76.8	71.9	149.7
						SSR	R008	62.00	1.4	33.6	0.0	1.4	33.6	31.5	65.1
						TTM	R002	50.50	4.3	53.7	0.0	4.3	53.7	96.7	150.5
			R007	32.00	37.50	JJM	Q001	49.00	2.1	24.1	0.0	2.1	24.1	46.2	70.3
						OOL	R007	61.50	3.2	76.8	0.0	3.2	76.8	70.4	147.2
			R003	24.00	29.00	CCG	R003	53.00	1.1	26.4	0.0	1.1	28.4	14.8	41.2
						SSI	R003	53.00	2.8	67.2	0.0	2.8	67.2	37.8	105.0
TOTAL IB TRAIN Q555									47.3	1024.4	2.2	45.1	971.6	766.6	1791.1

Table 3.4: Train Connection Summary Example

MAKE" are the average number of cars (on the IB train), potential car hours that can be avoided, number of missing connection cars, number of making connection cars, and potential car hours which is going to be avoided according to the model results.

From the model results, we can estimate the utilization of the terminal resources. Figure 3-10 gives an example of the terminal resource utilization, the utilization of the receiving yard. There are two peaks for using the receiving tracks, a big peak at the late evening (e.g., from 22:00 PM to 6:00 AM) and a small peak in the afternoon (e.g., for 11:00 AM to 16:00 PM). The maximum number of tracks used at the busiest time is 7.

From the model results, we can get the connection performance and average yard time. In this case, we get:

$$\begin{aligned} \%\ of\ cars\ making\ first\ connection &= \frac{cars\ making\ connection}{total\ cars} \\ &= \frac{756.8}{949.6} = 79.7\% \end{aligned} \tag{3.18}$$

$$avg\ yard\ time = \frac{total\ second\ conn.\ car\ hours - total\ PCH\ avoided}{total\ cars} \tag{3.19}$$

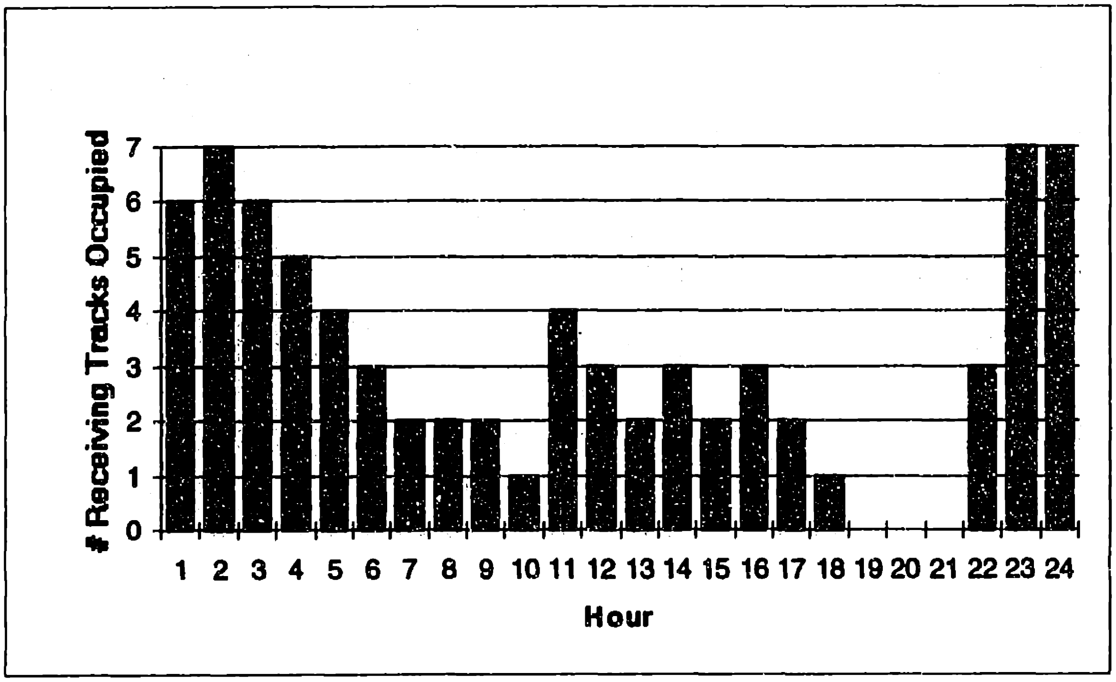

Figure 3-10: Terminal Receiving Yard Utilization

$$= \frac{41179.7 - 17650.8}{949.6} = 24.8\ (hours)$$

3.3.5 Summary and conclusions

The terminal processing sequencing model system developed in this section uses a concept called potential car hours avoided, which is the car hours avoided if the cars can make their first connections rather than their second connections. We develop a heuristic procedure to calculate the PCH avoided and a simple optimization model, which is a network flow problem, to solve the hump sequencing model first. After the hump sequencing is determined, the assembly sequencing and IB and OB processing sequencing models can then be solved using very similar procedures and modeling techniques.

The model system used actual data from a major hump terminal of a Class I railroad. The model results are generally regarded by the terminal managers and system level planning officer as reflecting the real situation and reasonable. The results from the sequencing model system show that the best sequencing from the model is not the same as that of FIFO, the First In/First Out rule. That is, the FIFO rules, which is very commonly used by terminal managers for processing available tasks, may not be a good one.

3.4 A stochastic terminal model for the schedule-adherence and the flexible operation strategies

3.4.1 Introduction

In the previous two sections, we presented an intermediate terminal model and a terminal processing sequencing model system. They model the terminal operations using the methodology introduced in section 3.1 (on page 61) and estimate the terminal performance for a day or a shift based upon the condition that the IB train arrival pattern and OB train departure requirement are given as model input.[16] They can estimate terminal performance under different operating strategies for a day or a shift if the IB arrival pattern and OB departure requirement are given. But different operating strategies may have different train arrival and departure behavior, since the major difference between these operating strategies is the way trains are run.

In this section, we will develop a stochastic terminal model (STM) to investigate the major characteristics of train arrival and departure behavior under schedule-adherence and flexible operation strategies.[17] The conclusion from this model helps us understand the IB train arrival patterns under different operating strategies and specify them in the models developed in Chapter 4 and 5 to evaluate terminal operations and rail network operations under different operating strategies.

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[16] They are from either the operating plan, a short-run plan, or the estimated time of arrival and departure.

[17] See Chapter 1 section 1.3.1 on page 18 for definitions of these operating strategies.

3.4.2 The stochastic terminal model

We assume that the arrival time of IB trains at the terminal is random around its scheduled arrival time with some (probably unknown) distribution function. In practice, the arrival time is not deterministic due to various internal and external operating conditions.[18] Also the traffic volume of these IB trains in terms of number of cars is not deterministic. The exact number of cars in an IB train is determined by the available traffic at the upstream terminal when the train was built there.[19] So, it may be realistic to assume that the IB trains' arrival times and the number of blocks and cars in each IB train are random variables.

We will consider only one OB train's formation process (e.g., what conditions make the terminal manager start to assemble an OB train) at a terminal to try to understand the major difference between schedule-adherence and flexible operation strategies.

Let consider an OB train, O. We define r as the set of all the possible IB trains that can make connections to O (all the IB trains from this set are numbered I_1, I_2, $\ldots$, I_r). The arrival time distribution function of IB train I_i is $P_i(t)$. To simplify the analysis so we can obtain a closed form solution, we assume that the arrival pattern of the IB train I_i is Poisson distributed with parameter λ_i. (See, for example, [20] for detailed description of the Poisson distribution). We also assume that the traffic volume (in terms of number of cars) on the IB train I_i is a random variable with a distribution function of $P_{N_i}(n)$. We use λ and N to represent the average arrival rate and traffic volume for the OB train, respectively. Based on the property of the Poisson distribution, we can convert the individual processes to a single process with:

$$\lambda = \sum_{i=1}^{r} \lambda_i \tag{3.20}$$

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[18] See section 2.4 on page 54 for discussions of these conditions.

[19] Assuming no pick-up and delivery operations are conducted in the intermediate terminals between the upstream terminal and the terminal under consideration.

$$P_N(n) = \frac{1}{\lambda}\sum_{i=1}^{r}\lambda_i P_{N_i}(n) \tag{3.21}$$

The average traffic volume and its variance for the OB train are then:

$$\mu_N = \frac{1}{\lambda}\sum_{i=1}^{r}\lambda_i \mu_{N_i} \tag{3.22}$$

$$\sigma_N^2 = \frac{1}{\lambda}\sum_{i=1}^{r}\lambda_i[(\mu_{N_i} - \mu_N)^2 + \sigma_{N_i}^2] \tag{3.23}$$

Now let: $N(T)$ represent the number of cars arriving in time period T. Then we have:

$$\begin{aligned} P_{N(T)}(n) &= \sum_{i=1}^{\infty}\frac{(\lambda T)^i e^{-\lambda T}}{i!}P_{\sum_{j=1}^{i} N_j}(n) & (3.24) \\ &\approx \sum_{i=1}^{\infty}\frac{(\lambda T)^i e^{-\lambda T}}{i!}[\Phi(\frac{n+0.5-i*\mu}{\sqrt{i}*\sigma_\mu}) - \Phi(\frac{n-0.5-i*\mu}{\sqrt{i}*\sigma_\mu})] & (3.25) \end{aligned}$$

where $\sum_{j=1}^{i} N_j$ in equation 3.24 is the sum of i iid (e.g., independently and identically distributed) variables, with the distribution of N. If $i > 5$, we can approximate the combined distribution using normal distribution based upon the central limit theory:

$$\sum_{j=1}^{i} N_j \sim N(i*\mu_N, i*\sigma_N^2) \tag{3.26}$$

Based on this, we go from equation 3.24 to 3.25.

Now let: T_{n^*} represent the time at which the number of cars arrived *first* exceed n^*, where n^* is a fixed number. Then we have:

$$\begin{aligned} P(T_{n^*} < t) &= P(N(t) > n^*) & (3.27) \\ &= 1 - P[N(t) <= n^*) \\ &= 1 - \sum_{i=1}^{\infty}\frac{(\lambda T)^i e^{-\lambda T}}{i!}P(\sum_{j=1}^{i} N_j <= n^*) & (3.28) \end{aligned}$$

$$\approx 1 - \sum_{i=1}^{\infty} \frac{(\lambda T)^i e^{-\lambda T}}{i!} \Phi(\frac{n^* - i * \mu_N}{\sqrt{i} * \sigma_N}) \tag{3.29}$$

Equations 3.24 to 3.25 can be considered as the major characteristics of the schedule-adherence operation, while the equations 3.27 to 3.29 can be considered as the major characteristics of the flexible operation.

Based upon the above analysis, we can estimate the means and variances of the average traffic volume for the schedule-adherence operation and the average time for the flexible operation as follows.

For schedule-adherence operation:

$$E(N(T)) = \sum_{i=1}^{\infty} n P_{N(T)}(n) \tag{3.30}$$

$$E[(N(T))^2] = \sum_{i=1}^{\infty} n^2 P_{N(T)}(n) \tag{3.31}$$

$$\sigma^2_{N(T)} = E[(N(T))^2] - [E(N(T))]^2 \tag{3.32}$$

For flexible operation:

$$E(T_{n^*}) = \int_{t_0=0}^{\infty} t_0 f_{T_{n^*}}(t_0) dt_0 \tag{3.33}$$

$$E(T^2_{n^*}) = \int_{t_0=1}^{\infty} t_0^2 f_{T_{n^*}}(t_0) dt_0 \tag{3.34}$$

$$\sigma^2_{T_{n^*}} = E(T^2_{n^*}) - [E(T_{n^*})]^2 \tag{3.35}$$

For schedule-adherence operation, the average traffic volume is $E(N(T))$ in time period T and there is a variance of $\sigma^2_{N(T)}$ associated with the average traffic volume. For flexible operation, the OB train will have a traffic volume that is always greater than n^*, but the average accumulation time is $E(T_{n^*})$ rather than T, with a variance of $\sigma^2_{T_{n^*}}$.

3.4.3 An example

Suppose that there are two processes of the arrivals of cars for the OB train O. One process is the main line train arrivals of a Poisson distribution with $\lambda_1 = 1.0$ train/hour. The other process is the local arrivals of a Poisson distribution with $\lambda_2 = 0.5$ train/hour. We also assume that the main line trains have the equal probability of having 5, 10, 15, and 20 cars for the OB train and the local trains have the equal probability of having 3, 5, and 7 cars for the OB train. That is,

$$P_{N_1}(5) = P_{N_1}(10) = P_{N_1}(15) = P_{N_1}(20) = \frac{1}{4}$$

and

$$P_{N_2}(3) = P_{N_2}(5) = P_{N_2}(7) = \frac{1}{3}$$

Suppose further, that for the schedule-adherence operation, the OB train departs the terminal every 8 hours (e.g., $T = 8$ hours) from the operating plan, and the minimum traffic requirement for flexible operation is 100 cars for the train (e.g., $n^* = 100$ cars). Using Maple software,[20] we estimate the following results.

For schedule-adherence operation,

$$E(N(8)) = 120 \ cars$$

$$Dev(N(8)) = 40 \ cars$$

For flexible operation,

$$E(T(100)) = 7.38 \ hours$$

$$Dev(T(100)) = 5.42 \ hours$$

where, *Dev* means the standard deviation (of some distribution).

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[20] The Waterloo Maple Software has many features; one of them is to estimate means and variances of probability distributions. It was installed on Athena computer system at MIT.

This example shows that for the scheduled operation with 8 hours of time to depart the OB train in the operating plan, the average traffic volume is 120 cars with a standard deviation of 40 cars. For the flexible operation, on the other hand, the OB train will wait average 7.38 hours to have a traffic of at least 100 cars to depart from the OB train and a standard deviation of 5.43 hours of the waiting time.

The estimated distributions for the scheduled and flexible operations are given in Figures 3-11 and 3-12, respectively.

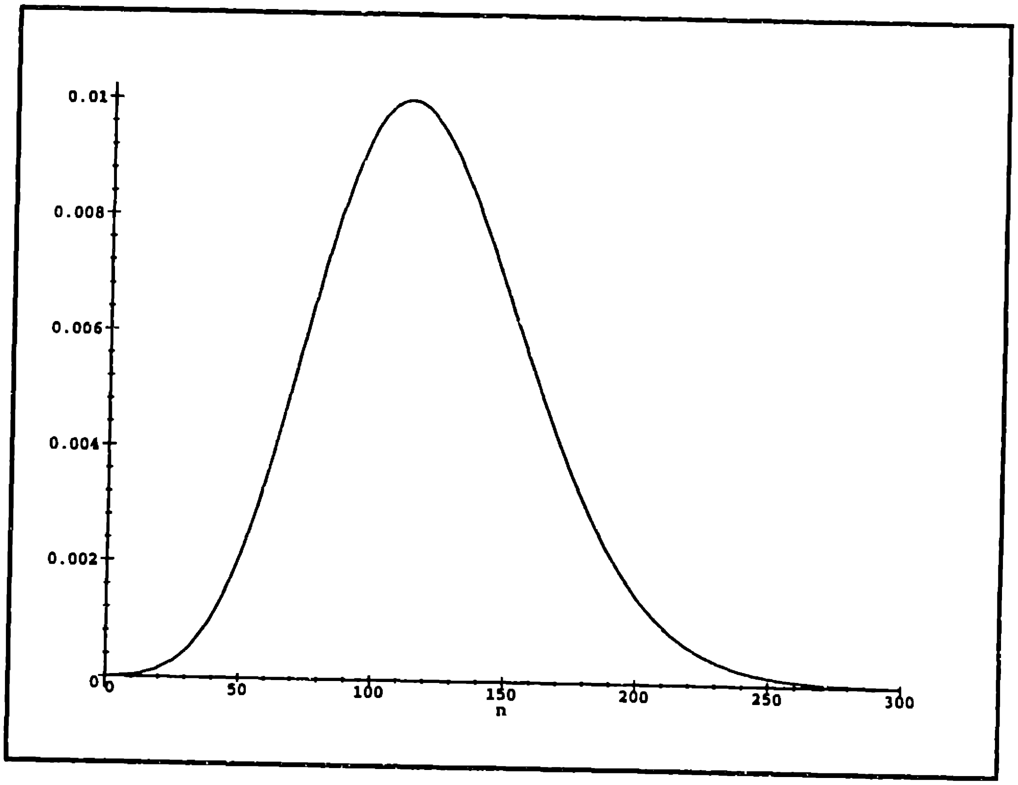

Figure 3-11: Traffic Volume Distribution for the Schedule-adherence Operation

3.4.4 Summary and conclusion

A stochastic terminal model (STM) is developed in this section by considering one OB train's formation process at a terminal. We assume that the arrival of IB trains which are connected to the OB train is Poisson distributed and the traffic volume of each IB train in terms of number of cars for the OB train can have any distribution. We developed the model by converting the individual arrival processes into a

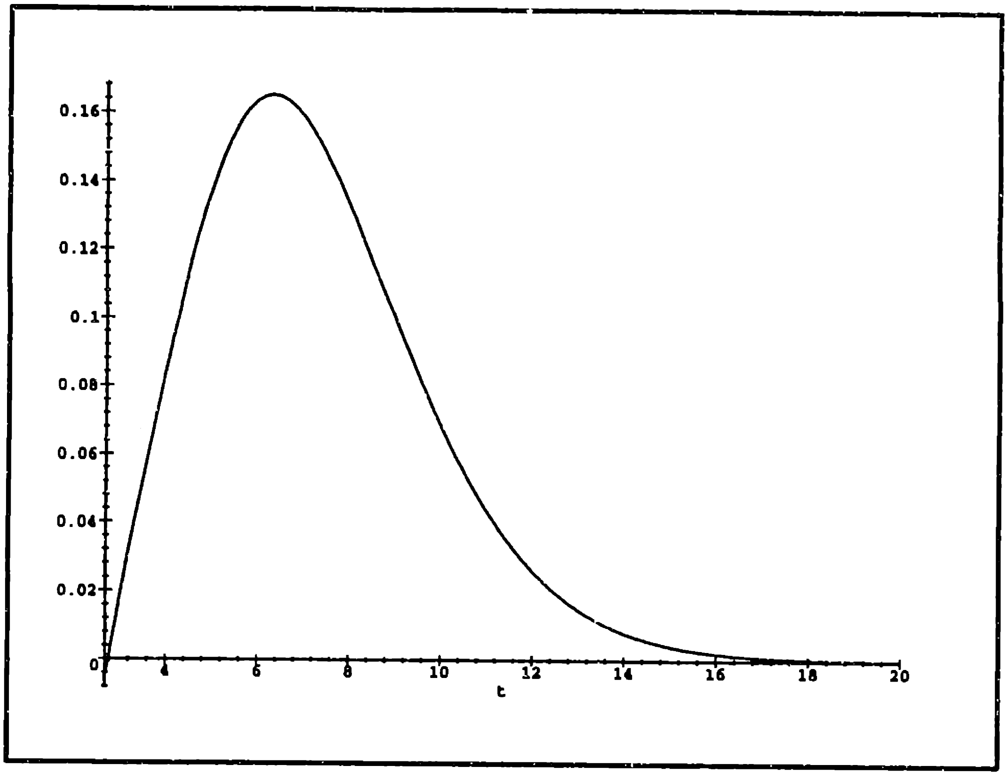

Figure 3-12: Departure Time Distribution for the Flexible Operation

single process based upon the property of the Poisson distribution and get the (approximate) formulas for the distributions of $N(T)$ and T_{n^*}, where $N(T)$ is a random variable representing the number of cars in time T and T_{n^*} is a random variable representing time required for the n^* cars to arrive for the OB train. These distributions can be considered as the major characteristics of the schedule-adherence and flexible operations.

Based on the traffic and time requirement distributions for the schedule-adherence and flexible operations, we derived the means and variances of these distributions using normal approximation based on the central limit theory. These means and variances (or standard deviations) give us useful measures about the schedule-adherence and flexible operations. For schedule-adherence operation, the departure time is fixed (every T hours from the operating plan), but the traffic volume is variable with some degree of variability (e.g., $\sigma^2_{N(T)}$). For flexible operation, on the other hand, the traffic volume is satisfied by a minimum number of cars (e.g., n^*), but the departure time is variable with some degree of variability (e.g., $\sigma^2_{T_{n^*}}$). The schedule-adherence operation will provide reliable train service for railroad operations, but the traffic volume on each train will be variable. Flexible operation will provide much less variable and more predictable traffic volume on each train, but the departure and arrival times of these trains will be very variable. For flexible short-run scheduling strategy, even though no analysis was conducted, this operating strategy seems to behave between the schedule-adherence and flexible operation strategies, since the train operations are organized in a way between the schedule-adherence and flexible operation strategies.

An example is used to show how to estimated the means and standard deviations of the traffic volume and time required for the schedule-adherence and flexible operations. The estimation shows that the schedule-adherence and flexible operations are indeed different in the way that is stated the above analysis.

3.5 Summary and conclusions

In this chapter, we presented a methodology which decomposes terminal operations into processes and tasks as in a general manufacturing setting. Three analytic terminal models were developed. The Intermediate Terminal Model (ITM) and the terminal Processing Sequencing Model system (PSM) were developed using the methodology and can be used to estimate terminal performance under different operating strategies for a short period of time such as a shift or a day by specifying, as the model input, specific IB arrival pattern and OB departure requirement. The Stochastic Terminal Model (STM) was developed to estimate IB train arrival patterns under different operating strategies.

The ITM predicts the consequences of a terminal operating plan not only in terms of system objectives (such as train connections and costs), but also in terms of the likelihood that the plan can be accomplished on a repeated basis. The plan, process and task level achievability is particularly important for managers and planners, since it allows them to determine which activities must be closely monitored if the system operating plan objectives are to be realized. It also allows managers and planners to consider the consequences of changes in the operating plan, and be alerted to the changes in the operating plan, which are likely to require significant adjustments to the TOP.

The PSM used a concept called potential car hours (PCH) avoided, which is the car hours avoided if the cars can make their first connections rather than their second connections. A heuristic procedure was developed to calculate the PCH avoided and an optimization model (e.g., a network flow problem) was developed to solve the hump sequencing problem. After the hump sequencing is determined, the assembly sequencing and IB and OB processing sequencing problems were solved using very similar procedures and modeling techniques. The model system used actual data from a major hump terminal of a Class I railroad. The model results showed that the best sequencing for terminal operations is not the same as that of FIFO, the First In/First Out rule, which is very commonly used by terminal managers.

The STM was developed by assuming that the arrival of IB trains which are connected to an OB train is Poisson distributed and the traffic volume of each IB train in terms of number of cars for the OB train can have any distribution. We derived the closed solution by converting the individual arrival processes into a single process based upon the property of the Poisson distribution. Based on the traffic and time requirement distributions for the schedule-adherence and flexible operations, we derived the means and variances of these distributions using normal approximation based on the central limit theory. The schedule-adherence operation will provide reliable train service for railroad operations, but the traffic volume on each train will be variable. Flexible operation will provide much less variable and more predictable traffic volume on each train, but the departure and arrival times of these trains will be very variable. The flexible short-run scheduling strategy seems to behave between the schedule-adherence and flexible operation strategies, since the train operations are organized in a way between the schedule-adherence and flexible operation strategies.

Based on the conclusion from the STM about IB train arrival patterns under different operating strategies and the modeling methodology implemented in the ITM and PSM, we will develop a terminal simulation model in Chapter 4 and a network simulation model in Chapter 5, which are used to evaluate railroad operations under different operating strategies.

Chapter 4

Simulating Rail Terminal Operations under Different Operating Strategies

4.1 Introduction

The models developed in Chapter 3 help us study terminal operations under different operating strategies. The intermediate terminal model (ITM) and the terminal processing sequencing model (PSM) system are two decision support tools to model terminal operations and estimate terminal performance for a shift or a day, and the stochastic terminal model (STM) helps us understand the major characteristics of different operating strategies. However, they cannot be used to estimate terminal performance under different operating strategies for a long period of time such as a month or a quarter, which is necessary to get any solid conclusions about railroad different operating strategies.

The practice and research review in Chapter 2 suggests that internal and external operating conditions[1] affect terminal operations and the choice of different operating strategies. These factors include stochastic demand, variable terminal processing

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[1] See section 2.4 on page 54.

times, accidents, extreme weather conditions, unscheduled maintenance, etc. and they are inherent in railroading, especially terminal operations. In order to estimate terminal performance based on a long time period of terminal operations while taking all the major factors affecting terminal performance into consideration, a detailed simulation model is an ideal technique and tool.

In this chapter, we will develop a microscopic simulation model to study detailed rail terminal operations under different operating strategies.[2] The methodology developed in Chapter 3[3] and implemented in the intermediate terminal model (ITM) and the terminal processing sequencing model system (PSM) is applied to the terminal simulation model and the network simulation model developed later in this thesis. Using the terminal simulation model, we try to understand, investigate, and evaluate which operating strategy is best under various operating conditions. The operating conditions are defined, in the simulation model, as a set of variables[4] representing internal and external operating conditions in terminal operations.

A case study using actual data from a major terminal of a Class I railroad is conducted. The case study includes a base case representing the normal terminal operating conditions, a sensitivity analysis in which the variable or parameter values are changed to evaluate the effects of these variables or parameters on terminal performance, and a scenario run in which nine cases representing different operating conditions are designed, used, and analyzed.

Before going to introduce the terminal simulation model, we will briefly review the literature about terminal simulation models.[5]

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[2] There are actually three simulation models, each simulating one of the three operating strategies: the schedule-adherence, the flexible short-run scheduling, and the flexible operation. Since they share common functions of terminal operations such as IB arrival, IB and OB inspection, and brake test and departure, the three models are combined into one programming code. Thereafter, we will refer the three models as *one* terminal simulation model.

[3] See Chapter 3 section 3.1 on page 61 for discussions of the methodology.

[4] See section 4.3.3 on page 114 for description of these variables.

[5] Line and network simulation models are also briefly reviewed.

4.2 Literature review

There has been much research done using simulation approaches for the rail industry, but very limited research has done to explicitly model terminal operations in great detail and to estimate terminal and system performance under different operating strategies.

Ferreira and Sigut [34] developed a simulation model to estimate the performance of intermodal freight terminals based on two operating strategies: random access and the use of skeletal trailers, which are commonly used in Europe and North America, respectively. The model only simulates two periods of peak demand on a terminal (e.g., a train unloading period and a train loading period) using queuing theory under steady state conditions, which may not realistic enough to get good estimates of the terminal performance. On the other hand, the simulation models developed by Sarosky and Wilcox [69] and by Weigel [76] can simulate much detailed operations for railroad intermodal terminal. But these models were designed to simulate operations for only a week and were mainly used in terminal design and capacity analysis.

A hump terminal simulation model was developed and presented by Klima and Kavicka [47] and by Cenek [12] from the same research. The methodology used in the simulation model was to use a graph to represent a hump terminal (e.g., the major locations are nodes and the tracks linking these nodes are arcs) and terminal operations are conducted and simulated using some path(s). Unfortunately, no results and applications were reported, which makes it difficult to validate the model.

Adams and Kolitz [1] presented a hierarchical rail traffic flow control concept. The key idea is that for a complex system to achieve good system-wide performance, it is necessary to split the system into interdependent parts, where each part is controlled locally but where interactions across the interdependent parts are coordinated within a hierarchical structure. This could be an interesting approach to model railroad network operations. Due to the complexity of the problem, no concrete modeling effort was made in this research.

Kwon and Martland [52] developed a network simulation model to evaluate network service reliability. The major focus of this research was to estimate the effects of traffic variability, line reliability, and controls on dispatching trains from terminals. The model used simplified assumptions for terminal and line haul operations. Kraft [48] proposed a very similar approach to estimate the effect of demand variability on service reliability. A simulation model was mentioned there but no model specification and result were discussed. Allman [2] used a network simulation approach to solve the train scheduling and car sorting problem, where detailed terminal operations were not explicitly modeled. Drucker, Jewell, and Borden [21] developed a simplified deterministic simulation model to study and improve the coal train movements from the coal storage sites to the shipping piers. Stochastic events which may have significant impact on the system performance were not modeled.

Romps [67] used a line haul simulation model as a tool to combine TRACS model and estimate the effects of track maintenance on train delay and train reliability. The model was not designed to simulate detailed line haul movement such as meet and pass. A more detailed line haul simulation model was developed by Robert [66], where the model was used to estimate the coal unit train performance for large networks. The network structure of the model is used in the network simulation model developed in this research.

Some early work in this area is worth mentioning even though at that time the computer technology might not be advanced enough to develop fast and efficient terminal or system simulation models. Duvalyan [23] developed a simulation methodology to evaluate different train make-up plan and ways to allocate classification workload over the network. Eberhardt [25] developed a simulation model to estimate the effects of shorter, more frequent trains on railroad classification yards. Nippert [62] developed a simplified terminal simulation model to simulate three days' operation.

For a detailed review of rail-related models, including simulation models, see Dong [16] and Robert [66].

We now proceed to discuss the terminal model discussed in this research.

4.3 The model specification and design

For use in this research, the microscopic model must be designed in such a way that detailed and realistic terminal operations can be simulated. On the other hand, the increase of the degree of detail in terminal simulation model will increase the requirements for computer software and hardware, which may be an issue if the simulation model is very large. The design of the model must consider the trade-off between the degree of detail of the simulation model and the computer requirements. Efficient and memory-saving data structures and algorithms must be developed and applied.

4.3.1 The model capability

The simulation model can simulate detailed terminal operations, including:

- **IB train arrival operation.** For each IB train, the model simulates: the wait (if any) outside the terminal before the train enters the terminal, when it enters the terminal, the detailed process of placing the cars of the IB train on the receiving track(s) (e.g., which car on which track, if more than one track is needed, then double-over operation is conducted), and when the IB train's arrival operation is finished.

- **IB inspection operation.** For each *loaded* receiving track with more than the minimum number of cars required, the model simulates: when the inspection of the track starts, how long it waited before it gets inspected,[6] and how long it takes to inspect the track.

- **Road crews' release, rest, and departure (with OB trains).** For each IB road crew, the model simulates: the time the crew is released and ready to go to the crew base, how long the crew rests, when the crew is available for next

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[6] When the number of cars on a receiving track first exceeds the number required, this track is ready for IB inspection. From this time, the track is "flagged on" and waits for IB inspection; no car can be placed on this track until it is inspected and humped.

trip, the time the crew is on duty to attach an OB train and conduct brake test operation, and the time the crew leaves the terminal.

- **Road power unit's release, preparation, and departure (with OB trains).** For each road power unit, the model simulates: the time the road unit is released and ready to go to the power shop, how long the preparation process is for the unit, when it is available for the next trip, when it is on duty to attach an OB train and conduct the brake test operation, when it leaves the terminal.

- **Hump operation.** We assume that the terminal being simulated is a single hump terminal. For each *inspected* receiving track, the model simulates: how long the track waited before it gets humped,[7] the time the cars on the track are pushed toward the hump, the detailed hump process (e.g., which car goes to which bowl track), and the time the hump is finished.

- **Assembly operation.** The assembly operation involves several *pulls* of blocks from different bowl tracks to a departure track for an OB train. For each assembly operation, the model simulates: the time the assembly starts, which departure track is used for the assembly operation, how many pulls are conducted, how many cars are pulled for each pull from which bowl track, when each pull starts and when it finishes, and when the assembly operation is finished.

- **OB inspection operation.** For each *assembled* OB train, the model simulates: when the inspection of the OB train starts, how long it waited before gets inspected, how long it takes to inspected the OB train, and when it finishes the OB inspection operation.

- **Brake test.** For each *inspected* OB train, the model simulates: when the brake test operation starts, the wait (if any) before the brake test and how long, which

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[7] When the IB inspection is finished, the track waits for hump.

road power unit(s) and road crew are attached to the OB train, how long it takes to conduct the brake test operation, and when it finishes the operation.

- **OB departure**. For each *brake-tested* OB train, the model simulates: when the departure operation starts, the wait (if any) before the departure and how long, and when the OB train leaves the terminal.

In order to simulate realistic situations, the following features are implemented in the model for all the operating strategies investigated:

- **Unscheduled train arrival**. Unscheduled trains arrive at the terminal by a specified probability distribution. The arrival time is a random variable from a given distribution (the exponential distribution is used in the study). The unscheduled trains are the second sections[8] of scheduled trains.

- **The effects of the rest of the rail network on the terminal operations**. These effects include the unscheduled line and terminal maintenance, extreme weather conditions, terminal and line congestion, and accidents. They also include deadheading in road crews and power units. The rest of the rail network will affect the terminal operations mainly via the arrival times of IB trains, the OB departure condition, and the road crew and power unit resources at the terminal. These effects may cause the IB train arrive late by some specified hours or even some IB trains are canceled. For OB train, these effects will change or delay OB trains' departure time. For road crews and power units, these effects will change number of available crews and power units and hence change availability of crew and power unit resources.

When the model simulates the terminal operations, it keeps track of the utilization of the major terminal resources and road crews and power units *at any time,* including:

- **Receiving tracks**, in terms of how many tracks are occupied with cars and how many cars on each receiving track;

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[8] See Chapter 2 section 2.3 on page 46 for the definition.

- **IB inspection teams**, in terms of how many teams are working;
- **Hump engine**, in terms of when it starts to hump a receiving track, how long the busy period is, when it idles, and how long the idle period is;
- **Assembly engines**, in terms of when each engine starts to assemble an OB train and when it finishes the assembly operation;
- **Bowl tracks**, in terms of how many cars on each bowl track;
- **OB inspection teams**, in terms of how many teams are working;
- **Departure tracks**, in terms of how many departure tracks are occupied with OB trains (waiting for departure) and how many cars on each departure track;
- **Road power units**, in terms of how many units are available for departure and how many units in preparation at the terminal's power shop;
- **Road crews**, in terms of how many crews are available and how many are in rest status at the terminal's crew base.

The model also keeps track of the queues at different places of a terminal during the simulation, including:

1. **IB train queue**, the number of IB trains waiting outside of the terminal due to lack of receiving capacity;
2. **IB inspection queue**, the number of receiving tracks waiting for IB inspection;
3. **Hump queue**, the number of *inspected* tracks waiting for hump;
4. **Assembly queue**, the number of OB trains waiting for assembly;
5. **OB inspection queue**, the number of *assembled* OB trains waiting for OB inspection;
6. **Brake test queue**, the number of *inspected* OB trains waiting for road power units and crews to conduct the brake test;

7. **Departure queue**, the number of *brake-tested* OB trains waiting for departure (due to lack of departure capacity or waiting for scheduled departure).

4.3.2 The model assumptions

IB train arrivals

The IB arrival pattern is known and given. This is based upon the conclusions of the stochastic terminal model developed in Chapter 3[9]. For schedule-adherence strategy, most of the IB trains will arrive at the terminal reliably but the number of cars (traffic volume) on the IB trains may be variable. For flexible operation strategy, on the other hand, the IB trains will arrive at the terminal much less reliably, but the traffic volume of the IB trains will quite stable. For the flexible short-run scheduling strategy, the IB arrival pattern is between the schedule-adherence and flexible operation strategies in that the IB train performance is better than flexible operation strategy but worse than the schedule-adherence strategy, and the traffic volume is less variable than schedule-adherence strategy but more variable than flexible operation strategy.

OB train departure requirements

For the schedule-adherence strategy, the OB train departure requirements are given from the operating plan. They are not changed during the simulation. For the flexible short-run scheduling strategy, however, the departure requirements are given from a short-run plan, which is developed during the simulation. The way the short-run plan is developed under this operating strategy is discussion in the next subsection. For the flexible operation strategy, the OB trains will be assembled whenever a minimum train length requirement is satisfied.[10]

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[9] See section 3.4 on page 93.

[10] The minimum train length requirement is specified in the input files discussed in section 4.3.3 on page 114.

The way the short-run plan is developed for the flexible short-run scheduling strategy

The estimated time of arrivals (e.g., ETAs) are given t hours ahead of time, based on IB train arrival pattern.[11] When an IB is estimated to arrive at time t_0, the cars from this train are estimated to be available in the bowl tracks at time $t_0 + t_1$, where t_1 is the IB processing time, which is specified in the simulation model. The model will check if any OB trains satisfy their minimum traffic requirements and can be assembled at time $t_0 + t_1$, if there is a road crew available at that time, and if there are enough road power units available at that time. If all the three conditions are satisfied, the OB train is scheduled to start assembly operation at time t_0+t_1, and the short-run plan will specify that this OB train will depart from the terminal at time $t_0 + t_1 + t_2$, where t_2 is the OB processing time, which is specified in the simulation model. If any of the three conditions does not hold, the OB train will wait until all of them are satisfied.

The available time for the road crews and power units at the terminal is estimated in a very similar way. The available time for road crew is: t_0+t_c, where t_c is the mean of the crew rest and preparation time, which is calculated by the model based on the crew rest and preparation time distribution.[12] The available time for road power units is: t_0+t_p, where t_p is the mean of the power preparation and maintenance time distribution, which is calculated by the model based on the power unit preparation and maintenance time distribution.

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[11] The IB train arrival pattern is discussed in subsection 4.3.2 on page 111 and t is a model parameter, which is at least 8 hours according to the definition of the flexible short-run scheduling strategy. See Chapter 1 on page 18.

[12] The crew rest and preparation time distribution is another set of model input. This is true for the power unit preparation and maintenance time distribution.

The way the cutoff is used to calculate the connection performance

For a car c_i arriving at the terminal with IB train i, its scheduled arrival time is t_{a_i}, the IB train i's scheduled arrival time. Its scheduled departure time, t_{d_i}, is given by:

$$t_{d_i} = t_{a_i} + \ cutoff \ + t_{min} \tag{4.1}$$

where t_{min} is the minimum time after the time $t_{a_i} + \ cutoff$ when an OB train which can carry the block of the car is scheduled to depart. This OB train is this car's first connection train. We call this OB train j. If the car leaves the terminal before its scheduled departure time, t_{d_i}, *or* if the car leaves the terminal with OB train j and j's actual departure time is not too late compared with its scheduled departure time,[13] the car makes its connection. Otherwise, it misses its connection.

The way extra IB trains are generated

Extra trains are the second section trains entering the hump terminal during the simulation to present one realistic aspect of railroad operations. The arrival of the extra trains is based on a predefined probability. When a scheduled train arrives at the hump terminal, the model will check if there is a second section train to arrive some time later by generating a random number and compare the random number with the predefined probability. If the random number is smaller than the probability, an extra train or a second section will come. The model randomly chooses one scheduled train from the operating plan as the second section train. The arrival time of the train is the current time (e.g., the time the scheduled train arrives at the terminal) plus a random time, which is generated by a probability distribution function[14]

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[13] A parameter is used to measure the lateness of the OB train departures. See Appendix A subsection A.1.11 on page 235 for discussions of the parameter ON_TIME_DEPT.

[14] An exponential distribution is used in the study, whose parameter is specified in an input file.

4.3.3 The model input

The detailed description of the model input files and parameters are listed in Appendix A section A.1 on page 221. The reader is encouraged to read the description to have a better understanding of the model.

The model input includes the operating plan, terminal resources, terminal processing parameters, terminal configuration, and other terminal operating variables or parameter as follows.

- An operating strategy to simulate;
- Days of terminal operations to simulate;[15]
- IB train schedule file;
- OB train schedule file;
- Track and block to bowl track assignment file;
- Terminal resource file;
- Train capacity file;
- Terminal processing time file;
- Cutoff time file;
- Road power unit preparation time file;
- Road crew rest time file;
- Terminal queuing strategy file;
- FSS input file;
- Other parameter file;

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[15] In principle, there is no limitation for number of days to be simulated. It depends on the capability of the PC in use. In the study, a Pentium 166 MHz PC is used and by the experiment, up to one year's (e.g., 365 days) operation can be simulated.

4.3.4 The model output

The major model output is a set of files containing the major terminal performance measures and detailed activities happened during the simulation. See Appendix A section A.3 (on page 240) for detailed output of the terminal simulation model.

The major terminal performance statistics include:

- **Train statistics**, which include the number of IB and OB trains received and departed during the simulation runs,[16] the number of IB and OB trains arrived or departed on time, the number of IB trains waited before entering the terminal, and the planned and actual arrivals of IB trains by the day of the week (e.g., from Sunday to Saturday).

- **Car statistics**, which include the total number of IB and OB cars received and that departed during the simulation run, the number of cars that arrived or departed on time, the number of cars missing their first connections, and the number of planned and actual arrival cars by the day of the week. Also the above statistics can be classified into different traffic priorities.

- **Road power statistics**, which include the number of units of road power received and that departed during the simulation run, the units that are deadheaded in and out (if the operation is allowed), the number of available units and units in preparing status at the end of the simulation, and the average yard time for the road power units.

- **Road crew statistics**, which is very similar to the road power statistics.

- **Terminal resources added**, which include the added IB and OB inspection teams, hump crews and engines, and assembly crews and engines during the simulation run.

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[16] Some "warm up" period of time is discarded from the performance collection process. For example, if a simulation run is made to simulate the terminal operations for a month (e.g., 30 days), the operations of the first 4 days and the last 3 days are not included in the performance statistics calculation.

- **Average yard time performance**, which include the average yard time for different traffic priorities and the overall cars and the percentage of cars whose yard time is less than 30 hours.[17]
- **Yard processing time performance**, which include the average process time for the processes of the terminal operations: arrival (e.g., yarding time), IB inspection, hump, assembly, OB inspection, and brake test and departure.
- **Connection performance**, which include the connection performance for the overall cars and by different traffic priorities. For flexible short-run scheduling strategy, it also includes a measure of connection performance compared with the operation plan besides the short-run plan.

If detailed output is specified,[18] the model will generate some detailed files about IB and OB trains and detailed activities. The train files will record each train's arrival or departure time, the crews and power units going with the train, all the cars on the train with detailed information about each car (car identification number, block name, traffic priority, etc.) The detailed activity files will record each activity's type (arrival, IB inspection, etc.), starting and end time of the activity, who performs the activity, which track or facility is used, etc.

4.4 The model structure

4.4.1 The model framework

The terminal simulation model is a *discrete event-driven* simulation model. Based on the methodology developed in Chapter 3,[19] the terminal operations under different operating strategies are decomposed by the simulation model into events or tasks, which will happen at different times during the simulation. A simulation *clock* is

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[17] The latter statistic is very useful to get the average yard time distribution, since more such kind of statistics can be obtained without any further difficulty. It can also used to verify the results.

[18] By setting the value of OUTPUT_DETAIL variable to 1 in *Other parameter file*.

[19] See section 3.1 on page 61.

used to keep track of the simulation time. When simulating the first event, the simulation clock is set to be the time at which the first event starts. After the first event is simulated, the simulation clock *jumps* to the time when the second event starts and the model simulates the second event. The model continues simulating events until there are no more events in the events list or the termination condition for the simulation is satisfied (such as a prespecified simulation time is reached).

When the model starts, it generates some initial events, put these events into an event list, and set the simulation clock to zero. The *event list* is a *heap* structure,[20] which provides a flexible way of organizing pending events in the simulation and makes it computationally efficient to find the next pending event and to add new events as they arise during the simulation's execution. Table 4.1 shows all the events that are explicitly modeled in the simulation. The *initialization part* of the terminal simulation model includes: generating some cars on the bowl tracks,[21] generating some IB trains sitting at the receiving tracks waiting for IB inspection, some events to be simulated such as the first IB train to be arrived, etc.

In Table 4.1, the *rehump* may be needed for a car if it has to be humped to a storage track first due to the capacity limitation of the bowl track the car is planned to go. ASSMBL event is only for SCH and FSS strategies since only under these two operating strategies, OB trains are assembled according a plan. CHK_RESOURCE event is conducted around 3 hrs before each shift to check the length of the queue in each process. If the queue length exceeds the specified one, one unit of extra terminal resource processing the queue will be added at the beginning of the shift.[22]

The model then begins the *simulation part*, where the model first checks if the termination of simulation is satisfied. In this case, it is the time duration for the simulation. If the end time of the simulation is reached, the model stops. Otherwise

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[20] The heap structure is a special binary tree structure in that the key value for every node is greater than or equal to the key value of its parent node. The key value is the time value of an event.

[21] The numbers of the cars generated are based upon the parameter, *INVT_LEVEL*, which is specified at the input file. See the *other parameter file* at section A.1.11 (on page 235).

[22] The specified queue length is a model parameter, which is discussed in Appendix A section A.1.11 on page 236.

Event Name	Event Description
ARRIVE	IB train arrives; Get another arrival; Process possible extra train arrival;
END_ARRIVE	Cars placed on receiving tracks; Check possible IB inspections;
FREE_CRW	Free crew and it is available for next trip;
FREE_PWR	Free power unit and it is available for next trip;
END_ININSP	Ends IB inspection; Process possible hump;
END_HUMP	Ends hump; Check assembly for FLX;
END_REHUMP	Ends rehump; Check assembly for FLX;
ASSMBL	Start assembling OB train;
PULL	Start individual pull; Check if the last pull;
END_PULL	Ends individual pull; Check possible OB inspection;
END_OBINSP	Ends OB inspection; Check available crew & power units, and possible brake test;
END_TEST	Ends brake test; Check possible departure;
END_DEPT	Ends departure;
CHK_RESOURCE	Check terminal processing queues; Generate add resource event;
ADD_RESOURCE	Adds extra terminal resources

Table 4.1: The Simulated Events in the Simulation Model

the model will get the first event from the heap,[23] update the simulation clock to the time that the event starts, and execute the event. During the simulation process, some statistics about the terminal operations (such as number of cars humped and the available capacity at the receiving track) are updated. When the model finishes simulating the event, it will usually generate another event of the same kind and add it to the heap. It may also generate some other events. For example, when the model finishes simulating one IB train's arrival, it will generate another IB train's arrival time and put this train's arrival event into the event list. It may also generate an IB inspection event if at least one IB inspection team is idle at that time. The process continues until the end simulation time is reached. Figure 4-1 shows the structure for the simulation part of the simulation model.

When the simulation is finished, the model starts the *output part,* which outputs the major results and statistics collected during the simulation.[24] Then the model stops, indicating the end of the simulation run.

4.4.2 The model flow chart

The major component of the simulation model is the simulation part. Figure 4-2 and 4-3 show the flow charts (e.g., IB and OB parts) of the simulation model.

When the model simulates an IB train arrival (e.g., ARRIVE event), the model will check the *remaining capacity* of the receiving yard. If the remaining capacity is less than the number of cars on the IB train, the IB train is put in an arrival train queue and waits for the receiving operation. Otherwise the train is received (e.g., the cars on the train are placed on the receiving track(s)) and an END_ARRIVE event is generated. If there is one track which has remaining capacity larger than the number of cars, this track is used to receive the cars. Otherwise a double over operation[25] is conducted.

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[23] The heap implemented has a useful feature. It first specifies the capacity of the heap in terms of number of events. If the actual number of events is to exceed the capacity, the model will increase the capacity by a fixed *increment* at the *running time*.

[24] The major statistics are discussed in section 4.3.4 on page 115.

[25] The double over operation is defined in Chapter 1 section 1.2 on page 15.

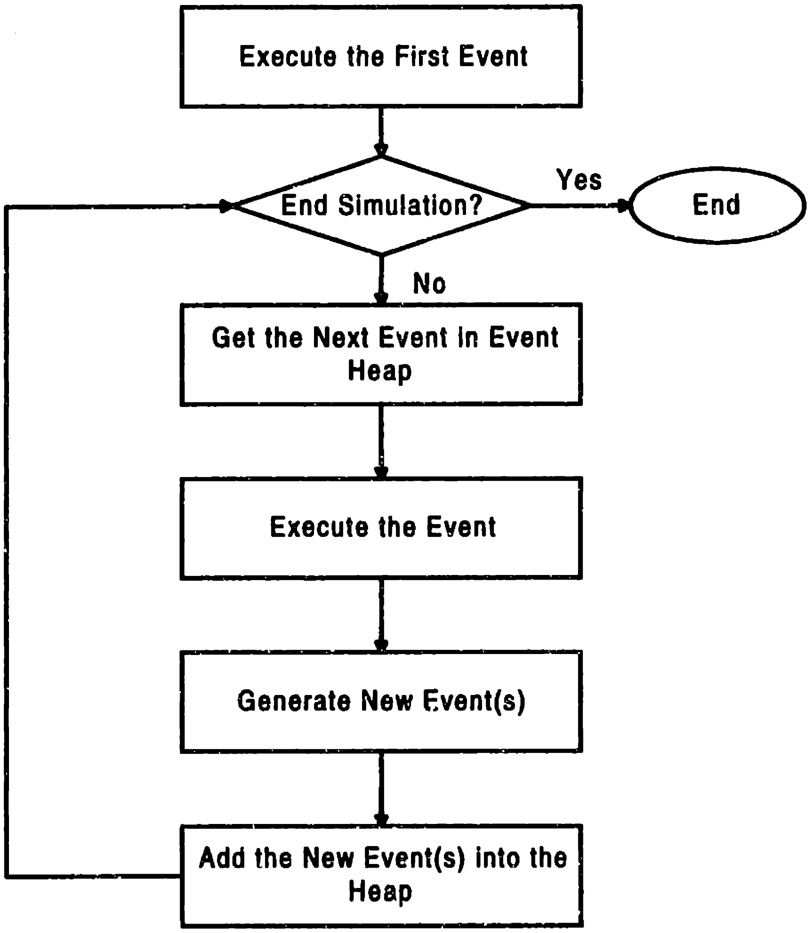

Figure 4-1: The Structure of Discrete Event Simulation

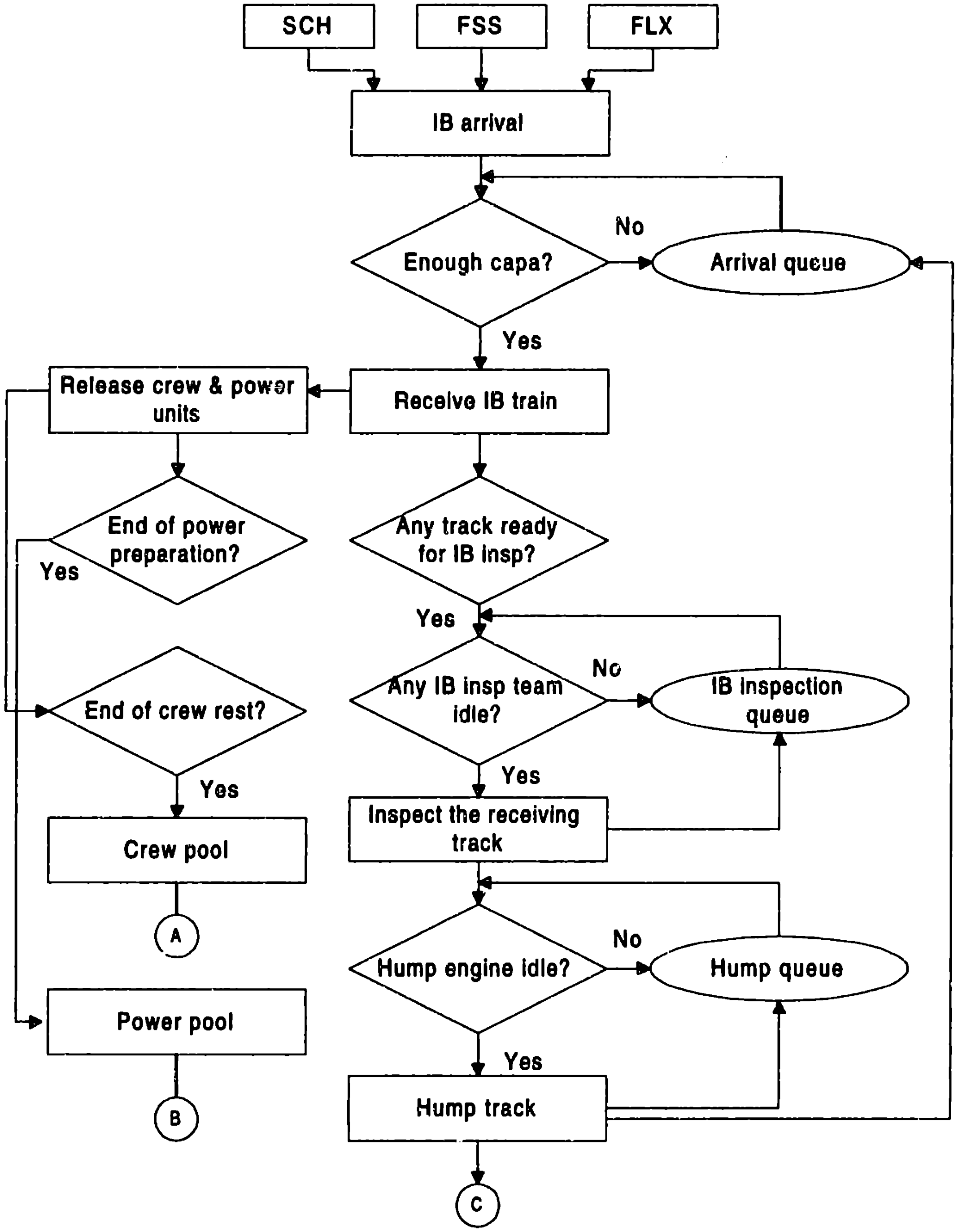

Figure 4-2: The Simulation Model Flow Chart: IB Part

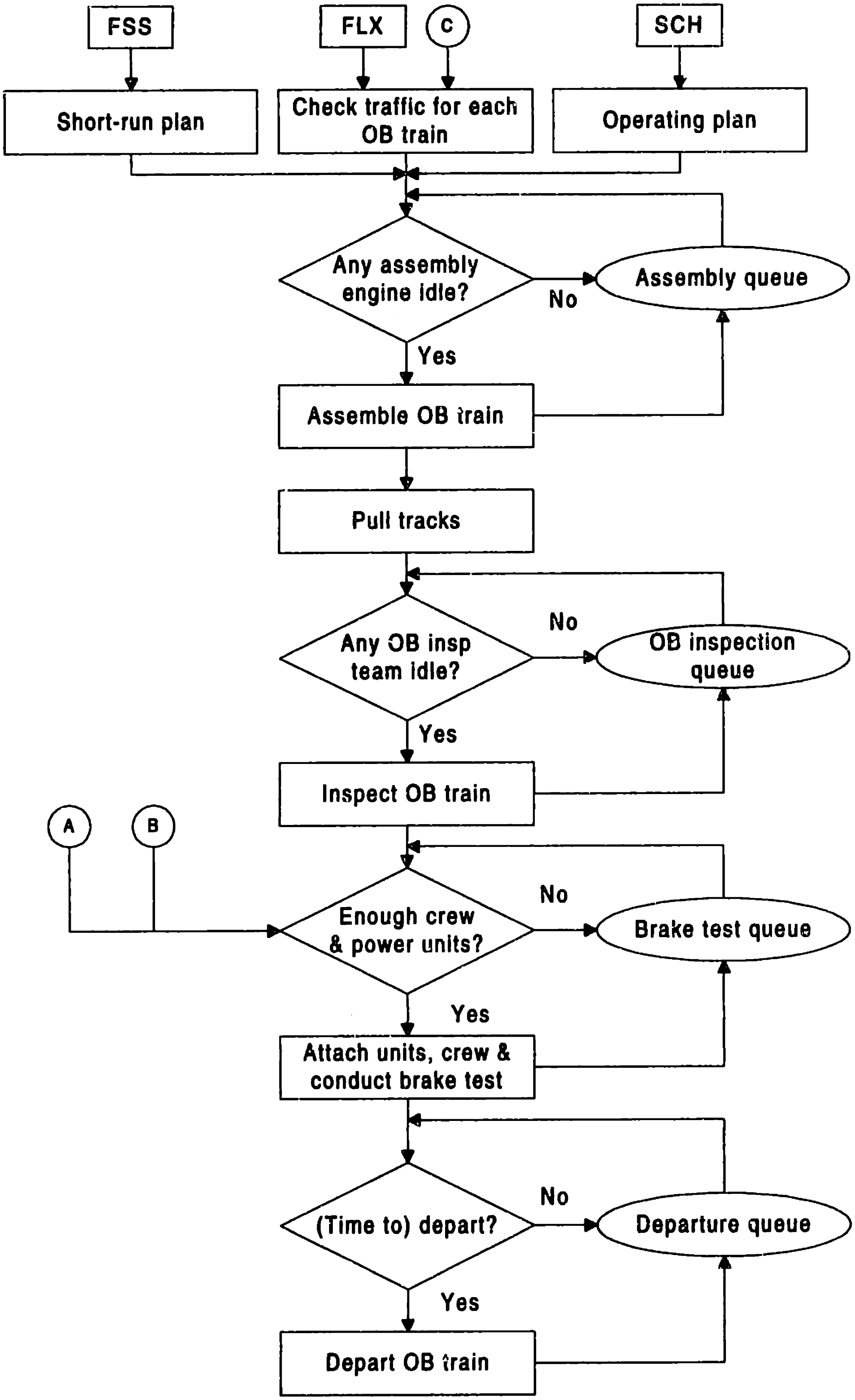

Figure 4-3: The Simulation Model Flow Chart: OB Part

After the receiving operation is finished (e.g., starts to execute the END_ARRIVE event), the crew and power units on the train are released and the events of FREE_CRW and FREE_PWR are generated and added into the heap. The model will also check if there is any receiving track which satisfies the IB inspection condition.[26] If the condition is satisfied and there is at lease one IB inspection team available, the IB inspection is conducted [27] and an END_IBINSP event is generated and added into the heap. Otherwise, the track is added into the IB inspection queue.

When it is the time to execute a FREE_CRW event for a crew, the crew is available for next trip, making the crew pool increment by 1. Similarly, when it is the time to execute a FREE_PWR event for a power unit, the unit is available for next trip, making the power pool increment by 1.[28]

When the IB inspection is finished (e.g., starts to execute the END_IBINSP event), the model will check if the hump crew and hump engine are idle. If they are idle, they will hump the track[29] and generate an END_HUMP event and add it into the heap. Otherwise, the track will be added into the hump queue and waits for hump. The model will also check if there is any receiving track waiting for IB inspection (since the IB inspection team just finishes its task, it can start another task now). If there is some track waiting for IB inspection, then the team starts to inspect a track, which is the first track in the IB inspection queue based upon the queuing strategy.[30]

When the hump is finished (e.g., starts to execute the END_HUMP event), the model will check if there is any receiving track waiting to be humped. If there is at least one receiving track waiting to be humped, the model will get a track from the hump queue and hump it (thus generate another END_HUMP event). The model will also check if there is any IB train waiting for arrival, since the END_HUMP event

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[26] It is specified by the parameter *INSP_LEVEL*. See page 235 for discussion.

[27] At this time, the track is *flagged on* and other cars cannot be placed on this track until it finishes the hump process (e.g., the remaining capacity of this track is 0).

[28] Different power units will have different preparation times even though they may come from the same IB train.

[29] When a bowl track is pulled by some assembly engine, the track cannot be used to hump cars. Rather, the cars will go to a *storage* track, whose purpose is to temporally store cars that cannot go to their specified tracks. Later on the storage track needs to be *rehumped*,.

[30] The queuing strategy is specified in Appendix A section A.1.10. See page 233 for discussion.

clears one receiving track. If the arrival queue is not empty, then the model will get an arrival train from the arrival queue based upon the arrival queuing strategy. For flexible operation, the model will also check the traffic volume for *each* OB train. See the flow chart for OB part. If there is an OB train whose traffic volume satisfies its minimum traffic volume requirement.[31], the OB train starts assembly if there is at least one assembly engine idle and the model generates an END_PULL event. For schedule-adherence strategy, the assembly time is determined based on the operating plan. For the flexible short-run scheduling strategy, the assembly time is determined based on a short-run plan.[32] For these two operating strategies, ASSMBL events are generated to start assemblies based on the planned times.

When starting to assembling an OB train (e.g., starts to execute an ASSMBL event), the model will estimate how many bowl tracks to pull and which block to pull from which bowl track. Then the model will divide the assembly operation into several pulls; each has two events (e.g., a PULL and an END_PULL events), which are added into the heap. The model simulates the assembly operation in detailed pull level.

When the assembly operation is finished (e.g., we execute an END_PULL event, which is the end of an assembly operation), the model will check if there is any OB inspection team idle. If there is at least one team idle, the assembled OB train will start the OB inspection and an END_OBINSP event is generated and added into the heap. Otherwise it is put at the OB inspection queue and waits for OB inspection.

When the OB inspection operation is finished (e.g., we execute an END_OBINSP event), the model will check if there are any road crew and power units available to satisfy the OB train based on the crew pool and power pool information. If the crew and power unit requirements are satisfied, the OB train is attached by the crew and power units[33], the brake test operation starts, and an END_TEST event is generated

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[31] The minimum traffic volume requirement is specified by the parameter *MIN_OB_CARS* in Appendix A subsection A.1.5 on page 230.

[32] See section 4.3.2 on page 112 for discussions of how a short-run plan is developed by the model.

[33] The number of available crews is decreased by 1 and the number of power units is decreased by n, the minimum number of power units to draw the OB train.

and added into the heap. Otherwise the OB train is put into the brake test queue.

When the brake test is finished (e.g., we execute an END_TEST event), the model will check if it is the time to depart the OB train.[34] If it is the time to depart the OB train, the OB train leaves the terminal. Otherwise it is put into the departure queue and waits for departure.

All the events generated during the simulation are stochastic in nature to reflect realistic terminal operating conditions. The stochastic mechanism to generate these events is discussed in Appendix A section A.1 (on page 221).

4.5 The model implementation

The simulation model is implemented using C and C++.[35] At the beginning of the implementation, commercially available simulation software was considered as a possible choice of the simulation languages. The available simulation languages are able to fit some situations very well, but for some complex situations, in the author's judgment, they are not flexible and powerful enough for simulating complex terminal operations. So the powerful C and C++ are chosen to be the simulation language.

The implementation is mainly on the PC environment (e.g., with a 166 MHz Pentium processor and a Borland C++ version 5 compiler) although the model can be run on the Unix system. The programming code is about 8000 lines.

4.6 A case study

In this section, a case study using actual data from a major hump terminal of a Class I railroad is conducted. The actual data[36] includes the IB and OB train schedules, terminal resources, terminal processing parameters, terminal configuration, and other parameters representing the terminal operating conditions. The case study includes

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[34] The line capacity can also be considered to depart OB trains to line segment.

[35] The model was first implemented in C. With the increase of the familiarity with C++, more C++ features were added into the model.

[36] The actual data is specified in Appendix A on page 221.

a base case which represents the current terminal operations, a sensitivity analysis in which the variable or parameter values are changed to evaluate the effects of these variables or parameters on terminal performance, and a scenario run in which nine cases representing different operating conditions are designed, used, and analyzed.

4.6.1 Base case results

The base case results are based on average of 5 model runs,[37], each simulating terminal operations for a month. A month's operation is long enough to estimate reasonable terminal operations under different operating strategies. For the simulation of a month's operation, three weeks' (e.g., 21 days) operations are used to collect the terminal performance statistics.[38]

Table 4.2 reports the model execution times based on 5 runs of the base case without detailed output (such as each activity and each IB and OB train consists).

	SCH	FSS	FLX
Execution Time (in sec.)	10.33	11.69	11.90

Table 4.2: Average Execution Time of the Terminal Simulation Model

Table 4.3 shows the base case summary results from the terminal simulation runs.

In Table 4.3, the total terminal processing time is the average time in hours that a car spends in arrival, IB inspection, classification or hump, assembly, OB inspection, brake test, and departure including waiting time for these processes. In other words, it is the car yard time minus the car waiting time at the bowl track. "DH" means deadhead and we use this notation throughout the thesis. Terminal manager can predict the crew or power unit shortage ahead of time and asks for additional crews or power unites, which may be satisfied by the system level managers in a

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[37] Experiments show that 5 runs are statistically good enough to get reasonable estimates of the terminal performance. The sensitivity analysis and scenario runs are also based on average of 5 model runs.

[38] The first 5 and last 4 days' operations are not included in the statistics collection to eliminate possible *end effects*.

	OB trains	OB on time	avg conn. perf.	avg yard time	total proc time	avg crew time	DH in crews	DH out crews	avg power time	DH out units
sch	421	410	99.16%	26.54	10.89	9.30	1.20	0	14.64	41
	1	18	0.52%	0.07	0.16	0.80	0.84	0.00	0.16	4
fss	375	194	91.33%	24.58	11.17	14.33	0.00	46	13.15	76
	3	6	0.31%	0.27	0.07	0.32	0.00	2.17	0.25	10
flx	349	177	80.35%	30.39	12.54	15.40	0.00	70	14.48	134
	2	7	1.25%	0.34	0.21	0.23	0.00	3.51	0.14	9

Table 4.3: Terminal Base Case Summary Results

probabilistic manner. Similarly, if the terminal has too many crews or power units, which is specified in Appendix A on page 236, the system level managers will ask the terminal manager to move some crews or power units out of the terminal to help other terminals.

In terms of OB trains run, the results show that the schedule-adherence (SCH) strategy operates the most trains and the flexible short-run scheduling (FSS) strategy operates more trains than the flexible operation (FLX) strategy. The train cost is the largest for SCH, and is larger for FSS than FLX. Since railroads often consider train cost as a big part of their operating cost in their budget, the results suggest that FLX will have the smallest operating cost, and FSS will have smaller operating cost than SCH. This conclusion seems consistent with the railroad practice in that the operating cost is still a major concern for many railroad managers so that the operations are managed like a flexible operation to achieve the savings in operating cost. Car cost is not considered as operating cost in current railroad budget. This conclusion also suggests that operating railroad under FSS or SCH may actually increase the operating cost rather than decreasing the operating cost as suggested by advocates of FSS and SCH. If, on the other hand, car cost is considered as a part of the operating cost, then FLX may have larger operating cost than SCH and FSS.

In terms of OB train performance, the results show that SCH has the best OB train on-time performance and FSS has better OB train performance than FLX. This suggests that under SCH more trains will depart on-time and hence more likely to arrive at the downstream terminals on time, and FSS is worse than SCH but better than FLX for this concern, indicating that the assumptions made for IB train arrival pattern (see section 4.3.2 on page 111) is consistent with the model output.

In terms of connection performance, the results show that SCH can provide the most reliable service and FSS can provide more reliable service than FLX. In the operating plan, there is extra time added as a connection buffer[39] while the short-run plan does not have a buffer. Under FLX, longer and fewer trains are assembled. The less frequent service makes cars more likely to miss their connections.

In terms of average yard time, the results show that under FSS cars can go through the terminal with the least time and less time under SCH than under FLX. The FSS tends to use less buffer time in the short-run plan while the SCH uses more buffer time in the operating plan to handle possible deviations from the daily operating situations. Under FLX, cars will stay at terminal longer due to less frequent OB trains.

In terms of total processing time, the results show that SCH has the least total processing time and FSS has less total processing time than FLX. There may be two reasons to explain the results. One is that the longer the OB trains, the more time is needed to process them. The other is the possible unbalanced operations under FLX and FSS. The unbalanced operations may cause queues at the processes and increase the total processing time.

In terms of average crew time, the results show that under SCH, the crews are the most utilized and more utilized under FSS than under FLX. The average crew time is tightly related to the number of OB trains run. The more the OB trains run, the lower the average crew time. In terms of average power time, the results show that FSS has the smallest average power time and FLX has smaller average power time than SCH. Note that the average power time is not only related to the number of OB trains run. It is also related to the traffic volume on the OB trains.

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[39] The average t_{min} for all the connections is about 9 hours, which is the extra time added as buffer time. See subsection 4.3.2 on page 113 for discussions of t_{min}.

In terms of road crew and power unit requirement (e.g., deadhead in and out), the results[40] show that SCH needs the most system level resources and FSS needs more system level resources than FLX. This suggests that under SCH, each terminal is more likely to ask for crew and power unit resources and is less likely to provide extra crews and power units to other terminals. On the other hand, under FLX, each terminal is more likely to provide extra system resources to other terminals, rather than asks for additional system level resources. This conclusion suggests that a local control strategy such as FLX, needs less system resources than a global control strategy such as SCH, since to keep the global control strategy work, more resources must be provided while the local control strategy just does its best based on the available resources.

Which operating strategy is the best?

The base case results show that no operating strategy achieves the best performance for all the performance measures used in the analysis. The answer to the question of which operating strategy is the best really depends on the performance measures used for the evaluation. If railroads place customer service as their top concern and can compromise in measures of resource requirements and operating cost, the SCH is the best one to achieve their goal. If resource utilization, especially car utilization, is the most important factor for railroads, they may consider FSS since it achieves the smallest average yard time and very good average power and crew times. If railroads want savings in operating cost by running fewer trains, FLX is the choice, since it runs fewest trains and saves operating costs in crews, power units, and fuel, but the service will be poor and car cost will be high.

Today, railroad operations are conducted under a tightly controlled budget, which makes many railroads more concerned with operating cost rather than service performance and resource utilization. They are more concerned with running fewer trains to achieve savings in operating cost; therefore, their operations are more traffic-oriented

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[40] The deadhead in power units are all zeros under different operating strategies.

and limited resources are purchased.

On the other hand, they are facing more pressure to improve their service and resource utilization. Competition forces them to improve their service for at least high priority traffic such as auto and intermodal traffic, where a more scheduled approach is used to operate these traffic. It is probably true that railroads do not have enough system resources and an urgent need to implement a more scheduled approach for more traffic, which can be very profitable. On the other hand, for low priority traffic such as unit coal trains, flexible operation is enough to achieve desired service and does not require extra system resources to do so. Between service and resource utilization, some railroads are more concerned and interested in improving resource utilization.[41] Improvement in resource utilization can, in some degree, overcome the effects of shortage in resources. So for general merchandise traffic, FSS fits the railroad current situations very well while FLX does not provide satisfactory service and railroads do not have an urgent need and enough resources to apply SCH.

4.6.2 Base case sensitivity analysis

The base case in previous section presents the normal terminal operating conditions. In this section, values of the variables or parameters representing internal and external operating conditions[42] are changed to estimate the effects of these variables or parameters on terminal performance under different operating strategies.

The effect of IB arrival variation on terminal performance

Figure 4-4 shows the effect of arrival variation[43] on average connection performance.

When the IB train arrival performance is worse, the connection performance is generally worse under all the three operating strategies. SCH is more robust in connection performance than FSS and FLX when the IB train arrival performance is

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[41] See, for example, [5, 38]

[42] Internal and external operating conditions are two major factors affecting terminal performance. See Chapter 2 section 2.4 on page 54 for discussions.

[43] Arrival variation is defined using parameter RANGE, which is the horizontal axis. See Appendix A page 234 for definition of this parameter.

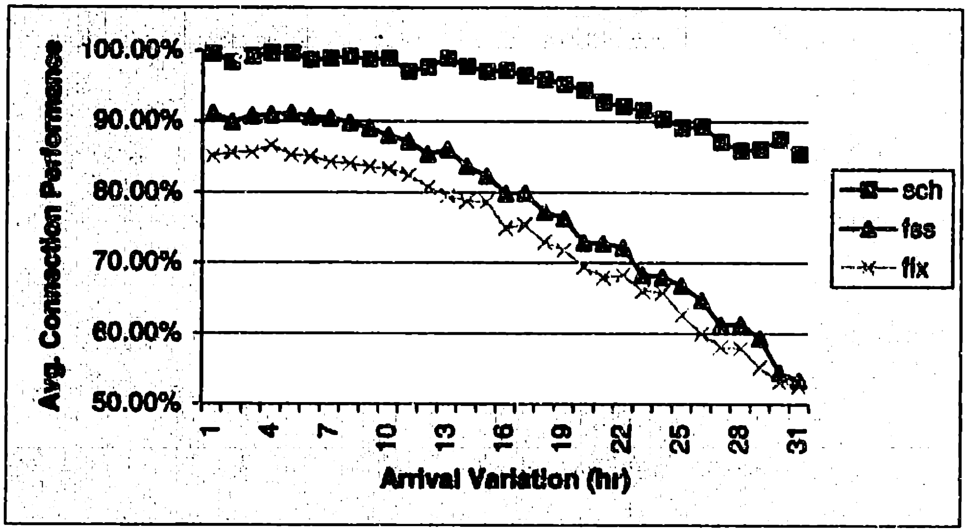

Figure 4-4: Sensitivity Analysis: Connection Performance vs. Arrival Variation

worse. Under the given operating conditions in the study, SCH has the best connection performance and FSS has better connection performance than FLX. Figure 4-4 also shows that all the three operating strategies have robust connection performance when the IB train arrival variation is less than 10 hours, which is the normal change of IB train arrival times. This may indicate that the cutoff time used (e.g., 20 hours) may be too large to have sensitive effect on connection performance even through arrival variation is large.

Figure 4-5 shows the effect of arrival variation on average yard time. With the initial increase of the arrival variation, the average yard time is actually decreased for all the three operating strategies. This is because the arrival variation results in more late arrivals but the cars from these late arrival trains still make their connections. For larger arrival variation, the average yard time is increased due to possible missed connections. FSS has the smallest average yard time and SCH has smaller average yard time than FLX under the given range of arrival variation.

Figure 4-6 shows the effect of the variations of arrival time and traffic volume on average yard time for FSS.[44] Again, some variation of arrival time can reduce average

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[44] The larger the numbers on axis of Variation of # Cars, the larger the variation of # of cars on IB trains. For the other two operating strategies, the behavior of average yard time is very similar to that under FSS.

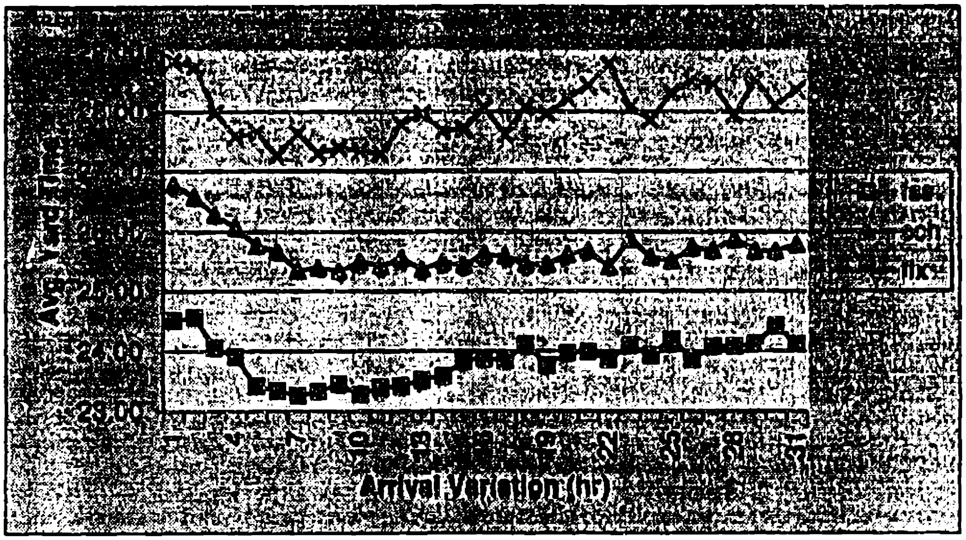

Figure 4-5: Sensitivity Analysis: Average Yard Time vs. Arrival Variation

yard time. It also shows that the increase in variation of number of cars will increase average yard time under FSS.

The effect of extra trains on terminal performance

Figure 4-7 shows the effect of average daily extra IB trains on connection performance. See subsection 4.3.2 on page 113 for the discussions of extra trains and how they are generated.

With the increase in extra IB trains, the connection performance is worse for all the three operating strategies. SCH has the best connection performance and FSS has the better connection performance than FLX. The results suggest that extra trains are not good to achieve good connection performance.

Figure 4-8 shows the effect of average daily extra IB trains on the average yard time performance.

With the increase in extra IB trains, the average yard time is generally increased. For the terminal with more than two daily extra IB trains, the average yard time may be significantly larger than that for not having two or more daily extra trains. Note the significant increase in average yard time under SCH.

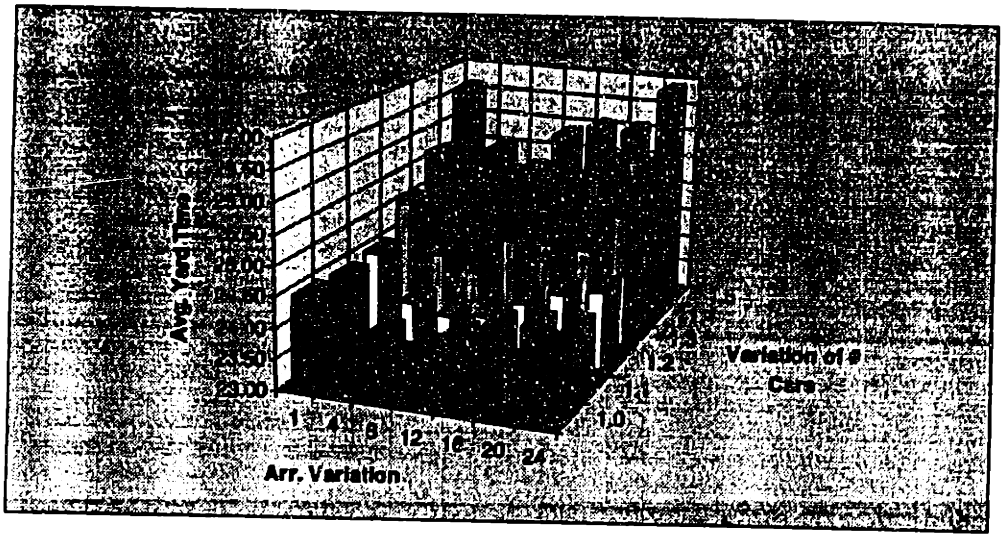

Figure 4-6: Sensitivity Analysis: Average Yard Time vs. Variations in Arrival and Traffic Volume

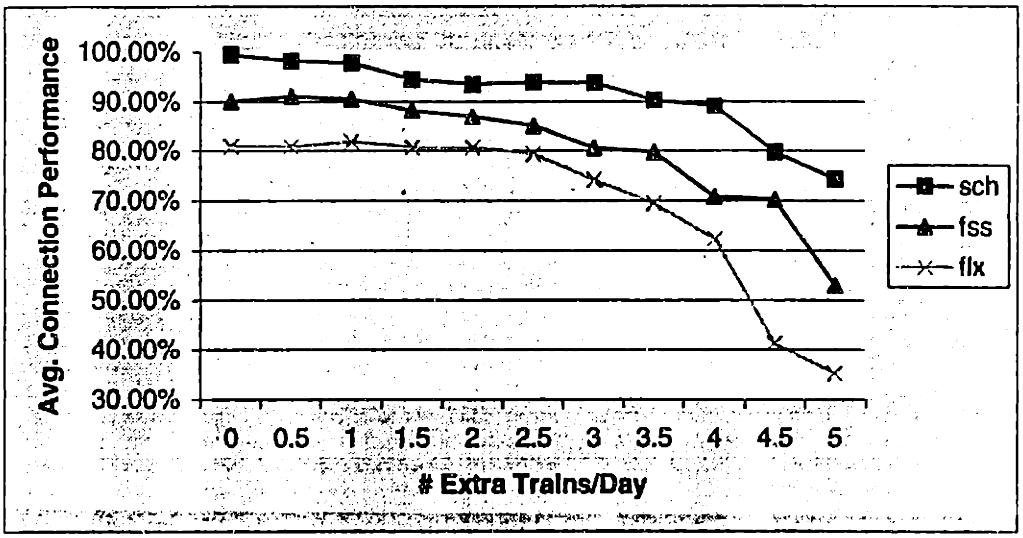

Figure 4-7: Sensitivity Analysis: Connection Performance vs. Extra IB Trains/Day

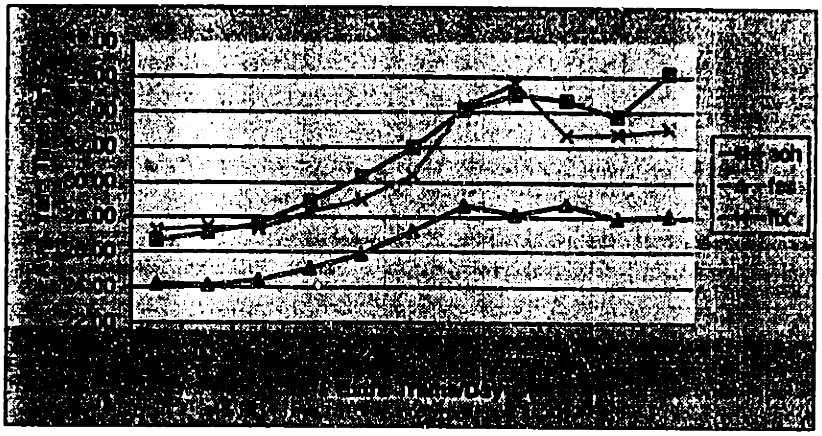

Figure 4-8: Sensitivity Analysis: Average Yard Time vs. Extra IB Trains/Day

The extra IB trains are not a good thing for terminal to achieve better performance in terms of connection performance and average yard time for all the three operating strategies evaluated. It is especially true for the schedule-adherence strategy. So it is better to run the trains according to train schedules under SCH or some short-run plans under FSS. For flexible operation, the increase of IB trains will also increase the average yard time and decrease the connection performance.

The effects of the delays caused by accidents, extreme weather conditions, and unscheduled maintenance on terminal performance

In the model, we specify that accidents, extreme weather conditions, and unscheduled maintenance will delay IB train arrivals. The amount of delay is around 1 to 6 hours.[45] The effects of accidents, extreme weather conditions, and unscheduled maintenance on terminal performance are equivalent to the delays of some IB trains. These effects are very similar to the effect of IB arrival variation on terminal performance and the graphical results are not given here.

With the increase of the probability of delays caused by accidents, extreme weather conditions, and unscheduled maintenance, more trains are delayed and the average yard time is decreased. The connection performance is not significantly affected by the changes of the probability of the delays. See the effect of arrival variation on

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[45] See Appendix A subsection A.1.11 on page 233 for discussions of parameters PROB_DELAY, MIN_DELAY, and MAX_DELAY

terminal performance for explanation.

The effect of terminal processing time variation on terminal performance

Figure 4-9 shows the effect of terminal processing time variation on terminal average yard time.[46] The results show that the increase in terminal processing variation will increase average yard time. This conclusion suggests that the increase in processing variability is not good for terminal average yard time. On the other hand, the effect of terminal processing time variation does not have significant impact on terminal connection performance. The graphical results are not presented here.

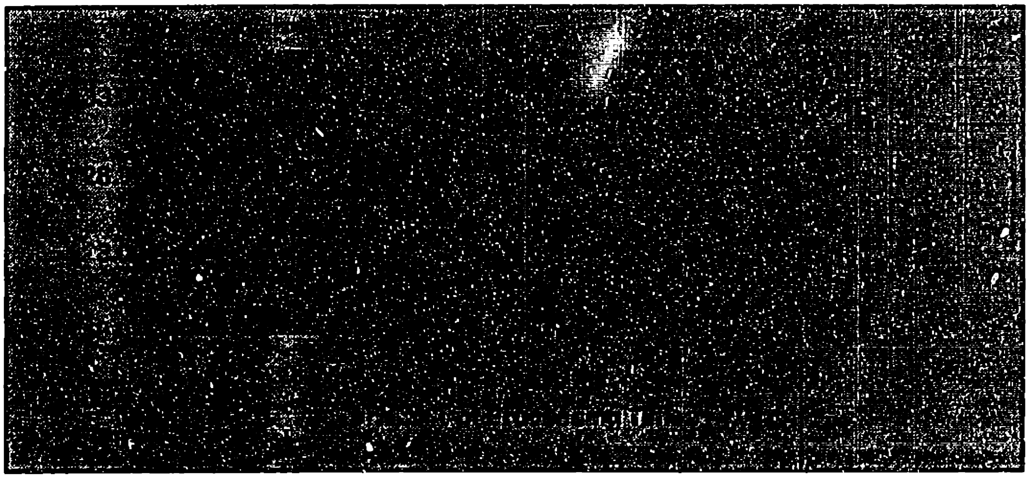

Figure 4-9: Sensitivity Analysis: Average Yard Time vs. Variation Of Processing Times

The effect of terminal resources on terminal performance

Figure 4-10 shows the effect of terminal resources on terminal connection performance. Here the numbers in the terminal resources represent the terminal resources used (e.g., the number of IB and OB inspection teams and assembly crews used, with the exception that the hump crews used is 1 or 2).

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[46] In Figure 4-9, the 5 in X axis is the variation of -5 and +5 minute range for arrival and brake test and -10 and +10 minute range for other processes.

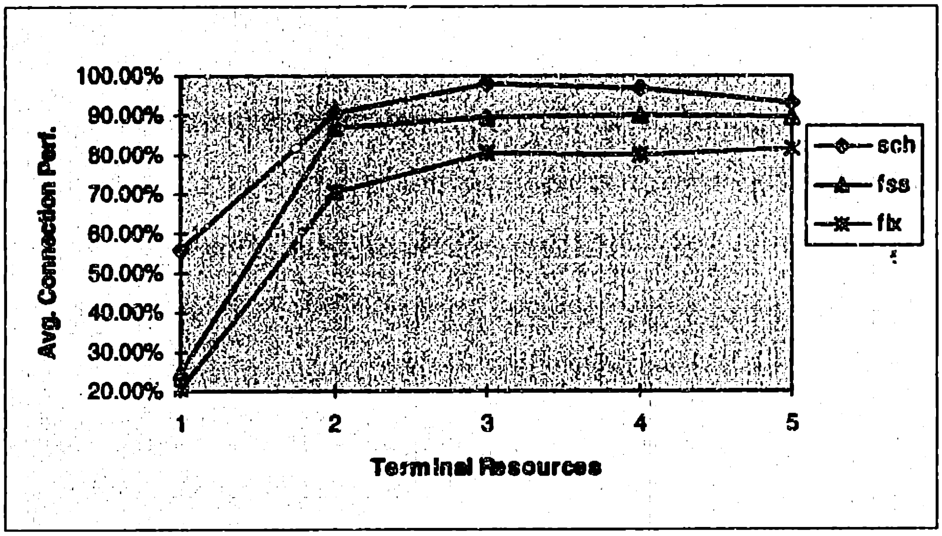

Figure 4-10: Sensitivity Analysis: Connection Performance vs. Terminal Resources

The results show that with the increase of terminal resources, the terminal connection performance is generally improved by all the three operating strategies. For the given change of terminal resources, SCH has the best connection performance and FSS has better connection performance than FLX. Similarly, the increase of terminal resources reduces average yard time for all the three operating strategies. For the given change of terminal resources, FSS has the smallest average yard time and SCH has smaller average yard time than FLX. The graphical results for average yard time is not presented here.

The effect of terminal queuing strategies on terminal performance

Various combinations of different terminal operating strategies for terminal processes are designed and tested. See Appendix A section A.1.10 on page 233 for discussions of terminal operating strategies. The general conclusion is that the departure strategy has more significant impact on terminal performance than the terminal operating strategies for other processes such as IB arrival, IB and OB inspection, hump, and assembly, where the waiting time in the queues are limited. For the departure strategy, if OB trains need to wait for scheduled departure time to leave the terminal, the average yard time is increased for all the three operating strategies compared with the departure strategy of departing the terminal whenever an OB train is ready for departure (e.g., does not need to wait for scheduled departure time). The increase in average yard time is the largest under FLX (e.g., more than 2 hours) and larger under FSS (e.g., around 2 hours) than SCH, which is around half an hour.

4.6.3 Scenario design and runs

In the previous two subsections, results from a base case and its sensitivity analysis are presented and conclusions are drawn. In this subsection, we will design more scenarios and cases to represent different terminal operating conditions, which are used to evaluate different operating strategies on terminal performance to generalize the results from the previous two subsections.

Define variables

The major variables affecting terminal performance are discussed in section 4.3.3 (on page 114) and are grouped into the following categories:

- IB traffic
    - Traffic volume (e.g., average # of IB trains/day)
    - IB arrival pattern (e.g., arrival time variation of IB trains)
    - IB train delays (due to stochastic events such as accidents, extreme weather conditions, unscheduled maintenance etc)
    - IB traffic variation (e.g., the variation of # of cars on each IB train)
- Terminal Capacity
    - Number of receiving tracks
    - Number of departure tracks
- Terminal processing time

  - Fixed time
  - variation
- Cutoff time
- Terminal queuing strategy (e.g., FIFO, LIFO, Priority, and Contribution rule)
- System level resources
  - Crew and power inventory
  - Probability of deadheading in crews and power units
  - Crew rest time distribution
  - Power preparation time distribution

The values of these variables are given in Appendix A subsection A.2.1 (on page 238) and are used in the scenario runs.

Define scenarios

The detailed scenarios are defined in Appendix A subsection A.2.2 (on page 240). The major characteristics of these scenarios can be summarized in Table 4.4.

Scn	traffic volume	traffic variation	proc time	proc variation	capacity	cutoff time	system resource	system prep
C 1	l	l	l	l	h	l	h	h
C 2	l	l	m	m	m	m	m	m
C 3	l	l	h	h	l	h	l	l
C 4	m	m	l	l	h	l	h	h
C 5	m	m	m	m	m	m	m	m
C 6	m	m	h	h	l	h	l	l
C 7	h	h	l	l	h	l	h	h
C 8	h	h	m	m	m	m	m	m
C 9	h	h	h	h	l	h	l	l

Table 4.4: Terminal Scenario Design

In Table 4.4, *traffic variation* includes IB arrival pattern, IB train delays, and IB traffic variation variables. The "l" means that the values of IB arrival pattern, IB train delays, and IB traffic variation are all "l" values.[47] Similarly, *capacity* includes both receiving tracks and departure tracks. The variable *system resource* includes both road crews and power units inventory and probability of deadheading in crews and power units. The variable *system prep* includes both the crew rest time distribution and power preparation time distribution.

Nine cases or scenarios are designed. These cases are changing from low traffic volume and traffic variation, small terminal processing time and variation, large terminal capacity and tight connection, and large system level capacity and longer system resource preparation time (e.g., Case 1) to high traffic and traffic variation, large terminal processing time and variation, small terminal capacity and long connection, and small system level capacity and quicker preparation of system level resources. Note that we assume that with less system level resources, the preparation time is smaller. This assumption is made to reflect the railroad situation. But the effects of these variables are conflict in terms of system level resource availability. These cases are designed to evaluate the effects of traffic, terminal processing time, terminal capacity, connection time (e.g., cutoff time), and system level resources on terminal performance under different operating strategies.

Major performance measures

The evaluation of different operating strategies under different operating conditions such as traffic, terminal capacity, system level resources, etc. are based on the following performance measures.

- Average yard time
- Connection reliability
- Average crew time

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[47] See Appendix A section A.2 on page 238 for values of these variables labeled with "l". The "m" and "h" have the same meanings.

- Average power time
- % OB trains on time
- # OB trains run

These are the major performance measures used in railroads to evaluate terminal performance. The connection reliability measures car connection reliability, which is one of the major customer service performance measures at terminals at car level. The % OB trains on time is a major train performance measure. The average yard time, average crew time, and average power time are major measures of railroad equipment utilization. The # OB trains run can be considered as an indicator of the cost of running OB trains, which is one part of the major terminal operating costs.

Results and conclusions

Table 4.5 shows the summary results for the terminal scenario runs of the nine cases under different operating strategies. The crews deadheaded in are zeros for all the cases except for Case 7, where about 1 crew is deadheaded in under FSS. The crews deadheaded in are not listed in Table 4.5.

In terms of OB trains run for the nine cases,[48] Table 4.5 shows that with the increase of IB trains, FSS and FLX run more OB trains but SCH does not. This is because SCH always runs OB trains according to schedules. It does not run extra trains, while FSS and FLX run extra trains if the traffic warrants assembly of OB trains. Among the nine cases, FLX always runs fewest trains, since this operating strategy allows traffic accumulate to a high level before the OB trains are assembled. The FLX has the least operating cost that is related to OB trains.

In terms of OB train on-time performance, Table 4.5 shows that SCH has much better on-time performance than FSS and FLX, while FSS and FLX have very similar on-time performance, which is around 50%.

In terms of average connection performance, Table 4.5 shows that the average connection reliability is the best under SCH and better under FSS than under FLX

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[48] See the column labeled with "trns".

Scenario	Oper. Str.	OB trains	OB on time	avg conn. perf.	avg yard time	avg crew time	avg power time	DH in units
Case 1	sch	421	97.57%	99.70%	25.39	12.04	15.96	1
	fss	374	53.10%	83.29%	24.55	16.77	14.74	0
	flx	355	50.73%	74.15%	29.31	17.62	15.76	0
Case 2	sch	420	98.14%	98.62%	26.46	10.58	15.33	1
	fss	374	52.51%	87.00%	25.74	15.61	14.20	0
	flx	351	51.00%	73.15%	31.28	16.57	15.24	0
Case 3	sch	420	96.00%	97.16%	27.47	7.28	14.65	*
	fss	372	51.32%	88.10%	26.79	14.84	13.89	*
	flx	348	52.59%	72.95%	33.42	15.44	14.53	*
Case 4	sch	421	96.30%	96.47%	28.91	16.11	14.37	0
	fss	415	50.96%	79.41%	27.94	15.75	13.91	0
	flx	390	52.08%	71.81%	30.46	16.46	14.71	0
Case 5	sch	421	95.53%	96.41%	28.77	15.14	13.81	0
	fss	414	51.96%	84.53%	26.70	14.57	12.94	0
	flx	386	53.05%	73.28%	32.62	15.33	14.06	0
Case 6	sch	420	95.34%	92.94%	31.18	14.37	13.27	*
	fss	409	51.05%	85.46%	27.10	13.94	13.01	*
	flx	383	54.18%	70.91%	34.97	14.59	13.92	*
Case 7	sch	422	94.17%	79.80%	32.73	16.37	14.97	0
	fss	462	49.25%	43.78%	29.00	13.64	13.49	11
	flx	405	53.39%	27.20%	34.90	16.19	14.95	0
Case 8	sch	420	95.52%	91.43%	30.60	14.94	13.84	0
	fss	457	49.89%	78.93%	26.30	13.20	12.78	4
	flx	409	54.59%	67.99%	34.38	14.98	13.94	0
Case 9	sch	420	93.57%	91.08%	28.72	14.38	13.69	*
	fss	460	51.24%	83.32%	26.02	11.67	12.81	*
	flx	385	55.95%	72.12%	31.09	14.56	14.24	*

(*) means deadhead is not allowed

Table 4.5: Summary Results of Scenario Runs

for all the nine cases. Another conclusion from Table 4.5 is that the increase of extra trains hurts average connection reliability. Compare results for Cases 1, 4, and 7; 2, 5, and 8; and 3, 6, 9, respectively. As the traffic increases, the connection time or cutoff time has significant impact on connection reliability. The results for group two (e.g., Cases 4, 5, and 6) and group three (e.g., Cases 7, 8, 9) show that scheduling loose connection (e.g., larger cutoff time) is good for improving connection reliability when extra trains increase.

In terms of average yard time, Table 4.5 shows that with the increase of traffic (e.g., extra trains), the average yard time is increasing. The reason is that the extra trains will increase the degree of terminal congestion and hence increase average yard time. Also the extra trains are more likely to be late[49] and are hence more likely to miss their connections. If the cars miss their connection, they will stay at the terminal longer waiting for their second connections.

Looking at group one (e.g., Cases 1, 2, and 3), we can see that under the same traffic level without extra trains, the average yard time increases with the decrease of terminal capacity and system resources. High terminal capacity and system resources help reduce average yard time when there is no extra IB trains. This conclusion does not hold for group two and three, where random arrivals of extra IB trains seem make the average yard time unpredictable. Table 4.5 also shows that under the same conditions, FSS will have the smallest average yard time and SCH will have smaller average yard time than FLX.

In terms of average crew time, Table 4.5 shows that FSS has the smallest average crew time for Cases 4 to 9, where there are extra trains, and SCH has the smallest average crew time for Cases 1 to 3, where there is no extra trains. The crew rest time is a major factor affecting the average crew time. The shorter the time, the shorter the average crew time. Similarly, the average crew time is related to the number of IB trains and OB trains. More IB trains, the higher average crew time; more OB trains, the smaller the average crew time.

In terms of average power time, Table 4.5 shows that FSS has the smallest average

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[49] See IB train arrival pattern variable in Appendix A subsection A.2.1 on page 238.

power time for all the nine cases and SCH has smaller average power time when the IB traffic level is high and FLX has smaller average power time when the IB traffic level is low. The power unit preparation time may be a major factor affecting average power time. The shorter the preparation time, the shorter the average power time. This does not hold for Case 6 and 9 for FSS and Case 9 for FLX. The reason is that the power unit inventory also has some effect on average power time. The more power units, the larger average power time, since some of them must wait in the available unit queue to serve the OB trains.

With the increase of extra trains, more power units arrive at the terminal, increasing availability of power units and average power time if only the IB process is considered. On the other hand, the extra trains bring extra traffic and larger and more OB trains need to be assembled to move the traffic, reducing average power time. The net effect of extra trains is that the power units are more utilized (e.g., larger and (or) more OB trains may be more important to affect average power time than the increase of IB trains).

Note that average crew time and average power time are related to each other. For example, if crews are a critical factor affecting OB train departures, the crews are more utilized than power units, making average crew time small and average power time comparative large. Compare the average crew time and average power time for group one (e.g., Cases 1, 2, and 3), we can see that the crews are more critical under SCH (with smallest average crew times and largest average power times) than under FSS and FLX.

In terms of power units and crews deadheaded in, Table 4.5 shows that FSS tends to require more power unit and crew resources when the traffic is high and SCH tends to require more power unit and crew resources when the traffic is low. On the other hand, FLX does not require additional system crews and power units for all the nine cases, indicating that FLX requires less crews and power units than SCH and FSS.

Table 4.6 shows the summary of the scenario runs, where if an operating strategy has the best performance for a performance measure, its name appears for that performance measure. Table 4.6 shows that FLX has significant savings in operating OB trains by reducing number of OB trains run. Also FLX does not need to deadhead in much of crew and power unit resources. The scenario runs also show that when extra trains increase, FLX has robust average yard time and connection reliability while SCH and FSS worsen these measures significantly.

Scenario	OB trains	OB on time	avg conn. perf.	avg yard time	avg power time	DH in units	avg crew time	DH in crews
C 1	flx	sch	sch	fss	fss	same	sch	fss/flx
C 2	flx	sch	sch	fss	fss	same	sch	fss/flx
C 3	flx	sch	sch	fss	fss	*	sch	*
C 4	flx	sch	sch	fss	fss	same	fss	same
C 5	flx	sch	sch	fss	fss	same	fss	same
C 6	flx	sch	sch	fss	fss	*	fss	*
C 7	flx	sch	sch	fss	fss	same	fss	sch/flx
C 8	flx	sch	sch	fss	fss	sch/flx	fss	sch/flx
C 9	flx	sch	sch	fss	fss	*	fss	*

(*) means deadhead is not allowed

Table 4.6: Terminal Scenario Runs: Summary

SCH provides the best connection reliability and OB train on-time performance. It also has good crew utilization. FSS provides the highest car through put (e.g., the smallest average yard time), the highest power utilization (e.g., the smallest average power time), and the highest crew utilization for most of the cases.

Considering the current railroad operations, it seems that FSS has more potential to be used as a strategic tool to improve railroad operations. The reason is that FSS provides the best resource utilization, which is the most concern to some railroads.[50] The improvement of the system level resource utilization may have significant impact on service performance improvement.

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[50] See, for example, [5, 38].

4.7 Summary and conclusions

In this chapter, we presented a terminal simulation model, which simulates detailed terminal operations under different operating strategies. We use this terminal simulation model to evaluate terminal performance and system level resource utilization under different operating strategies.

A case study was conducted using actual data from a major hump terminal of a Class I railroad. The data set includes the train schedules (both IB and OB), terminal resources, terminal processing parameters, terminal configuration, and other parameters representing the terminal operating conditions. The case study includes a base case, a sensitivity analysis, and scenario runs. The major conclusions from the case study are as follows.

- No operating strategy achieves the best performance for all the performance measures used in this research. Each operating strategy has its advantages and disadvantages;

- The schedule-adherence strategy (SCH) provides the best connection performance and OB train on-time performance. It also provides very good crew utilization, measured by average crew time, when the traffic is low. To achieve its goal of schedule-adherence, SCH needs additional crew and power unit resources deadheaded in the terminal under study while it is very hard for the terminal to support other terminals with extra crews and power units.

- The flexible short-run scheduling strategy (FSS) provides the best car utilization measured by average yard time. The terminal through put is the largest under this operating strategy. It also provides very good system level resource utilization, especially the power unit utilization, measured by average power time. The connection performance under this operating strategy is also better than FLX. FSS requires additional crew and power unit resources, especially when the traffic is high. It is difficult that the terminal can provide other terminals with extra road crews and power units (e.g., deadhead out crews and power units to other terminals).

- The flexible operation strategy (FLX) runs fewest OB trains and provides the largest savings in train cost. It also requires the least additional crew and power unit system resources. This operating strategy works very well when there is limited supply of system level resources such as crews and power units. Compared with the other operating strategies, FLX often has large average yard time, poor connection performance, and lower resource utilization.
- The answer to the question of which operating strategy is the best really depends on which performance measure(s) is the most important one(s) to railroads and the degree to which they can compromise other performance measures. Considering current railroad operations, it seems that the cost saving goal is very important to railroads so they may continue to run unit trains such as unit coal trains using FLX. But they may no longer run fewer trains while providing satisfactory service performance for general merchandise traffic. FSS seems to be a good choice for this traffic. On the other hand, railroads may not have an urgent need and enough system level resources to apply SCH for all the traffic. It seems that SCH can be used to run high priority traffic such as auto and intermodal traffic. Applying different operating strategies to different traffic priorities can potentially be a very effective tool for railroads to achieve better operations and performance.

Chapter 5

Simulating Rail Network Operations under Different Operating Strategies

5.1 Introduction

In this chapter, we will present a rail *network* simulation which models the railroad network operations, including terminal operations and line haul movement operations, under different operating strategies.

The network considered in this research consists of several hump terminals, intermediate terminals, and the line haul segments. The work in this chapter is the continuation and extension of the terminal simulation model developed in Chapter 5, where the effects of the rest of the rail network on the terminal is specified by different arrival patterns and the line capacity is not considered when OB trains depart. The methodology used in the network simulation model is similar to the terminal simulation model, both coming from the methodology developed in Chapter 3, which decomposes railroad operations into processes and tasks. (See section 3.2 on page 63 and section 3.3 on page 79). The arrival pattern of IB trains entering the network is, as in the terminal simulation model, the input of the network model, which is specified based upon the stochastic model for schedule-adherence and flexible operation strategies presented in Chapter 3 section 3.4.2 (on page 94).

For given terminal resources and line capacity, the network simulation model simulates detailed system operations under various operating conditions and under different operating strategies. Two case studies are conducted using the network simulation model. Case study one uses a *service lane network* (the layout of the service lane network is in section 5.4 on page 154) which contains two hump terminals and four intermediate terminals and case study two uses an *area network* which contains three hump terminals and six intermediate terminals (the layout of the area network is in section 5.5 on page 178). Service lane and area networks are important for railroads to implement new plans or approaches to improve their operations and service. CSX, for example, tests its alternative operating plans on a service lane network and tests its blocking policy on an area network [73, 74].

The operations of a large network can be decomposed as the operations of several smaller networks such as service lane and area networks, since the crews and power units often cycle around these smaller networks and many railroads such as CSX and Union Pacific indeed organize their operations by divisions, which are smaller networks. So the results from these two small networks can be generalized to larger networks. The two case studies use two portions of a physical network from a Class I railroad not revealed here for reasons of confidentiality.

5.2 The model input and output

The input of the network simulation model includes all the input (files) from the terminal simulation model[1] and the network files which specify the network structure. The network files include *node* and *arc* files. The node file specifies all the terminals to be simulated with the node *identification number, type* (1: hump terminal, 2: intermediate terminal), *capacity* (number of trains that can be held), *arrival period* (minimum time in minutes that separates consecutive arrivals at the terminals), *de-*

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[1] The input files include input for all the hump terminals rather than for just one hump terminal.

parture period (minimum time in minutes that separates consecutive departures), *fix time* (fixed time ($T1$) in minutes for the intermediate terminal operations), *variable time* (variation time ($T2$) in minutes for the intermediate terminal operations), and *processing time per car* ($T3$) in minutes. The intermediate terminal process time T in minutes can be expressed using the following formula:

$$T = f(T1 + T3 * n - T2,\ T1 + T3 * n + T2) \tag{5.1}$$

where, n is the number of cars processed at the intermediate terminal and f is any probability distribution (uniform distribution was used in the model runs). See Appendix B section B.1.1 (on page 246) for detailed node input file for the service lane network and section B.2.1 (on page 248) for detailed node input file for the area network.

The arc file specifies the line (haul) segment characteristics, including line segment *identification number, IB and OB nodes* of the line segment, *length* of the line segment[2], *capacity* of each direction in terms of number of trains, *arrival*and *departure periods*, and the *speed* of each direction in miles per hour (mph). See Appendix B section B.1.2 (on page 247) for detailed arc input file for the service lane network and the section B.2.2 (on page 248) for detailed arc input file for the area network.

The major model output includes, for each origin destination pair (OD), the number of trains run during the simulation, the average time (in hours) each train spends at the *intermediate* terminals, the average line haul movement time (in hours) during the simulation, the average trip time (in hours) of trains moving from one hump terminal to another hump terminal, the number of trains delayed due to lack of road power units or crews before departing the hump terminals, and the average delay (in hours) of those trains that waited for road power units or crews before departing the hump terminals. See Appendix B section B.3 (on page 249) for detailed output file.

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[2] We assume that the length of the line segment is the same for either direction. For double track line segments, it may not be true. In the latter case, another column of line segment length can be added.

5.3 The model description

The model is implemented in C and C++. It is a program of around 10,000 lines of code. The model simulates a rail network operations, including terminal operations, line haul movement operations, and system resources (e.g., road crews and power units) preparations at the hump terminals as follows.

5.3.1 The hump terminal operations

The hump terminal operations are the same as in the terminal simulation model. Each hump terminal in the network has a very similar operating plan (e.g., train schedules, IB/OB connection information, etc.). The only difference is the specification of the destinations for the OB trains assembled at different hump terminals. Different hump terminals may have different IB train arrival patterns, resources, capacity, and processing capability by specifying different values for these parameters or variables for different hump terminals.

We assume that the IB trains entering the network enter the hump terminals first. Then they go through all the IB processes (e.g., IB arrival, IB inspection, and hump). After the IB processes are finished, the cars from the IB trains wait at the bowl tracks for assembly operation. Similarly, an OB train assembled at any hump terminal goes through all the OB processes (e.g., assembly, OB inspection, and brake test and departure). Then the OB train departs from the hump terminal if the line segment it is to enter has capacity. Which line segment the train is to enter from one terminal (hump or intermediate terminal) to another terminal on its route to its destination is determined by the destination of the train in such a way that it will go from its original hump terminal to its destination hump terminal by the shortest path in terms of the expected travel time.[3] The travel time is determined using the speed without serious line congestion (e.g., the speed specified in the input file in Appendix B on page 246).

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[3] Of course, for service lane network, where there are only two hump terminals, there is only one path from any one terminal to the other, and hence the only path is also the shortest path.

We assume that the hump terminals have road crew facilities and power shops, where road crews are rested and power units are prepared and maintained. A given number of crews and power units are placed at the hump terminals at the beginning of the simulation. These crews and power units move trains within the network. They are never moved out of the network. Resources are conserved but no new resources come in either.[4] When they move trains to the destination hump terminal, the crew will go through rest and preparation process and the power units will go through preparation and maintenance process. After they go through their processes, they are ready for another trip (e.g., moving trains from the terminal to another hump terminal).[5] The usage of available crews and power units at each terminal is based upon the First In/First Out rule, meaning that the crew (or power unit) who (or which) becomes ready first will move a train out of the terminal first. The crews and power units coming with the IB trains entering the network will be moved out of the network with OB trains leaving the network and cannot be used for trains moving among the terminals within the network.[6] The purpose of the network simulation model is to evaluate the system level resource utilization and terminal and train performance for a given level of system resources (e.g., no deadheading crews and power units) under different operating strategies.

5.3.2 The intermediate terminal operations

At the intermediate terminals, only pick up and delivery, and simple crew and power operations such as sanding and watering are conducted. The intermediate terminal processing time[7] is given in formula 5.1. See section 5.2 on page 149.

Each intermediate terminal has specified capacity in terms of number of trains

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[4] A parameter in the network model is set up to determine if crews and power units can be deadheaded in or not. If deadhead is allowed, the model also requires a probability of deadheading in crews and power units when they are needed. All the model runs are made, however, by using a parameter value that does not allow deadhead.

[5] The crew and power units coming from the same train may have different preparation times and may be ready at different times.

[6] These crews and power units are not the major concern of the model and hence not modeled.

[7] The intermediate terminal processing time does not include waiting time for entering the line segment.

it can hold. When a train is to enter an intermediate terminal, the model will first check if the intermediate terminal has available capacity to receive the train, and both the departure period of the line segment the train is going to leave and the arrival period of the intermediate terminal are satisfied.[8] If these three conditions (e.g., intermediate terminal capacity, line segment departure period, and terminal arrival period) are satisfied, then the train enters the intermediate terminal. Otherwise the train waits on the line segment until these three conditions are satisfied; at that time the train enters the terminal for its terminal operation.

Similarly, when a train is to leave an intermediate terminal, the model will first check if the line segment the train is to enter has the capacity in the direction of the train's movement to receive the train, and both the departure period of the terminal and the arrival period of the line segment are satisfied. If these three conditions (e.g., the line segment capacity, intermediate terminal departure period, and the line segment arrival period) are satisfied, the train leaves the intermediate terminal and starts the line haul movement operation on the line segment. Otherwise it waits at the intermediate terminal until these three conditions are satisfied; at that time the train enters the line segment and starts its the line haul movement operation.

5.3.3 The line haul movement operations

The model logic for line haul movement operations are similar to the intermediate terminal operations. The line haul movement time[9] for a train is calculated using the following formula:

$$T_{line} = length/speed \tag{5.2}$$

where, T_{line} is the line haul movement time, the *length* is the length of the line segment, and *speed* is the speed of the train moving on the line segment. The speed

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[8] See section 5.2 on page 148 for discussions about the arrival and departure period variables.

[9] The line haul movement time does not include the waiting time for entering the terminal (hump terminal or intermediate terminal).

of the train is a function of traffic on the line in terms of number of trains as:

$$If\ trains\ \geq\ 80\%\ capacity\ \Rightarrow\ 50\%\ speed \tag{5.3}$$

$$Else\ if\ trains\ \geq\ 60\%\ capacity\ \Rightarrow\ 80\%\ speed \tag{5.4}$$

$$Else \Rightarrow\ 100\%\ speed \tag{5.5}$$

where, the *capacity* and *speed* are specified according to each direction. (See Appendix B on page 246 for the values of these variables.)

When a train is to enter a line segment, the model will first check if the line segment in the direction of the train's movement has the capacity to receive the train, and both the departure period of the terminal the train is going to leave and the arrival period of the line segment are satisfied. If these three conditions (e.g., line capacity, terminal departure period, and line arrival period) are satisfied, the train enters the line segment and starts the line haul movement operation. Otherwise the train waits at the terminal until these three conditions are satisfied; at that time the train enters the line segment for its line haul movement operation.

Similarly, when a train is to leave a line segment, the model will first check if the terminal the train is to enter has capacity, and both the terminal's arrival period and the line segment's departure period are satisfied. If these three conditions (e.g., terminal capacity, terminal arrival period, and line segment departure period) are satisfied, the train leaves the line segment and enters the terminal for terminal operations (either hump terminal operations or intermediate terminal operations depending on the type of terminal the train enters). Otherwise, the train waits on line segment until these three conditions are satisfied; at that time the train enters the terminal for its terminal operation.

5.4 Case study one: service lane network

Figure 5-1 shows the layout of the service lane network used in the case study, where terminals A and B are hump terminals, and terminals c, d, e, and f are intermediate terminals. The node and arc files for the base case are given in Appendix B section B.1 (on page 244). The IB arrival patterns to the hump terminals in the network, the terminal resources, terminal capacity, and terminal processing capability are the same as in the base case of terminal simulation in Chapter 4 except that the total number of crews in the network is 35 (18 at hump terminal A and 17 at hump terminal B) and the total number of power units in the network is 100 (50 at each hump terminal).

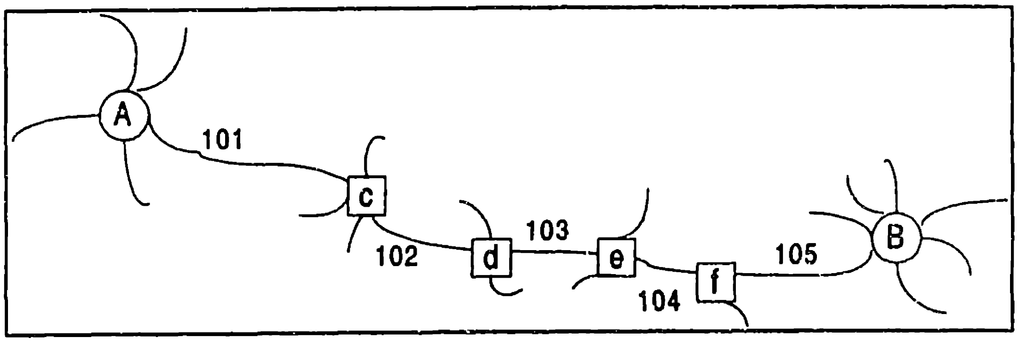

Figure 5-1: Service Lane Network

5.4.1 Base case results

Table 5.1 reports the model execution times for different operating strategies. The results are based on 5 runs of the model, each simulating the service lane network operations for a month (e.g., 30 days) without detailed output (such as each activity and each IB and OB train consists).

	SCH	FSS	FLX
Execution Time (in sec.)	21.93	24.94	24.85

Table 5.1: Average Execution Time of the Service Lane Network Model

Table 5.2 shows the trip time summary for trains of both OD pairs (e.g., A to B and B to A) under different operating strategies. The statistics in the table is based on five runs of the network simulation model, with each simulating one month (e.g., 4 weeks' operations) and three week's (e.g., 21 days) statistics are collected. The second record for both OD pairs under different operating strategies presents the standard deviation of the measures listed in the table.[10]

	Orig	Dest	# of trains	intermediate yard time	avg line time	avg trip time	# of delays	avg delay time
sch	A	B	419	4.18	6.78	10.96	17	0.63
			2	0.05	0.02	0.06	19	0.25
	B	A	419	4.14	6.79	10.93	5	0.39
			2	0.05	0.01	0.04	6	0.36
fss	A	B	415	4.23	6.83	11.06	49	1.24
			3	0.04	0.02	0.04	50	0.71
	B	A	417	4.22	6.81	11.03	59	1.15
			1	0.02	0.02	0.04	108	0.94
flx	A	B	373	4.53	6.76	11.28	133	2.60
			3	0.05	0.01	0.06	112	2.04
	B	A	369	4.55	6.75	11.30	28	1.36
			3	0.02	0.00	0.02	42	1.06

Table 5.2: Train Trip Time Summary for Service Lane Network

In terms of number of trains run, Table 5.2 shows that the schedule-adherence (SCH) strategy runs a fixed number of trains with balanced number of trains run in each direction; the flexible short-run scheduling (FSS) strategy runs fewer trains than schedule-adherence strategy and the number of trains run at each direction is less balanced than that for schedule-adherence strategy; the flexible operation (FLX) strategy runs fewest trains among the three operating strategies and the number of trains run at each direction is least balanced among the three operating strategies. The standard deviation of the number of trains run is largest for flexible operation strategy. Since trains move the same amount of traffic under different operating strategies, the results show that flexible operation strategy runs slight fewer and larger trains than flexible short-run scheduling strategy, which runs fewer and larger trains than schedule-adherence strategy.

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[10] This is true for the hump terminal performance summary in this case study and the train trip time summary and the hump terminal performance summary in case study two.

In terms of average intermediate yard time, Table 5.2 shows that the SCH strategy has slightly smaller average intermediate yard time (in hours) than the FSS strategy, which has smaller average intermediate yard time than FLX strategy. The reason is that the intermediate terminal processing time is a function of number of cars on trains and with more cars on the trains, more time needed for the intermediate terminal operations.

In terms of average line haul movement time, the results show that different operating strategies may have different levels of congestion due to different number of trains run and possibly different degree of "bundleness" of train movement, but the difference is really small among the three operating strategies.

The average trip time is the sum of the average intermediate terminal time and the average line haul movement time. SCH has a smaller average trip time than FSS, which has a smaller average trip time than FLX.

The number of delays and the average delay are two measures of the availability of crews and power units at hump terminals. Table 5.2 shows that SCH has the smallest delays and average delay and FSS has smaller delays and average delay than FLX. Using the same level of road crews and power units, SCH will have highest level of availability of these resources, and FSS will have higher level of availability of these resources than FLX. This could be one of the biggest advantage of SCH over FSS and FSS over FLX. Also note that for FLX strategy, one hump terminal (e.g., A) has much more delays (e.g., 36% trains delayed) than the other (e.g., B only 8% trains delayed), indicating that the road crews and power units may accumulate at one terminal (e.g., B) and causing unbalanced usage of both crews and power units.

Table 5.3 shows the hump terminal performance summary. Again, the statistics in Table 5.3 is based on five runs of the network simulation model, with each simulating one month (e.g., 4 weeks' operations) and three week's (e.g., 21 days) statistics are collected.[11] Note that the results in Table 5.3 are consistent with the terminal studies

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[11] Note that the number of OB trains in this table is slightly different from the trains run in Table 5.2. They are different statistics. In Table 5.2, # of trains is the number of trains reaching to their destinations during statistics collection time, while OB trains in Table 5.3 is the number of OB trains departed from the hump terminals during statistics collection time.

(See results in Table 4.3 in Chapter 4 on page 127.) The OB train performance is best under SCH, and it is much the same under FSS and under FLX. One conclusion from this set of results is that SCH provides very good OB train performance; FLX provides poor OB train performance; FSS does not necessarily provide good OB train performance. The reason for FSS not having good OB train performance is that the short-plan developed may be very different from the operating plan. As discussed in Chapter 4, FSS develops a short-run plan based on the predicted traffic at bowl tracks, and the predicted road crews and power units at the hump terminals. Whenever predicted traffic is enough to assemble an OB train and the predicted crews and and power units can satisfy the OB train at that time, then the OB train is scheduled to be assembled at that time in the plan. FSS is similar to FLX except that FSS uses predicted traffic *and* crews and power units information in the short-run plan development. FSS runs more and shorter trains than FLX.

	Terminal	IB trains	IB on time	OB trains	OB on time	avg power time	avg crew time	avg yard time	avg conn. perf.
sch	A	442	362	421	407	8.94	9.13	27.95	97.38%
		3	11	2	12	1.32	0.79	0.98	2.64%
	B	444	356	420	411	9.12	10.99	28.08	95.85%
		5	12	2	6	1.41	0.84	0.82	2.14%
fss	A	441	313	416	212	9.43	9.85	25.50	91.09%
		4	18	2	7	0.54	2.58	0.60	0.44%
	B	442	314	416	209	9.21	10.44	25.97	90.05%
		2	11	2	10	0.42	2.50	0.97	1.02%
flx	A	443	204	372	197	8.71	10.04	33.68	78.66%
		5	2	4	15	1.37	4.10	2.38	2.82%
	B	442	206	369	197	11.28	14.87	31.91	81.42%
		4	12	4	9	1.18	4.06	1.09	1.55%

Table 5.3: Hump Terminal Performance Summary for Service Lane Network

In terms of system resource utilization, Table 5.3 shows that power units and crews are most utilized under SCH and are more utilized under FSS than FLX. The system resource utilization is tightly related number of OB trains departed from the terminals. More trains departed, higher level of system resource utilization.

In terms of average yard time, Table 5.3 shows that FSS has the smallest average yard time, and SCH has smaller average yard time than FLX. The reason for FLX having the largest average time is that FLX runs fewest OB trains and hence a car is expected to wait the longest time at terminal before it goes out with some OB train. There are two reasons for FSS to have shorter average yard time than SCH. First, under SCH there are some trains departing without any car on it, which reduces the actual number of nonempty trains run. The number of empty OB trains (e.g., these are deadhead in effect) run changes from 0 to 12, with an estimate of 5 to 9 empty trains for the three weeks' operations. The reason for SCH having so many empty trains is that a second section train is placed in the train schedule as the regular train. The model results show that the second section does not run one day out of three. That is to say, SCH does not run more trains than FSS. Second, FSS takes traffic into consideration when scheduling OB train's departure time. It was verified that under FSS, the traffic volume of the OB trains are less variable than that under SCH. For some trains with very few cars on it under SCH, the effect is similar to having less trains.

In terms of connection reliability, Table 5.3 shows that SCH has the best average connection performance, and FSS has better average connection performance than FLX. The reason for FSS having better average connection performance is that FSS runs shorter and more frequent trains than FLX, a means to improve connection performance proposed many years ago (See [28, 29, 59] for example). The reason for SCH having better average connection performance than FSS is that the train schedules are developed in such a way that if IB trains arrive at the terminal on time and the terminal has resources to do a reasonably good job, most of the cars can make their connections. On the other hand, the departure time for FSS is not fixed. Sometimes OB trains may depart early but many more times it will depart late,[12] reducing the connection reliability.[13]

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[12] The OB train performance under SCH is much better than FSS as just discussed early.

[13] See Chapter 4 section 4.3.2 on page 113 for discussions of how missed connection is calculated.

Which operating strategy is the best?

The base case results show that no operating strategy achieves the best performance for all the performance measures. The answer to the question of which operating strategy is the best depends on the performance measures used for the evaluation. If railroads place customer service as their top concern and can compromise in measures of resource utilization and operating cost, the schedule-adherence strategy is the best one to achieve their goal. If resource utilization, especially car utilization, is the most important factor for the railroads, they may consider flexible short-run scheduling strategy since it achieves the smallest average yard time and very good average power and crew time as well, improving the terminal through put and car utilization. If railroads want savings from running fewer trains, flexible operation strategy is a choice, since it runs fewest trains and saves operating costs in crews, power units, and fuel cost, but the service and car utilization will be poor.

We may still face the challenge of answering the question based on the results of the simulation. We transfer all the measures into cost so we can compare which operating strategy will have the minimum cost. Since all the three operating strategies apply the same level of terminal and system resources, the major differences causing different costs among different operating strategies are the OB trains run and average yard time. We use the following cost information:[14]

- Train crew cost: \$3 per train-mile;
- Power cost: \$1 per power unit-mile;
- Car-time cost: \$0.75 per car-hour

To calculate the total cost, the following formulas are used.

$$Crew\ cost = \#\ trains * distance * 3 \tag{5.6}$$

$$Power\ cost = \#\ power\ units * distance * 1 \tag{5.7}$$

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[14] The cost information was used by some studies. See, for example, [61, 4, 51, 55].

$$Car - time\ cost = \#\ cars * (avg\_yard1 + avg\_trip + avg\_yard2) \quad (5.8)$$

$$Total\ cost = Crew\ cost + Power\ cost + Car - time\ cost \quad (5.9)$$

where, distance is the distance from hump terminal A to B.

Table 5.4 shows the total operating costs[15] of the service lane network for three week's operations under different operating strategies.[16]

	SCH	FSS	FLX
Total operating costs (in millions)	\$3.21 M	\$3.07 M	\$3.44 M

Table 5.4: Total Operating Cost for Service Lane Network Base Case

For this case, the car time cost is much larger than crew and power unit cost, since the distance from hump terminal A to B is only 300 miles, which is not very long. Based on this case, we would say that FSS is the best operating strategy under the base case conditions. But if the distance and the crew and power unit cost are increased, the results would be different. The longer distances and higher crew and power unit cost would favor FLX operating strategy.

5.4.2 Base case sensitivity analysis

In this subsection, the sensitivity analysis is conducted by changing the number of power units, crews, and IB trains entering the network around the base case.

Effects of power units on network performance

Figure 5-2 shows the percentage of OB trains delayed at the hump terminals under different levels of power units within the network.[17] With the increase of power units,

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[15] The total operating costs should also include the car switching cost, which is the same for the different operating strategies, since the same amount of traffic goes through the hump terminals.

[16] The results for # cars and power units are not shown in the summary tables.

[17] In this power unit sensitivity analysis, the crews used are very large so that crews will never have shortage. By doing this we separate the effect of power units from the effect of crews on the system performance. A good match of # crews and power units can be obtained by analyzing the sensitivity analysis results of crews and power units.

fewer trains are delayed for all the three operating strategies. At the same level of power units, SCH strategy has the smallest percentage of delays. With the increase of power units, FSS has faster decrease of the percentage of delays than FLX. With 95 or more power units, where the average yard time measure is becoming stable for all the three operating strategies (see Figure 5-5 on page 163), the FSS has less delays than FLX.

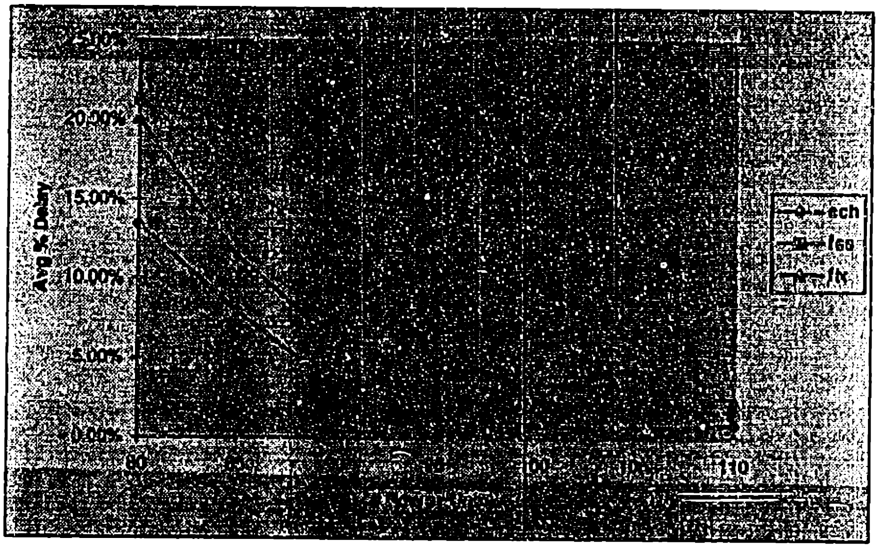

Figure 5-2: Effects of Power Units on Percentage Delays for Service Lane Network

The above analysis and conclusions hold for average delay measure, which is shown in Figure 5-3.

Figure 5-4 shows the effects of power units on average power time. With the increase of power units, the average power time increases, since more power units are waiting for departure at hump terminals. This figure also clearly shows that under the same power unit level, SCH strategy has the smallest average power time, and FSS has smaller average power time than FLX. The number of trains run is an important factor to determine the average power time. SCH runs the most trains and FSS runs more trains than FLX.[18]

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[18] When SCH runs some empty trains, it still needs one power unit to move the "empty" trains, which is equivalent to deadhead out one power unit to the other hump terminal. The empty trains' movement is the same as that of loaded trains.

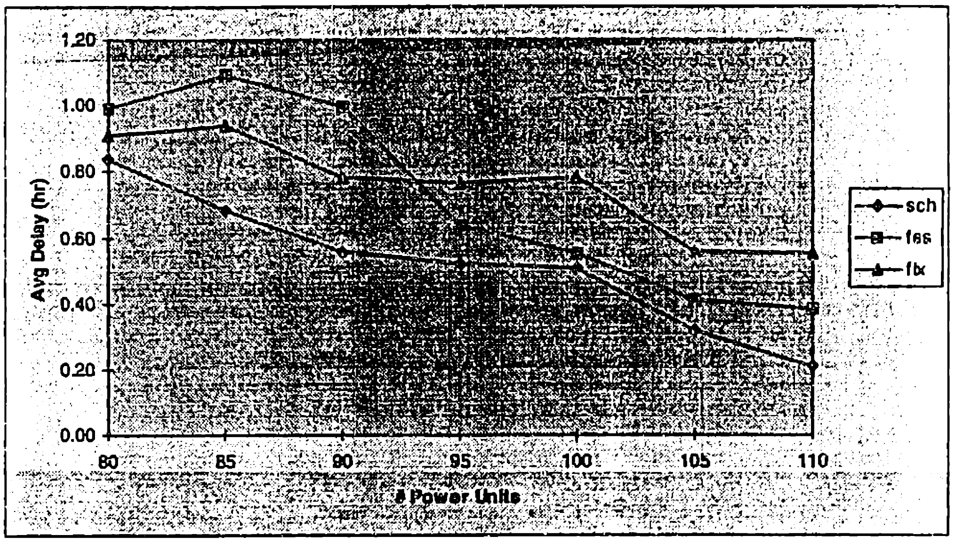

Figure 5-3: Effects of Power Units on Average Delay for Service Lane Network

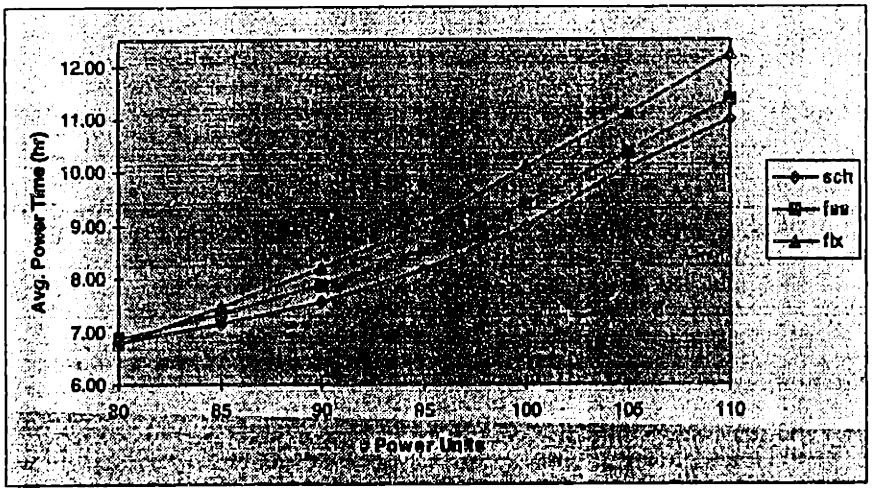

Figure 5-4: Effects of Power Units on Average Power Time for Service Lane Network

Figure 5-5 shows the effects of power units on average yard time. FSS has the smallest average yard time in the range of power unit change. The decrease of average yard time under SCH and FSS when power units increase from 80 to 95 is very much larger than that under FLX, indicating that SCH and FSS need more power units to achieve small average yard time. On the other hand, under FLX, the average yard time is more robust than that under SCH and FSS, especially when the power units are in limited supply.

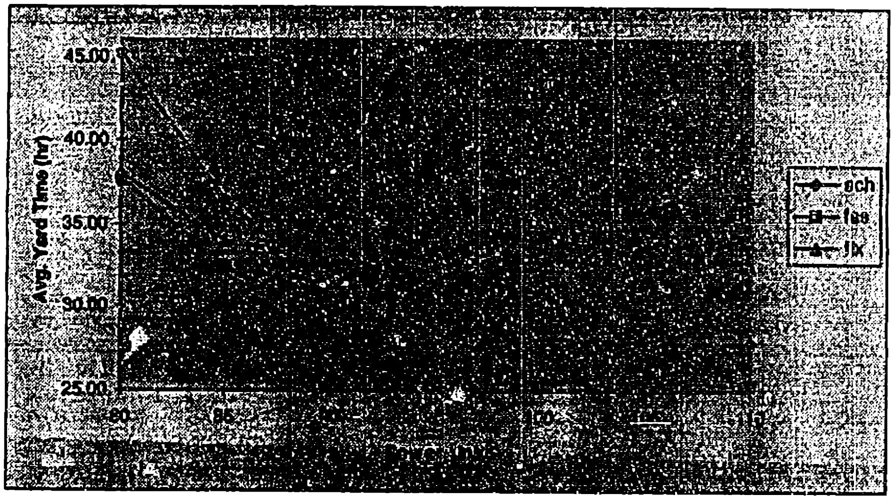

Figure 5-5: Effects of Power Units on Average Yard Time for Service Lane Network

Figure 5-6 shows the effects of power units on connection performance. With the increase of power units, the connection performance is generally improved for all the three operating strategies. Under the range of power unit change, SCH strategy has the best connection performance and FSS has better connection performance than FLX. On the other hand, FLX has robust connection performance. The sharp increase of connection performance under SCH and FSS operating strategies when the power units increase from 80 to 95 suggests that in order to achieve better connection performance, SCH and FSS must have large power units as buffer.

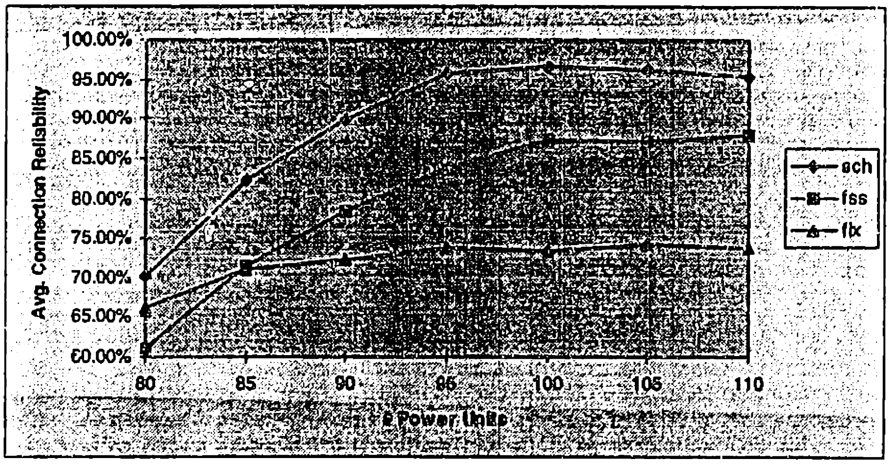

Figure 5-6: Effects of Power Units on Connection Performance for Service Lane Network

Effects of crews on network performance

Figure 5-7 shows the percentage of OB trains delayed at the hump terminals under different levels of crews within the network.[19] With the increase of crews, less trains are delayed for all the three operating strategies. At the same level of crews, SCH strategy has smallest percentage of delays while it is hard to compare the percentage of delays for FSS and FLX. But after some level of crews such as 40 in the case, the FSS has less delays than FLX.

For average delay, Figure 5-8 shows that when the network has more than 30 crews, the average delay for all the three operating strategies are small and SCH has smallest average delay. But when the network has less than 30 crews, FLX is very robust in that it has much smaller average delay than SCH and FSS.

Figure 5-9 shows the effects of crews on average crew time. With the increase of crews, the average crew time increases, since more crews are waiting for departure at hump terminals. This figure also shows that under the same crew level, SCH and FSS strategies have similar average power time, which is smaller than FLX.

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[19] In this crew sensitivity analysis, the power units used are very large so that power units will never have shortage. By doing this we separate the effect of crews from the effect of power units on the system performance.

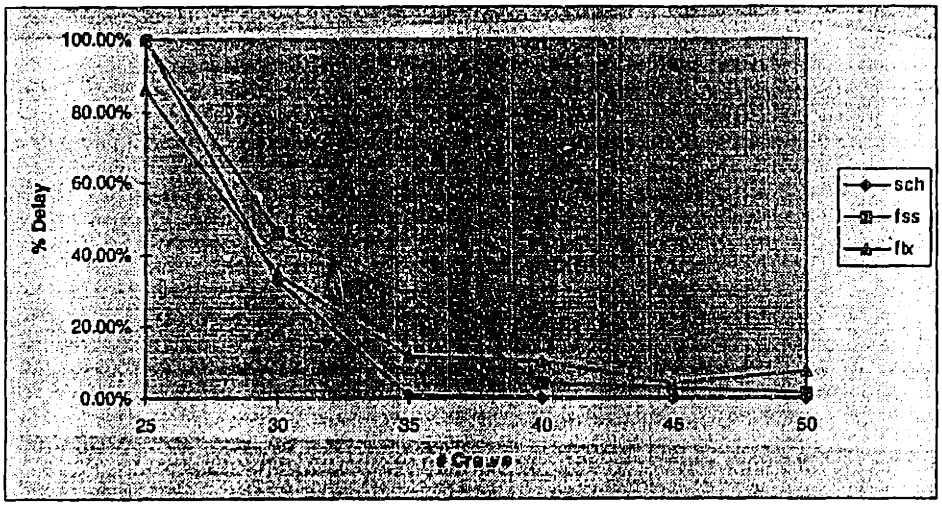

Figure 5-7: Effects of Crews on Percentage Delays for Service Lane Network

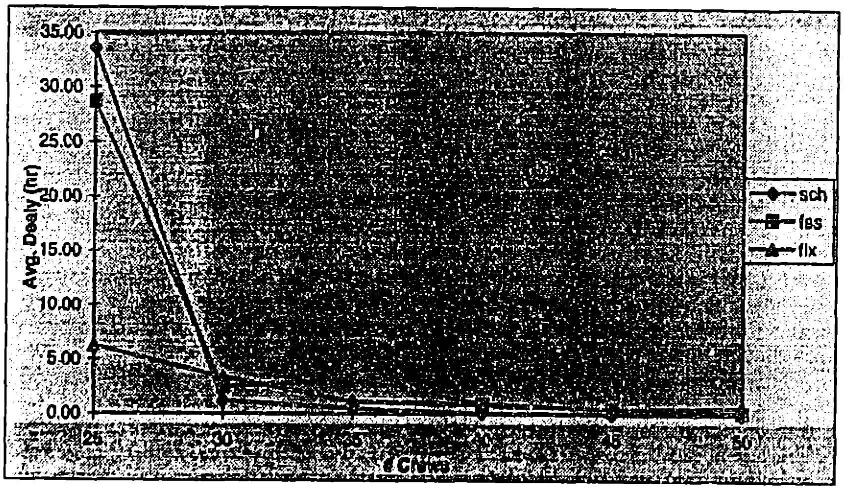

Figure 5-8: Effects of Crews on Average Delay for Service Lane Network

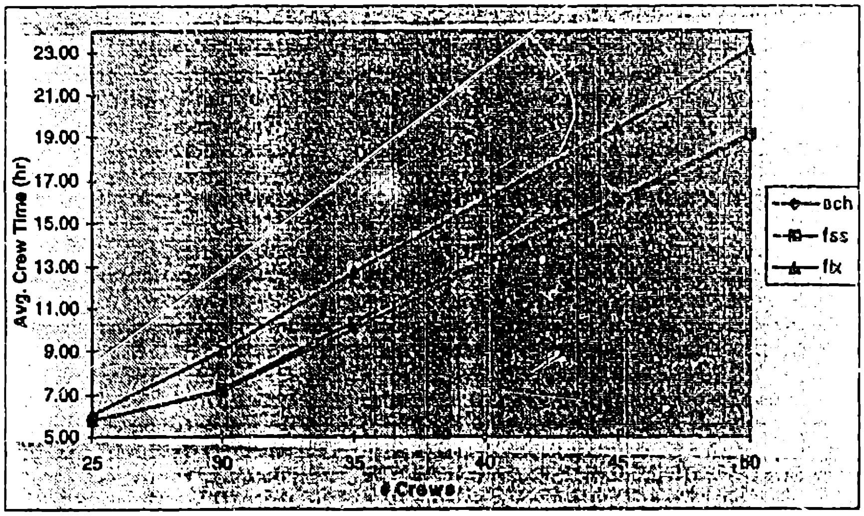

Figure 5-9: Effects of Crews on Average Crew Time for Service Lane Network

Figure 5-10 shows the effects of crews on average yard time. When the network has more than 30 crews, the average yard time tends to be stable, where FSS has the smallest average yard time. *When the network has a shortage of crews, FLX is very robust in that it has much smaller average yard time than SCH and FSS, indicating that to achieve better average yard time, SCH and FSS need more crews as buffer (and hence increasing crew cost for SCH and FSS) while FLX does not. This conclusion from this case contradicts with what advocates of SCH and FSS argues. The service and car utilization under FLX are poor.*

Figure 5-11 shows the effects of crews on connection performance. With the increase of crews, the connection performance is generally improved for all the three operating strategies. When the network has more than 30 crews, the connection performance tends to be stable, where SCH has best connection performance. On the other hand, *when the network has a shortage of crews (e.g., less than 30 crews), FLX is very robust in that it has much better connection performance than SCH and FSS, indicating that FLX is robust when crews are in limited supply and SCH and FSS need more crews than FLX as buffer to achieve better connection performance.*

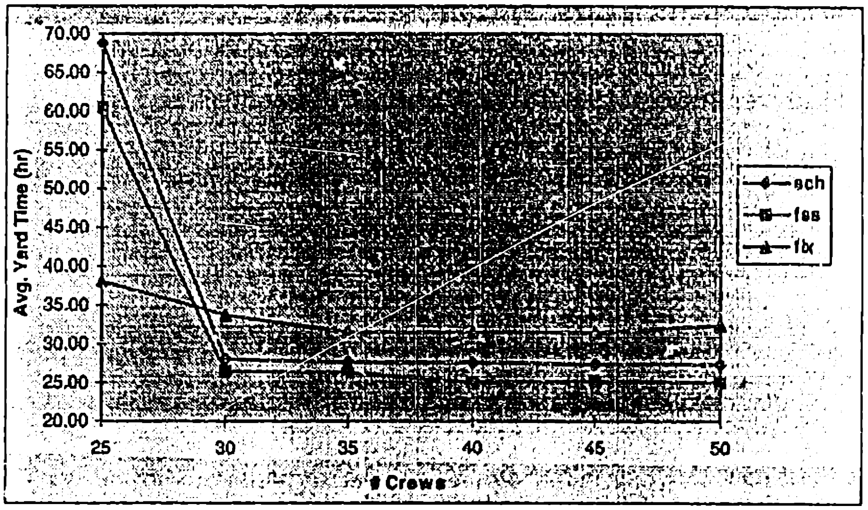

Figure 5-10: Effects of Crews on Average Yard Time for Service Lane Network

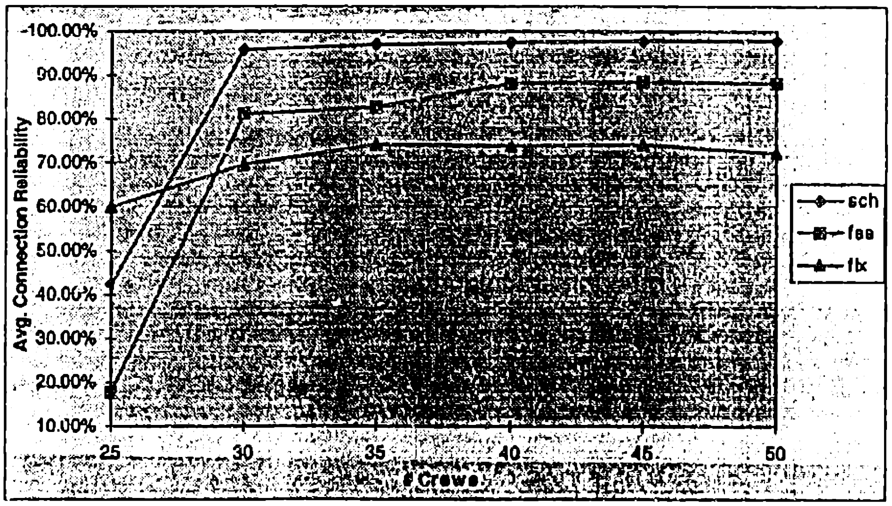

Figure 5-11: Effects of Crews on Connection Performance for Service Lane Network

Effects of extra trains[20] on network performance

In the operating plan, there are 20 IB trains for each hump terminal. The 10% increase in IB traffic means that there are 2 second section trains or extra trains on average per day for each hump terminal.

Figure 5-12 shows the percentage of OB trains delayed at the hump terminals under different levels of traffic increase.[21] With the increase of IB traffic, more trains are delayed for all the three operating strategies. FLX and FSS have more trains delayed than SCH because with the increase of IB traffic, these two operating strategies run more and possibly longer OB trains and SCH only runs longer trains. This is also true for average delay, which is shown in Figure 5-13.

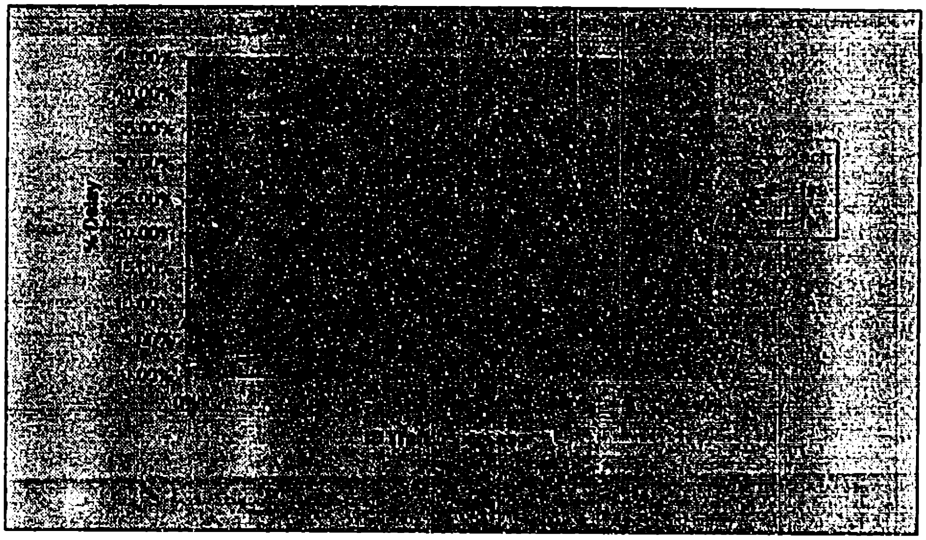

Figure 5-12: Effects of IB Traffic on Percentage Delays for Service Lane Network

Figure 5-14 shows the effects of IB traffic on average power time. With the increase of IB traffic, more and (or) longer OB trains are run and hence improving average power time.

Figure 5-15 shows the effects of IB traffic on average crew time. With the increase of IB traffic, FSS and FLX have smaller average crew time (since they run more OB

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[20] See Chapter 4 subsection 4.3.2 on page 113 for discussions of extra trains and how they are generated.

[21] In this IB traffic sensitivity analysis, the power units and crews used are the same as in the base case. (e.g., 100 power units and 35 crews).

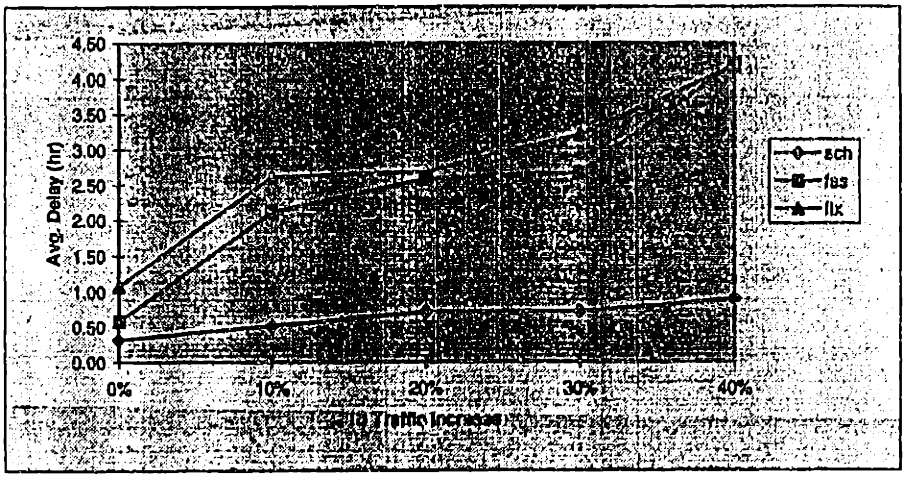

Figure 5-13: Effects of IB Traffic on Average Delay for Service Lane Network

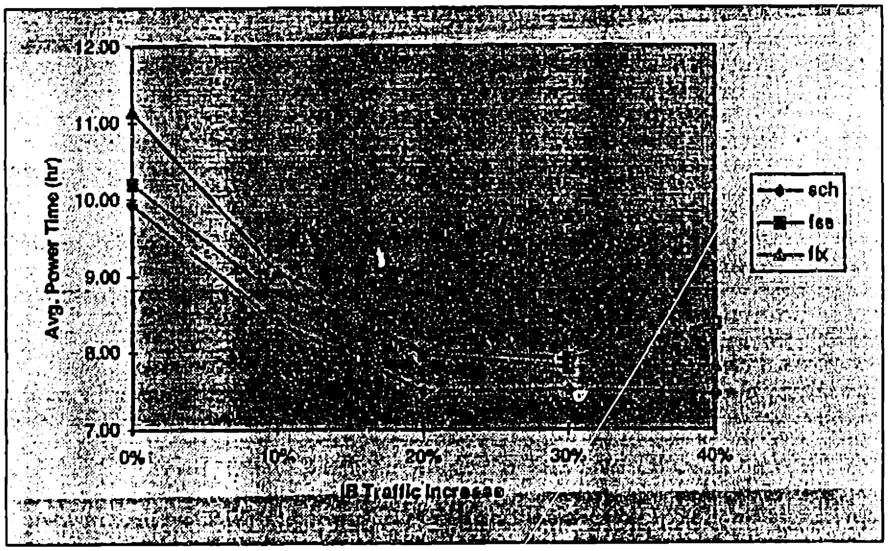

Figure 5-14: Effects of IB Traffic on Average Power Time for Service Lane Network

trains, improving average crew time) and SCH does not change (since it runs the same number of OB trains).

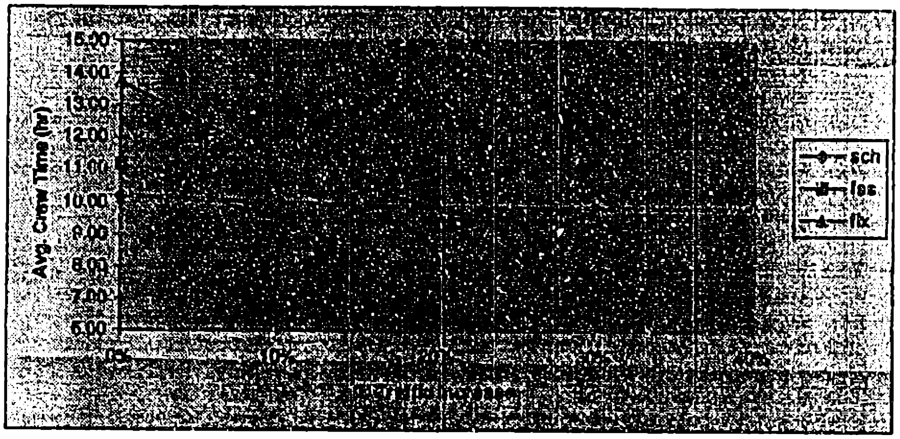

Figure 5-15: Effects of IB Traffic on Average Crew Time for Service Lane Network

Figure 5-16 shows the effects of IB traffic on average yard time. When the IB traffic increases by less than 20%, the FSS has smallest average yard time, and SCH has smaller average yard time than FLX. When the IB traffic increases by more than 20%, a significant increase, FLX is very robust in that it increases average yard time much slower than FSS and SCH, indicating also that FSS and SCH need more crew and power unit resources to handle the extra traffic to improvement the average yard time.

Figure 5-17 shows the effects of IB traffic on connection performance. With the increase of IB traffic, the connection performance is generally worse for all the three operating strategies. This is because the increase of IB traffic will make more cars miss their connections due to limited train capacity, which is constrained by the crews and power units. SCH has the best connection performance and FSS has better connection performance than FLX.

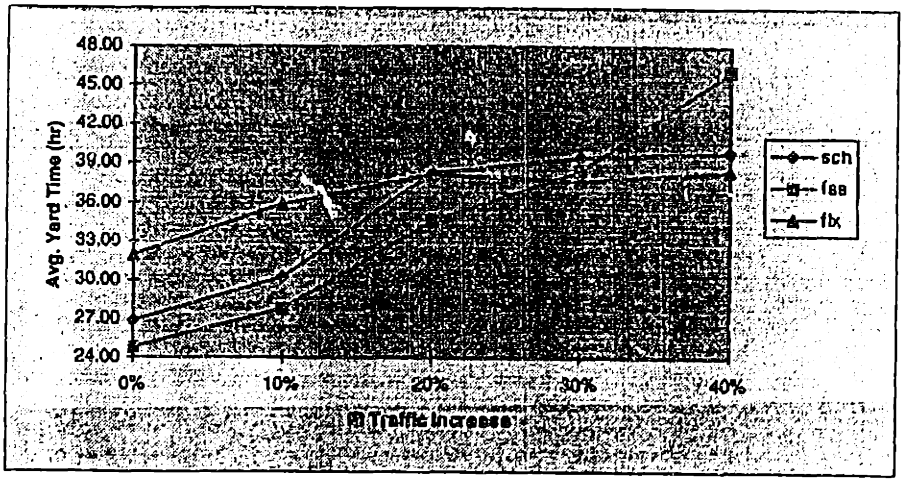

Figure 5-16: Effects of IB Traffic on Average Yard Time for Service Lane Network

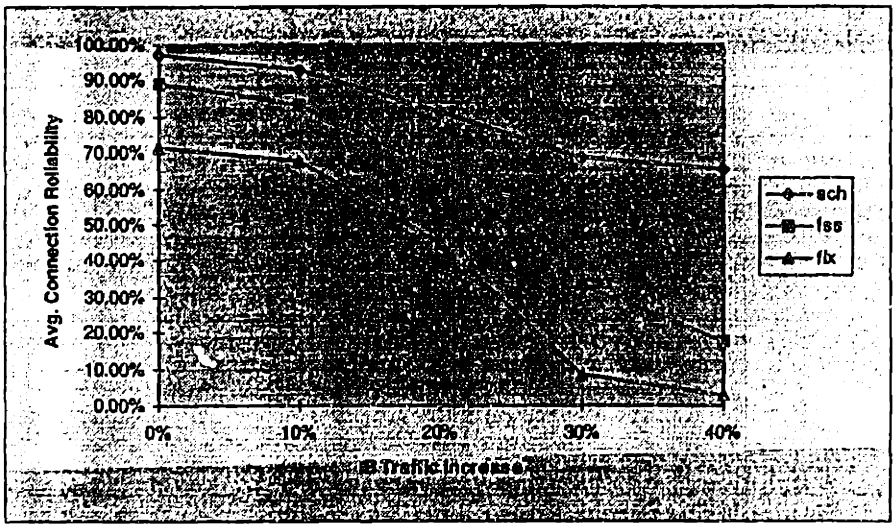

Figure 5-17: Effects of IB Traffic on Connection Performance for Service Lane Network

5.4.3 Scenario design and runs

Scenario design

Table 5.5 shows the designed scenarios for the network simulation model for the service lane network. It is also used for the area network. Sixteen cases are designed so we can evaluate the network performance under different operating conditions. We change the traffic, terminal resource, cutoff, system crews and power units, and their preparation variables, while keeping the changes as realistic as possible, to see the effect of these variables on the network performance. The traffic variable is changed from low to high and the terminal and system resources are changed from high level of resources to low level of resources, while the cutoff is changed from low to high in a large cycle across cases.[22] Note that the change of the system level resources and their preparation times are not in the same direction due to consideration of practical reasons.[23] This may be a factor that causes the results in the scenario runs not always be consistent.

In Table 5.5, the traffic variable includes both traffic volume and traffic variation variables. The traffic is "h" means that the traffic volume, the IB arrival time variation, the probability of train delays, and the traffic variation (in terms of # of cars on IB trains) are all " h". See Chapter 4 subsection 4.6.3 (on page 137) for definitions of these variables. Similarly, the terminal resource variable includes terminal capacity variable (e.g., # of receiving and departure tracks), terminal processing variable (e.g., fixed time and variation time). The system resource variable includes # of crews and power units within the network, crew and power unit rest and preparation time distribution. All the "l" and "h" values of these variables are the same as the "l" and "h" values in Appendix A section A.2 (on page 238), except for the network part variables whose values are listed in the four tables in Appendix B section B.1.3 (on

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[22] The terminal queuing strategy is also changed but the change is not as important as the other variables. The reason is that we used a departure strategy that OB trains can depart whenever they are ready (e.g., do not wait for scheduled departure time if can depart early) in the network simulation model runs for both service lane and area network case studies. See results and conclusions about this concern in Chapter 4 section 4.6.2 on page 136.

[23] For a given number of preparation facilities in the system, more power units and crews in the system, more time is needed to prepare them, a conclusion from queuing theory.

Scn	traffic	terminal resource	cutoff time	terminal queuing	system resource	system prep
C 1	l	h	l	Contribution	h	h
C 2	l	l	l	FIFO	h	h
C 3	l	h	l	Priority	l	l
C 4	l	l	l	LIFO	l	l
C 5	l	h	h	FIFO	h	h
C 6	l	l	h	Contribution	h	h
C 7	l	h	h	LIFO	l	l
C 8	l	l	h	Priority	l	l
C 9	h	h	l	LIFO	h	h
C 10	h	l	l	FIFO	h	h
C 11	h	h	l	Contribution	l	l
C 12	h	l	l	Priority	l	l
C 13	h	h	h	Contribution	h	h
C 14	h	l	h	FIFO	h	h
C 15	h	h	h	Priority	l	l
C 16	h	l	h	LIFO	l	l

Table 5.5: Network Scenario Design

page 247).

The terminal queuing strategies (e.g., FIFO, LIFO, Contribution, and Priority) are defined and discussed in Appendix A section A.1.10 on page 233.

The results from the scenario runs are given in Table 5.6 and Table 5.7, each showing eight cases.

Scn	OS	trns run	int. yard time	avg line time	avg trip time	# of delay	avg delay time	avg power time	avg crew time	avg yard time	avg conn. perf.	OB on time
C 1	sch	420	4.00	6.09	10.09	0	0.04	15.00	13.90	25.81	99.51%	94.41%
	fss	398	4.23	6.14	10.37	0	0.13	15.21	15.00	24.26	85.56%	49.66%
	flx	352	4.52	6.05	10.57	0	0.00	16.19	17.97	29.96	72.75%	51.63%
C 2	sch	420	3.95	6.08	10.02	0	0.00	14.88	13.98	26.88	97.63%	98.49%
	fss	398	4.22	6.07	10.29	0	0.00	15.15	15.08	24.51	88.17%	55.62%
	flx	347	4.52	6.04	10.56	3	0.18	16.29	18.49	33.01	66.49%	51.15%
C 3	sch	420	4.38	7.84	12.22	26	0.56	10.71	8.78	25.95	99.41%	96.91%
	fss	395	5.46	8.14	13.60	20	1.10	10.10	8.87	25.48	84.86%	49.64%
	flx	355	4.66	7.74	12.40	21	1.00	12.10	12.36	29.78	74.00%	52.11%
C 4	sch	420	4.24	7.79	12.02	24	0.68	10.83	8.96	26.90	96.51%	97.03%
	fss	397	4.32	7.79	12.11	18	0.67	11.28	10.11	24.88	85.76%	53.87%
	flx	350	4.61	7.68	12.29	13	1.33	12.38	13.01	33.02	66.32%	51.33%
C 5	sch	419	4.02	6.09	10.11	0	0.00	14.87	13.92	25.98	98.82%	97.98%
	fss	398	4.1[illegible]	6.13	10.32	1	0.09	15.26	15.08	24.21	92.34%	48.93%
	flx	356	4.46	6.05	10.51	18	0.90	16.21	17.84	29.73	80.34%	52.62%
C 6	sch	420	4.00	6.07	10.07	0	0.00	14.82	13.93	26.61	99.18%	98.77%
	fss	397	4.20	6.07	10.27	1	0.15	15.21	15.10	24.70	92.90%	55.21%
	flx	349	4.52	6.05	10.56	8	1.00	16.14	18.35	33.22	73.30%	51.22%
C 7	sch	420	4.43	7.85	12.27	35	0.79	10.71	8.74	26.17	98.91%	96.15%
	fss	397	4.78	7.98	12.76	29	0.99	10.58	9.38	24.57	75.96%	49.77%
	flx	352	4.61	7.73	12.34	23	0.88	12.31	12.65	29.72	79.59%	52.08%
C 8	sch	420	4.22	7.78	12.00	26	0.64	10.91	9.01	26.74	98.36%	97.30%
	fss	397	4.55	7.81	12.36	18	0.70	11.05	9.85	24.85	92.55%	54.08%
	flx	350	4.60	7.68	12.27	35	1.12	12.20	12.99	33.25	73.07%	53.20%

Table 5.6: Results of Scenario Runs for Service Lane Network: Part 1

Scn	OS	trns run	int. yard time	avg line time	avg trip time	# of delay	avg delay time	avg power time	avg crew time	avg yard time	avg conn. perf.	OB on time
C 9	sch	420	4.32	6.08	10.40	0	0.14	12.05	13.63	27.42	92.29%	93.93%
	fss	473	4.08	6.16	10.24	67	1.02	12.21	11.11	24.47	76.93%	50.91%
	flx	403	4.49	6.06	10.55	142	1.73	13.03	14.50	29.81	68.15%	53.83%
C 10	sch	420	4.52	6.08	10.60	7	0.27	10.84	13.44	35.41	84.91%	89.10%
	fss	463	4.17	6.10	10.28	130	3.00	11.69	11.47	26.48	79.36%	53.10%
	flx	424	4.55	6.06	10.62	148	3.39	11.39	13.17	39.00	53.72%	55.27%
C 11	sch	420	4.57	7.84	12.41	23	0.71	8.30	8.56	33.29	89.02%	90.81%
	fss	417	4.23	7.89	12.12	49	1.13	8.17	7.88	31.24	76.42%	55.98%
	flx	405	4.67	7.77	12.43	62	1.29	8.94	9.28	33.01	63.25%	54.69%
C 12	sch	418	4.89	7.86	12.75	62	1.20	7.27	8.32	38.70	80.16%	85.40%
	fss	421	4.86	8.12	12.98	134	2.59	7.52	6.22	28.97	70.03%	53.05%
	flx	433	4.70	7.81	12.52	196	3.21	7.60	7.87	38.59	57.23%	55.16%
C 13	sch	420	4.34	6.08	10.41	1	0.18	12.06	13.57	32.14	90.50%	97.11%
	fss	469	4.13	6.17	10.30	110	1.04	12.22	11.22	27.77	79.86%	50.73%
	flx	409	4.51	6.07	10.58	138	1.52	12.83	14.11	33.93	69.76%	54.37%
C 14	sch	420	4.50	6.08	10.57	3	0.39	10.82	13.46	34.00	90.77%	93.67%
	fss	467	4.23	6.10	10.33	141	2.21	11.42	11.20	27.36	83.33%	51.69%
	flx	429	4.53	6.07	10.60	152	2.99	11.26	12.92	36.79	66.75%	55.28%
C 15	sch	420	4.56	7.82	12.38	14	0.64	8.24	8.65	30.02	92.16%	94.52%
	fss	415	4.56	7.85	12.41	89	2.12	7.91	6.06	29.65	83.79%	54.11%
	flx	406	4.72	7.80	12.51	77	1.32	9.00	9.19	31.12	72.80%	51.75%
C 16	sch	420	4.79	7.83	12.63	78	1.03	7.31	8.41	38.89	81.41%	84.67%
	fss	434	4.62	7.95	12.58	231	2.91	8.28	6.72	29.08	81.15%	55.30%
	flx	428	4.73	7.81	12.54	227	3.91	7.83	8.07	38.88	66.16%	54.62%

Table 5.7: Results of Scenario Runs for Service Lane Network: Part 2

Effects of traffic on system performance Compare results of Case 1 with Case 9, Case 2 with Case 10, etc. to see the effects of traffic on system performance while other parameters are the same except the terminal queuing strategy, which does not have significant impact on terminal performance. FSS and FLX run more trains when traffic is increased, while SCH runs almost a fixed number of trains. This causes SCH to have larger intermediate yard time when traffic is increased since trains carry more cars, while this conclusion does not hold for FSS and FLX since they run more trains when traffic is increased, not necessary meaning more cars on trains. The line haul movement time does not change much when traffic is increased, resulting in average trip time roughly the same for FSS and FLX and increased for SCH. This also indicates that there is no significant congestion on line haul movement operations within the network. Also the increase of IB traffic causes the increase of # of delays, average delay, the decrease of average power, crew, and yard time, and the decrease of connection performance for all the three operating strategies. OB on time performance is worse for SCH but does not change much for FSS and FLX.

Effects of train speed on system performance The train speed has significant impact on line haul movement time (and hence average trip time) for all the three operating strategies and # of trains run for FSS and FLX. The results show that the increase of the speed increase the network capacity and reduce train trip. See the difference of average line haul movement time (and average trip time) for cases 1, 2, 5, 6, 9, 10, 13, 14 (e.g., cases with high system resources) with other cases. See also the trains run under FSS and FLX operating strategies for these cases.

Effects of cutoff on system performance Using smaller cutoff time will make more cars miss their connections. The effect of cutoff time on connection performance for FSS and FLX are not clear since FSS has a short-run schedule which is derived based on predicted traffic and resources and FLX runs trains according to available traffic and resources. The results from the scenario runs show that the following is true: scheduling smaller cutoff time will make more cars miss their connections and scheduling larger cutoff time will make more cars make their connections. Compare connection performance of Cases 1 with Case 5, Case 2 with Case 6, etc. for SCH. Two pairs of the comparison do not hold, indicating the terminal queuing strategy may have some effect on connection performance as well.

Which operating strategy is the best? Table 5.8 shows the summary of the scenario runs. For each performance measure, if an operating strategy is best for a case, this operating strategy will appear in this case for this performance measure.

From Table 5.8, we conclude:

- SCH provides best connection performance and OB train on-time performance;
- FSS results in smallest average yard time;

Scn	trns run	int. yard time	avg line time	avg trip time	# of delay	avg delay time	avg power time	avg crew time	avg yard time	avg conn. perf.	OB on time
C 1	flx	sch	flx	sch	all	flx	sch	sch	fss	sch	sch
C 2	flx	sch	flx	sch	sch/fss	sch/fss	sch	sch	fss	sch	sch
C 3	flx	sch	flx	sch	fss	sch	fss	sch	fss	sch	sch
C 4	flx	sch	flx	sch	flx	fss	sch	sch	fss	sch	sch
C 5	flx	sch	flx	sch	sch	sch	sch	sch	fss	sch	sch
C 6	flx	sch	flx	sch	sch	sch	sch	sch	fss	sch	sch
C 7	flx	sch	flx	sch	flx	sch	fss	sch	fss	sch	sch
C 8	flx	sch	flx	sch	fss	sch	sch	sch	fss	sch	sch
C 9	flx	fss	flx	fss	sch	sch	sch	fss	fss	sch	sch
C 10	sch	fss	flx	fss	sch	sch	sch	fss	fss	sch	sch
C 11	flx	fss	flx	fss	sch	sch	fss	fss	fss	sch	sch
C 12	sch	flx	flx	flx	sch	sch	sch	fss	fss	sch	sch
C 13	flx	fss	flx	fss	sch	sch	sch	fss	fss	sch	sch
C 14	sch	fss	flx	fss	sch	sch	sch	fss	fss	sch	sch
C 15	flx	sch/fss	flx	sch	sch	sch	fss	fss	fss	sch	sch
C 16	sch	fss	flx	flx	sch	sch	sch	fss	fss	sch	sch

Table 5.8: Summary and Comparison of Scenario Runs for Service Lane Network

- FLX has smallest line haul movement time;
- In terms of trains run, FLX runs fewest trains except for some cases where traffic is high and SCH runs fewest trains;
- In terms of trip time, SCH has smallest trip time when traffic is low and it is hard to tell when traffic is high;
- In terms of delays and average delay, SCH is the best for most of the cases;
- In terms of average power time, SCH is the best for most of the cases;
- In terms of average crew time, SCH is the best when traffic is low and FSS is the best when traffic is high.

The results in Table 5.6 and 5.7 show that no operating strategy achieves the best performance for all the performance measures. The answer to the question of which operating strategy is the best is really depends on the performance measures used for the evaluation. But if we compare the costs of running the trains and car cost at the hump terminals for different operating strategies as in section 5.4.1 (on page 159), we can conclude that FSS is the best in terms of having minimum costs in all the 16 cases and SCH is better than FLX in most cases except in Case 11, where FLX is better than SCH.

5.5 Case study two: area network

Figure 5-18 shows the layout of the area network used in the case study, where terminals *A*, *B* and *C* are hump terminals, and terminals *d*, *e*, *f*, *g*, *h*, and *i* are intermediate terminals. The node and arc files for the base case are given in Appendix B section B.2 (on page 246). The IB arrival patterns to the hump terminals in the network, the terminal resources, terminal capacity, and terminal processing capability are the same as in the base case of terminal simulation in Chapter 4 except that the total number of crews in the network is 45 (15 at each hump terminal) and the total number of power units in the network is 120 (40 at each hump terminal).

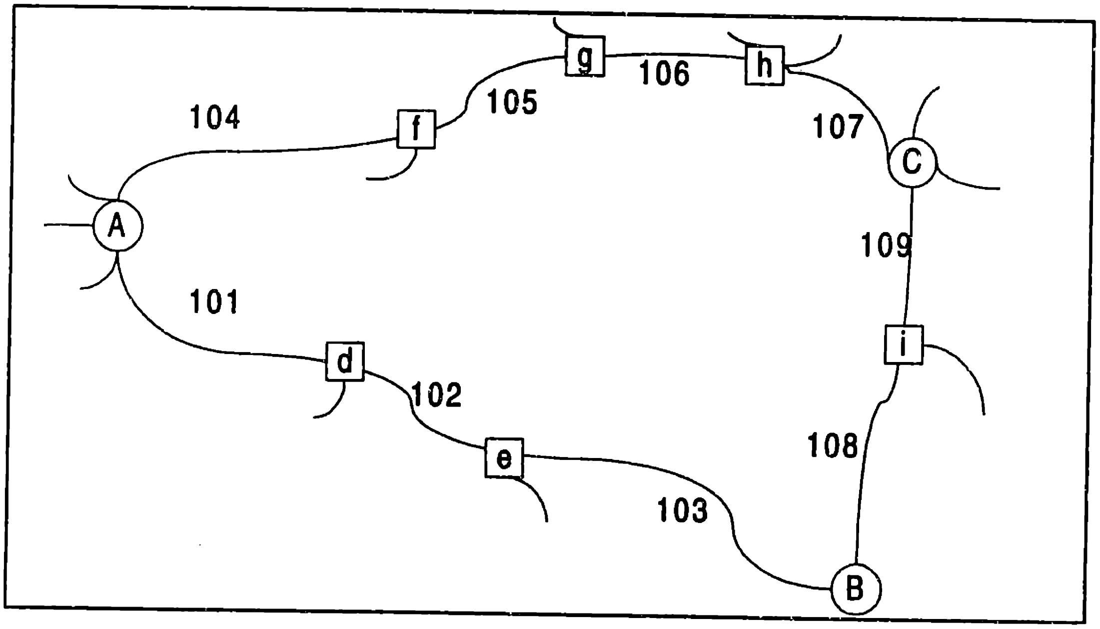

Figure 5-18: Area Network

5.5.1 Base case results

Table 5.9 reports the model execution times for different operating strategies. The results are based on 5 runs of the model, each simulating the service lane network operations for a month (e.g., 30 days) without detailed output (such as each activity and each IB and OB train consists).

	SCH	FSS	FLX
Execution Time (in sec.)	27.95	34.94	33.94

Table 5.9: Average Execution Time of the Area Network Model

Table 5.10 shows the trip time summary for trains of each OD pair under different operating strategies.

In terms of number of trains run, Table 5.10 shows that the schedule-adherence (SCH) strategy runs a fixed number of trains with balanced number of trains run in each direction; the flexible short-run scheduling (FSS) strategy runs fewer trains than SCH and the number of trains run at each direction is less balanced than that for SCH; the flexible operation (FLX) strategy runs fewest trains among the three operating strategies and the number of trains run at each direction is the least balanced among the three operating strategies. The standard deviation of the number of trains run is largest for FLX. Since trains move the same amount of traffic under different operating strategies, the results show that FLX runs fewer and larger trains than FSS, which runs fewer and larger trains than SCH.

In terms of average intermediate yard time, Table 5.10 shows (after doing simple averages over all the OD pairs) that SCH has smaller average intermediate yard time (in hours) than FSS, which has smaller average intermediate yard time than FLX, the same conclusion as in service lane network.

In terms of average line haul movement time, the results show that the line haul movement time is almost the same, indicating that the line haul movement does not have any serious congestion problems.

For the average trip time, SCH has the smaller average trip time than FSS, which

	Orig	Dest	# of trains	intermediate yard time	avg line time	avg trip time	# of delays	avg delay time
sch	A	B	211	2.65	4.46	7.10	5	0.65
			1	0.02	0.00	0.03	4	0.29
	A	C	210	3.00	5.58	8.58	4	0.55
			0	0.06	0.00	0.06	3	0.32
	B	A	210	2.27	4.47	6.74	2	0.38
			0	0.04	0.00	0.04	2	0.38
	B	C	210	1.73	2.45	4.19	1	0.21
			0	0.02	0.01	0.02	2	0.21
	C	A	209	3.51	5.58	9.09	1	0.24
			1	0.07	0.00	0.07	1	0.31
	C	B	210	1.53	2.45	3.98	1	0.32
			1	0.05	0.00	0.05	3	0.48
fss	A	B	217	2.46	4.47	6.94	24	1.91
			3	0.07	0.00	0.06	30	0.46
	A	C	200	3.34	5.58	8.92	26	1.15
			3	0.05	0.00	0.05	29	0.71
	B	A	198	2.52	4.47	6.99	30	1.40
			4	0.03	0.01	0.03	34	1.28
	B	C	218	1.65	2.46	4.11	35	1.39
			2	0.04	0.00	0.04	38	1.20
	C	A	216	3.33	5.58	8.91	5	0.68
			3	0.06	0.01	0.05	5	0.78
	C	B	200	1.68	2.46	4.13	3	0.63
			2	0.04	0.01	0.04	4	0.59
flx	A	B	196	2.66	4.46	7.12	38	2.04
			4	0.04	0.00	0.04	24	0.34
	A	C	177	3.55	5.57	9.12	33	1.72
			2	0.07	0.01	0.06	21	0.41
	B	A	174	2.69	4.46	7.16	14	0.88
			2	0.06	0.00	0.06	29	1.20
	B	C	193	1.81	2.45	4.27	18	0.75
			6	0.02	0.00	0.02	35	1.30
	C	A	193	3.54	5.57	9.11	39	1.99
			3	0.09	0.00	0.09	60	2.51
	C	B	176	1.80	2.45	4.26	33	2.07
			4	0.04	0.01	0.04	50	2.87

Table 5.10: Train Trip Time Summary for Area Network

has smaller average trip time than FLX, the same conclusion as in case study one.

Table 5.10 shows that SCH has the smallest delays and average delay and FSS has smaller delays and average delay than FLX. SCH has the highest level of crews and power units availability among the three operating strategies. Again, the conclusion is the same as in the service lane network study. Also note that for FSS and FLX strategies, different hump terminals have different delays and average delay.

Table 5.11 shows the hump terminal performance summary.[24] The OB train performance is best under SCH, and it is much the same under FSS and under FLX, suggesting that SCH provides very good OB train performance; FSS runs more and shorter trains than FLX.

In terms of system resource utilization, Table 5.11 shows that power units and crews are most utilized under SCH and are more utilized under FSS than FLX, the same conclusion as in service lane network result. System resource utilization is tightly related to the number of OB trains that depart from the terminals. The more trains departed, the higher level of system resource utilization.

In terms of average yard time, Table 5.11 shows that FSS has the smallest average yard time, and SCH has smaller average yard time than FLX. This is the same conclusion as in service lane network case study. The explanation there seems reasonable here too.

In terms of connection reliability, Table 5.11 shows that SCH has the best connection performance, and FSS has better connection performance than FLX, the same conclusion as in service lane network case study.

Which operating strategy is the best?

The base case results show, again, that no operating strategy achieves the best performance for all the performance measures. The answer to the question of which operating strategy is the best is really depends on the performance measures used

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[24] Note that the number of OB trains in this table is slightly different from the trains run in Table 5.10. They are different statistics. In Table 5.10, # trains is the number of trains reaching to their destinations during statistics collection time, while OB trns in Table 5.11 is the number of OB trains departed from the hump terminals during statistics collection time.

	Terminal	IB trains	IB on time	OB trains	OB on time	avg power time	avg crew time	avg yard time	avg conn. perf.
sch	A	441	354	421	401	8.63	9.83	28.17	96.48%
		5	8	1	14	0.88	0.98	0.40	1.20%
	B	442	370	420	411	9.03	12.40	27.72	97.18%
		7	10	0	8	1.16	1.29	0.66	2.50%
	C	443	357	420	402	10.73	11.96	27.69	96.35%
		5	8	1	14	1.09	1.13	0.70	2.76%
fss	A	441	314	415	209	9.75	11.23	25.64	87.20%
		4	12	4	7	1.95	3.25	0.91	1.32%
	B	440	302	417	219	9.58	11.04	25.59	86.95%
		6	5	5	7	1.93	3.94	1.01	2.15%
	C	440	304	416	207	9.71	12.28	25.20	87.84%
		3	6	4	9	1.05	1.02	0.51	0.74%
flx	A	444	207	374	207	9.38	11.96	32.30	72.92%
		5	13	6	3	1.62	3.10	1.36	1.10%
	B	440	196	368	201	10.93	16.16	32.23	73.06%
		2	7	6	11	2.15	5.17	1.40	2.18%
	C	441	209	370	196	10.53	12.59	33.20	70.27%
		4	13	4	6	2.14	4.77	3.20	6.40%

Table 5.11: Hump Terminal Performance Summary for Area Network

for the evaluation. To this concern, the behavior of the performance measures of the area network base case is the same as that of the service lane network base case.

The total operating cost is calculated in Table 5.12 using the same cost information as in base case study one[25]

	SCH	FSS	FLX
Total operating costs (in millions)	\$3.73 M	\$3.50 M	\$4.14 M

Table 5.12: Total Operating Cost for Area Network Base Case

This, again, shows that FSS is the best operating strategy based on the base case conditions. The car cost is much larger than crew and power unit costs. But if the distances are longer and the crew and power unit costs are increased, the results would be different. The increase of the distances and the crew and power unit costs would favor the FLX.

5.5.2 Base case sensitivity analysis

The results from the sensitivity analysis for the area network is very similar to that for the service lane network. We only present the sensitivity analysis for power units in this subsection.

Figure 5-19 and 5-20 show the percentage of OB trains delayed and the average delay (in hours) at the hump terminals under different levels of power units within the area network.[26] With the increase of power units, less trains are delayed for all the three operating strategies. At the same level of power units, SCH strategy has the smallest percentage of delays and average delay, and FSS has less delays and average delay than FLX. The results, again, show that SCH has the highest level of crew and

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[25] See subsection 5.4.1 on page 159. Note, however, the average distance is 186.67 miles and there are three hump terminals now.

[26] In this power unit sensitivity analysis, the crews used are very large so that crews will never have shortage, separating the effect of power units from the effect of crews on the system performance. A good match of # crews and power units can be obtained by analyzing the sensitivity analysis results of crews and power units.

power unit availability and FSS has higher level of crew and power unit availability than FLX.

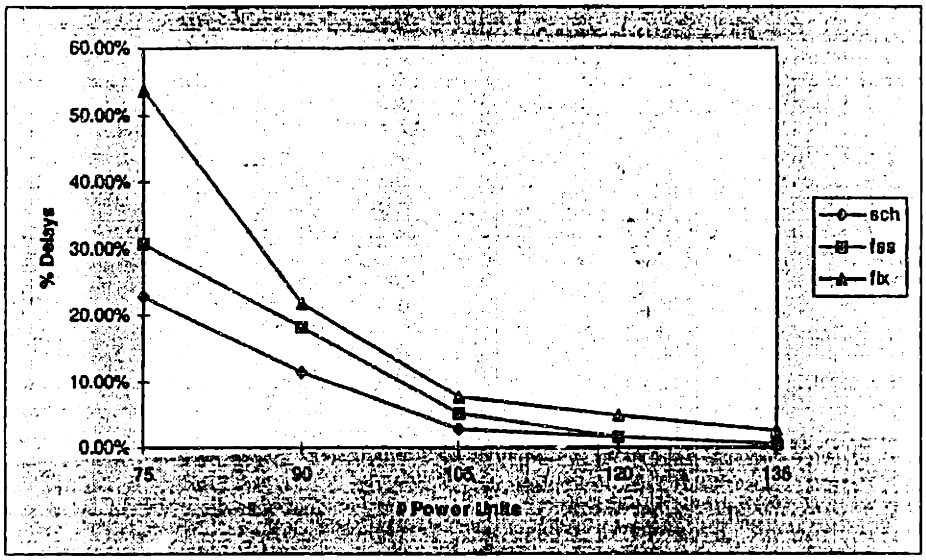

Figure 5-19: Effects of Power Units on Percentage Delays for Area Network

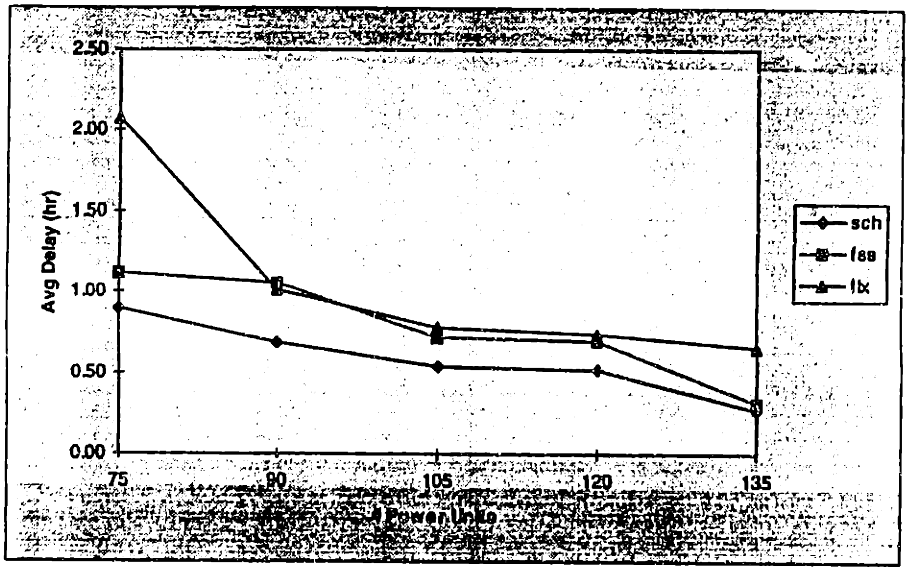

Figure 5-20: Effects of Power Units on Average Delay for Area Network

Figure 5-21 shows the effects of power units on average power time. With the increase of power units, the average power time increases, since more power units are waiting for departure at hump terminals. This figure also shows that under the same power unit level, SCH strategy has the smallest average power time, and FSS has very close average power time with SCH, which is smaller than FLX. The conclusion, again, is the same as in the service lane network analysis.

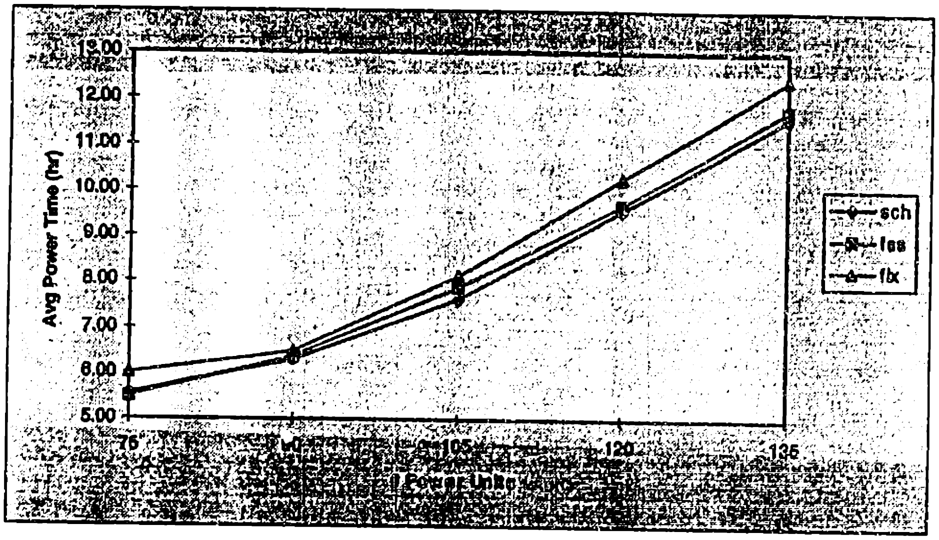

Figure 5-21: Effects of Power Units on Average Power Time for Area Network

Figure 5-22 shows the effects of power units on average yard time. FSS has the smallest average yard time in the range of the power unit change. The decrease of average yard time under SCH and FSS when power units increase from 75 to 105 is much larger than that under FLX, indicating that SCH and FSS need more power units to achieve small average yard time. On the other hand, under FLX, the average yard time is more robust than that under SCH and FSS, especially when the power units are in limited supply. This conclusion, again, is the same as in the service lane network case study.

Figure 5-23 shows the effects of power units on connection performance. With the increase of power units, the connection performance is generally improved for all the three operating strategies. Under the range of the power unit change, SCH strategy has the best connection performance and FSS has better connection performance than FLX. On the other hand, FLX has robust connection performance. The sharp increase of connection performance under SCH and FSS operating strategies when the power units increase from 75 to 105 suggests that in order to achieve better connection performance, SCH and FSS must have large power units as buffer, which

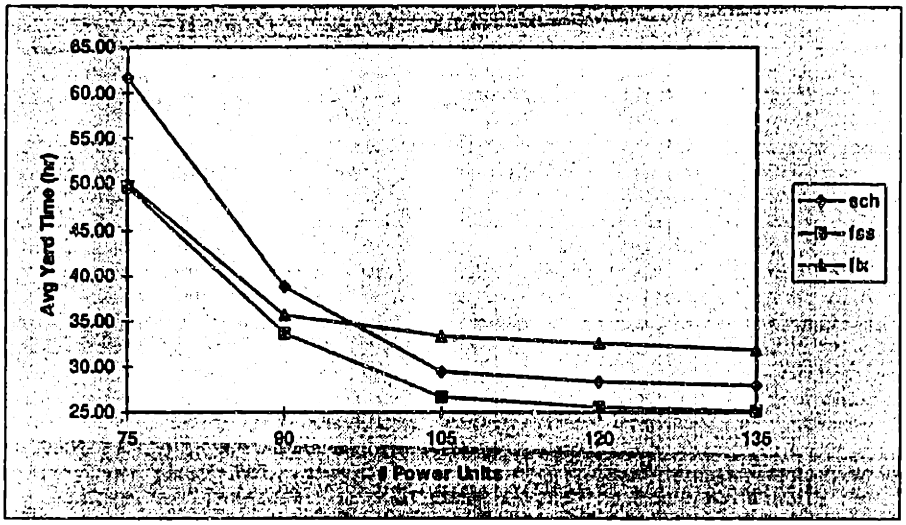

Figure 5-22: Effects of Power Units on Average Yard Time for Area Network

will increase the cost of SCH and FSS. Again, this conclusion is almost the same as in the service lane network case study.

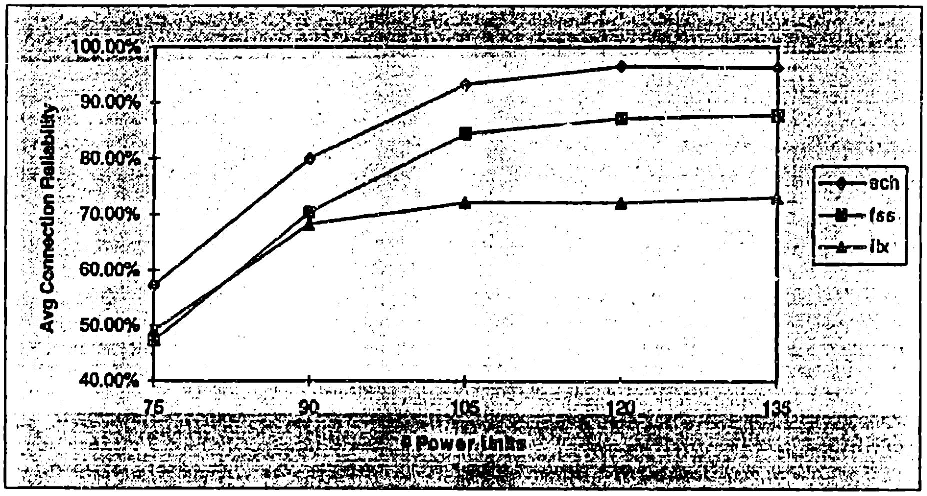

Figure 5-23: Effects of Power Units on Connection Performance for Area Network

5.5.3 Scenario runs

The scenarios used in this case study for the scenario runs is the same as those defined in service lane network case study, which is in Table 5.5.[27]

All the "l" and "h" values of the variables in Table 5.5 are the same as the "l" and "h" values in Appendix A section A.2 (on page 236), except for the network part variables whose values are listed in the tables in Appendix B section B.2.3 (on page 246).

The results from the scenario runs are given in Table 5.13 and Table5.14, each showing eight cases. The results are very similarly to those in service lane network scenario runs and the effects of traffic, train speed, and cutoff on the system are also very similar for these two scenario runs. So we do not discuss them here.

Which operating strategy is the best? Table 5.15 shows the summary of the scenario runs.[28]

Based on Table 5.15, we can get the conclusions that are the same as that in the scenario runs for service lane network. (See section 5.4.3 on page 176).

The results in Table 5.13 and 5.14 show that no operating strategy achieves the best performance for all the performance measures. The answer to the question of which operating strategy is the best is really depends on the performance measures used for the evaluation. But if we compare the costs of running the trains and car cost at the hump terminals for different operating strategies as in section 5.4.1 (on page 159), we can conclude that FSS is the best in terms of having minimum costs in all but 1 case (e.g., Case 10, where SCH is the best one) and SCH is better than FLX in most cases except in Case 11, 12, 15, and 16, where FLX is better than SCH.

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[27] See subsection 5.4.3 on page 172 for detailed scenario design.

[28] For each performance measure, if an operating strategy is best for a case, this operating strategy will appear in this case for this performance measure.

Scn	OS	trns run	int. yard time	avg line time	avg trip time	# of delay	avg delay time	avg power time	avg crew time	avg yard time	avg conn. perf.	OB on time
C 1	sch	420	2.39	3.75	6.13	0	0.03	11.95	13.87	25.48	99.48%	97.41%
	fss	398	2.50	3.75	6.25	5	0.48	12.15	14.85	23.89	86.64%	50.87%
	flx	356	2.66	3.74	6.40	5	0.61	12.93	17.24	29.27	73.36%	50.70%
C 2	sch	421	2.35	3.74	6.10	0	0.09	11.96	13.91	29.57	95.15%	96.17%
	fss	398	2.51	3.74	6.25	1	0.18	12.14	14.87	28.28	79.66%	54.36%
	flx	351	2.67	3.74	6.42	20	1.05	13.04	17.59	37.15	60.04%	54.80%
C 3	sch	421	2.41	4.70	7.11	15	0.60	8.28	8.87	25.89	98.72%	94.56%
	fss	397	2.53	4.72	7.25	24	1.15	8.45	9.66	24.55	84.87%	50.89%
	flx	356	2.71	4.70	7.41	35	1.71	9.12	11.48	30.05	72.96%	51.73%
C 4	sch	420	2.37	4.70	7.06	19	0.73	8.33	8.93	28.23	90.72%	91.78%
	fss	398	2.49	4.70	7.20	21	0.98	8.51	9.68	26.61	81.91%	54.19%
	flx	352	2.68	4.69	7.37	32	1.74	9.14	11.70	34.28	64.77%	53.75%
C 5	sch	420	2.39	3.75	6.13	1	0.15	12.01	13.87	25.57	99.15%	97.65%
	fss	397	2.51	3.75	6.26	4	0.33	12.19	14.87	23.95	92.69%	50.56%
	flx	356	2.67	3.74	6.41	10	0.79	12.92	17.18	29.32	80.42%	51.19%
C 6	sch	420	2.37	3.74	6.11	1	0.04	11.98	13.88	27.42	98.74%	98.15%
	fss	397	2.51	3.75	6.25	4	0.44	12.22	14.90	25.93	90.77%	54.42%
	flx	348	2.70	3.74	6.44	13	0.92	13.02	17.67	33.96	71.79%	53.40%
C 7	sch	422	2.37	4.70	7.07	10	0.51	8.26	8.92	26.08	98.11%	94.52%
	fss	399	2.57	4.72	7.29	21	1.15	8.37	9.61	24.52	91.21%	49.96%
	flx	356	2.68	4.70	7.37	49	2.12	9.12	11.48	30.98	77.62%	51.89%
C 8	sch	420	2.38	4.70	7.08	12	0.57	8.29	8.93	28.17	95.20%	93.55%
	fss	398	2.52	4.70	7.22	15	1.01	8.48	9.69	26.40	89.51%	54.70%
	flx	351	2.70	4.69	7.39	37	1.48	9.06	11.74	34.04	72.57%	53.26%

Table 5.13: Results of Scenario Runs for Area Network: Part 1

Scn	OS	trns run	int. yard time	avg line time	avg trip time	# of delay	avg delay time	avg power time	avg crew time	avg yard time	avg conn. perf.	OB on time
C 9	sch	421	2.55	3.74	6.30	1	0.28	10.06	13.70	27.54	93.56%	93.14%
	fss	477	2.36	3.75	6.11	45	1.58	10.40	11.63	26.34	73.95%	51.21%
	flx	403	2.66	3.74	6.41	52	1.81	10.70	14.40	29.40	68.25%	56.11%
C 10	sch	420	2.52	3.74	6.27	2	0.17	10.31	13.72	30.87	71.33%	90.73%
	fss	483	2.35	3.75	6.10	32	1.26	10.49	11.39	30.80	37.13%	52.60%
	flx	385	2.70	3.74	6.44	23	1.02	11.06	15.33	35.31	21.34%	55.37%
C 11	sch	420	2.57	4.70	7.26	24	0.70	6.85	8.75	36.34	86.13%	95.22%
	fss	479	2.50	4.74	7.24	54	1.59	6.78	6.81	31.43	58.28%	50.46%
	flx	409	2.67	4.70	7.37	59	1.68	7.21	9.04	34.64	62.45%	54.30%
C 12	sch	420	2.52	4.70	7.22	22	0.68	7.23	8.82	34.77	78.30%	86.68%
	fss	476	2.38	4.73	7.11	69	3.21	7.06	7.10	27.75	67.82%	52.13%
	flx	390	2.69	4.70	7.38	87	3.24	7.58	9.81	34.53	56.17%	54.11%
C 13	sch	420	2.56	3.74	6.31	1	0.23	10.04	13.70	33.22	90.24%	97.06%
	fss	486	2.36	3.76	6.13	45	1.09	10.14	11.25	28.24	73.16%	50.26%
	flx	406	2.66	3.74	6.40	42	1.38	10.61	14.25	34.04	68.17%	54.34%
C 14	sch	420	2.53	3.74	6.27	2	0.18	10.32	13.72	30.19	76.65%	93.20%
	fss	484	2.35	3.75	6.10	47	1.38	10.48	11.36	27.78	49.84%	51.15%
	flx	390	2.69	3.74	6.43	49	1.84	11.11	15.13	35.47	25.86%	55.01%
C 15	sch	419	2.57	4.70	7.26	17	0.68	6.94	8.75	34.59	87.89%	93.43%
	fss	476	2.45	4.73	7.18	57	1.52	7.00	6.99	28.58	76.14%	50.42%
	flx	411	2.69	4.70	7.39	69	1.94	7.09	9.02	31.55	71.48%	55.52%
C 16	sch	419	2.53	4.70	7.22	27	0.75	7.19	8.78	33.87	82.26%	85.93%
	fss	478	2.35	4.72	7.07	55	1.96	7.42	7.09	31.17	75.55%	53.93%
	flx	394	2.66	4.70	7.36	51	1.60	7.54	9.88	32.30	70.12%	54.31%

Table 5.14: Results of Scenario Runs for Area Network: Part 2

Scn	trns run	int. yard time	avg line time	avg trip time	# of delay	avg delay time	avg power time	avg crew time	avg yard time	avg conn. perf.	OB on time
C 1	flx	sch	flx	sch	sch	sch	sch	sch	fss	sch	sch
C 2	flx	sch	all	sch	sch	sch	sch	sch	fss	sch	sch
C 3	flx	sch	flx	sch	sch	sch	sch	sch	fss	sch	sch
C 4	flx	sch	flx	sch	sch	sch	sch	sch	fss	sch	sch
C 5	flx	sch	flx	sch	sch	sch	sch	sch	fss	sch	sch
C 6	flx	sch	sch/flx	sch	sch	sch	sch	sch	fss	sch	sch
C 7	flx	sch	flx	sch	sch	sch	sch	sch	fss	sch	sch
C 8	flx	sch	flx	sch	sch	sch	sch	sch	fss	sch	sch
C 9	flx	fss	sch/flx	fss	sch	sch	sch	fss	fss	sch	sch
C 10	flx	fss	sch/flx	fss	sch	sch	sch	fss	fss	sch	sch
C 11	flx	fss	sch/flx	fss	sch	sch	fss	fss	fss	sch	sch
C 12	flx	fss	sch/flx	fss	sch	sch	fss	fss	fss	sch	sch
C 13	flx	fss	flx	fss	sch	sch	sch	fss	fss	sch	sch
C 14	flx	fss	sch	fss	sch	sch	sch	fss	fss	sch	sch
C 15	flx	fss	sch	fss	sch	sch	sch	fss	fss	sch	sch
C 16	flx	fss	sch	fss	sch	sch	sch	fss	fss	sch	sch

Table 5.15: Summary and Comparison of Scenarios Runs for Area Network

5.6 Summary and conclusions

In this chapter, we presented a network simulation model which simulates rail network operations, including hump terminal, intermediate terminal, and line haul movement operations. We use this network simulation model to evaluate terminal performance, train trip time performance, and crew and power unit availability and utilization under different operating strategies.

Two case studies were conducted using two portions of a physical network from a Class I railroad. The service lane network includes two hump terminals and several intermediate terminals and line segments between them; the area network includes three hump terminals and several intermediate terminals and line segments between them. The service lane and area networks are often used by railroads to test new approaches and operating strategies.

Each case study includes a base case, which represents normal operating conditions, sensitivity analysis, in which some operating conditions or variables are changed to evaluate the effects of these variables on system performance, and scenario runs, in which many cases are designed to represent different operating conditions.

The model results show that even though these two case studies are different in various aspects such as number of hump terminals studied, physical configurations, system level resources, etc., they have very similar system performance behavior and the conclusions from these two case studies are basically the same.

The major conclusions from these two case studies are:

- No operating strategy achieves the best performance for all the performance measures used in this research. Each operating strategy has its advantages and disadvantages;

- The schedule-adherence strategy provides the best connection performance and OB train on-time performance at (hump) terminals. It has the highest level of crew and power unit availability and the fewest OB train delays due to lack of crews and power units. This operating strategy also has very high level of crew and power utilization measured by average crew and power time. It works best when there are extra resources, such as crews and power units, and extra capacity available as buffers. When the system resources of crews and power units are in a limited supply, the schedule-adherence strategy tends to incur large delays for a large number of OB trains, and the average yard time and other performance measures quickly worsen;

- The flexible short-run scheduling strategy provides the best car utilization at terminals measured by the average yard time. The terminal through put is the largest under this operating strategy. It also provides very good resource utilization and often better connection performance and OB train on-time performance than the flexible operation strategy. The availability of system resources of crews and power units are lower and many OB trains incur larger delays than the schedule-adherence strategy. This operating strategy, like the schedule-adherence strategy, requires extra resources and capacity as buffers and when the system resources of crews and power units are in a limited supply, it tends to incur large average yard time, more and larger OB train delays, and lower connection performance;
- The flexible operation strategy runs the fewest trains and hence provides the largest savings in train cost. This operating strategy is very robust in that when the system resources of crews and power units are in a limited supply, it can still achieve reasonably good performance on all the performance measures while the schedule-adherence and flexible short-run scheduling strategies cannot. Compared with the other operating strategies, it often has large average yard time, poor connection performance and OB train performance, and lower resource utilization;
- The answer to the question of which operating strategy is the best really depends on which performance measure(s) is the most important one(s) to railroads and the degree to which they can compromise other performance measures. When the same level of terminal and system resources are available, the flexible short-run scheduling strategy is the best one in terms of car and train costs.

Considering current railroad operations, it seems that the cost saving goal is very important to railroads but they can no longer run fewer trains if they want to provide satisfactory service performance. On the other hand, railroads may not have an urgent need and enough system level resources to apply the schedule-adherence strategy. It seems that FSS fits current railroad situations very well and it can potentially be a very effective tool for railroads to achieve better operations and performance.

Chapter 6

Conclusions and Future Studies

6.1 Research summary and conclusions

The research in this thesis aimed to model railroad operations under different operating strategies and address the question of what kind of operating strategy is the best for the railroads under what kind of operating conditions.

Four areas were identified and researched to accomplish these objectives.

First, the research defined three operating strategies, examined the major characteristics of these three operating strategies, and provided a framework for evaluating railroad operations under different operating strategies. The research is helpful to the rail industry in clearly defining their operating strategies and provides the industry a better framework to evaluate their operating strategies.

Second, the research reviewed and analyzed the practice and research in other complex systems, including other transportation systems, and in railroads in terms of what kind of operating strategies were used and what were the major characteristics of these systems that led to adoption of these operating strategies. The review and analysis of the practice and research in other complex systems is of interest to the rail industry to identify factors affecting what kind of operating strategies might be effective under what kind of operating conditions.

Third, terminal operations, which were identified as a major part of railroad operations in this research, were modeled and evaluated under different operating strategies.

Two analytic terminal models, the Intermediate Terminal Model (ITM) and the terminal Processing Sequencing Model system (PSM), provided a methodology to study terminal operations and estimate terminal performance. The Stochastic Terminal Model (STM) provided a better understanding of train performance under different operating strategies. Based on the methodology developed in ITM and PSM, and train performance estimated by STM, the Terminal Simulation Model (TSM) was developed to evaluate detailed terminal operations under different operating strategies. Efficient data structures and algorithms were developed in the simulation model, making the model easily simulate realistic terminal operations for several months in less than a minute.[1] A case study was conducted using the model and actual data from a major hump terminal of a Class I railroad.

Fourth, a rail Network Simulation Model (NSM) was developed to study railroad operations under different operating strategies. Rail network operations include operations at hump terminals, intermediate terminals, and line haul segments between terminals. Two small networks, a service lane network and an area network, were used in two case studies. These two networks are two portions of a physical network from a Class I railroad. Railroads often test their new initiatives and approaches using a service lane or an area network. The results from these two case studies can be generalized to larger networks since the operations of a large network can be decomposed as the operations of several smaller networks such as service lane and area networks and railroad operations are organized by divisions which are smaller networks such as service lane and area networks.

The research and conclusions from the research are summarized as follows.

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[1] Of course, high speed of advanced computer technology is a factor for achieving such a computation performance.

6.1.1 Three operating strategies: schedule-adherence, flexible short-run scheduling, and flexible operation

The schedule-adherence strategy is a strategy under which railroad operations are conducted according to the operating plan, with a focus on adhering to train schedules specified in that plan. The major characteristic of this strategy is that railroads, like airlines and passenger railroads, create schedules based on an operating plan on a regular basis (monthly or quarterly) and then stick to the schedules in their operations, although minor changes are inevitable. The schedule-adherence approach emphasizes the active role of the operating plan, especially train schedules.

Under the flexible short-run scheduling strategy, a short-run plan is developed at least eight hours (e.g., a shift) ahead of time to accommodate the current situation; railroad operations are then conducted according to this plan. This strategy acknowledges the importance of the long-term operating plan and train schedules for railroad operations, but also recognizes the significant stochasticity and uncertainty in railroad operations resulting from variability in demand, uncertain terminal processing times, weather, track maintenance requirements and other factors. The short-run plan is developed to have a clear and achievable goal for managing trains, crews and power units. This short-run schedule will often be different from the schedule as given in the operating plan. This strategy is flexible in the sense that it responds to actual conditions such as resource availability and predicted traffic volume. It is scheduled in the sense that there is always a clear plan for the near future, which is adhered to.

Under the flexible operation strategy, the railroad operations are conducted according to some rules with no requirement of formal plans such as train schedules or short-run plans being developed and adhered to. The tonnage-based assembly rule, which allows the terminals to assemble outbound trains whenever some predefined number of cars are available, is commonly used in practice and is the flexible operation strategy investigated in this research. This strategy emphasizes the need to respond to current conditions. The major characteristic of this strategy is that railroads establish operations in real-time, or close to real-time, depending on traffic, weather condition, and resource availability.

In essence, the differences in these strategies reflect different philosophies in terms of how railroads should be operated. It involves the *degree of schedule-adherence in railroad operations*. It also related to the issue of *global vs. local control* or *centralized vs. decentralized control* in railroad operations. The schedule-adherence strategy is the most strict schedule-adherence and can be considered as a global or centralized control tool to coordinate the railroad operations among different terminals and other subdivisions; the flexible operation strategy has no schedules and can be considered as a local or decentralized control tool since each terminal could conduct its operations according to its own situation without considering much about the impact of its actions on the network. The flexible short-run scheduling strategy has a degree of schedule-adherence, which is between the schedule-adherence and the flexible operation strategies. This operating strategy can be considered as a control tool which considers both the network and terminal conditions to determine day-to-day operations.

From the railroad hierarchical management point of view, the issue of which operating strategy is the best is at the operational management level, rather than strategic and tactical management levels. It is under this management level, that railroad operations are conducted and railroad performance is achieved.

6.1.2 Factors determining which operating strategy is used

From the review and analysis of the practice and research in other complex systems, including other transportation systems, and in railroads, we conclude that the following factors are the most important in determining which operating strategy is used in day-to-day operations.

- Processing variability. For systems with large processing variability, schedules may not be achievable if not enough buffer times are added in the schedules and they may not be useful if too much buffer times are added to waste capacity. The flexible approach may be a good choice.

- System operational structure. For systems with highly related components or with a highly related hierarchical structure, scheduled approaches with buffered times are important to coordinate operations and achieve good performance.

- Cost of resources. High cost of resources makes schedules more attractive to better utilize these resources such as in airline operations. On the other hand, the low cost of resources makes schedules not a necessary means to schedule the usage of these resources. Under this condition, flexible strategy may be a good choice.

- Capacity. Very large system capacity sometimes make the schedules unnecessary such as in telecommunication systems. On the other hand, when the capacity is limited, scheduled approaches may be a good way to better utilize the capacity.

- Service frequency. Very high service frequency makes the schedules unnecessary such as airport shuttle bus services. It also requires good organization of resources. On the other hand, when the service frequency is relatively low, schedule-adherence is important and very helpful to organize system operations and customers' activities.

- Recovery time. A system with recovery time has advantages in applying scheduled approaches over a system without recovery time. Passenger airline operations, for example, have a recovery time (e.g., at night), which helps airlines to use a scheduled approach in their operations.

- The need to handle extreme situations. For systems that need to handle extreme situations,[2] a flexible strategy, developing contingency plans, is often used to handle the extreme situations. The occurrence of these extreme situations will trigger the system operations being conducted under the contingency plan, rather than the normal plans.

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[2] Otherwise, the cost of the occurrence of these extreme situations, if not properly handled, may be quite high.

- Stochastic demand. Highly stochastic demand, unbalanced demand, and very large peak demand favors the flexible approach. During peak hours, flexible strategies such as real-time or close to real-time control strategies are often used to deal with peak demand and other current situations. On the other hand, if demand is very deterministic and stable, the scheduled approach can maximize utilization of resources and capacity by optimizing the schedules.

- Customer service requirement. Low customer service requirement makes the schedules unnecessary such as for coal and other bulk trains. Service reliability is not a major concern to them while costs are. On the other hand, very high customer service requirement makes the schedules an important tool to reserve capacity and resources to satisfy the service requirement such as auto and intermodal trains.

- Uncertain events such as accidents, weather, unscheduled maintenance, etc. The more likely these uncertain events' occurrence, the better the flexible approach is, since occurrence of these events hurt the schedules.

These factors can be summarized as internal conditions and external conditions.[3] Of the above factors, the last three factors are external conditions and other factors are internal conditions. How these factors affect adoption of different operating strategies are summarized in Figure 6-1.

Figure 6-2 shows how internal and external conditions affect use of different operating strategies. Figure 6-3 shows some examples mainly from different transportation modes from the review of the practice and literature conducted in this research.

6.1.3 Modeling terminal operations under different operating strategies

We summarize this part of the research as follows. The conclusions of the terminal study, together with those of the network study, are given in subsection 6.1.5.

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[3] See Chapter 2 section 2.4 on page 54 for definition of internal and external conditions.

Values Favoring Flexible Approach	Key System Parameters	Values Favoring Scheduled Approach
	Internal Conditions:	
High	Processing Variability	Low
Less Related	System Components	Highly Related
Low	Cost of Resources	High
Large	Capacity	Small
High	Service Frequency	Low
Not Available	Recovery Time	Available
Need	Handle Extreme Situations	Not Needed
	External Conditions:	
High	Stochastic Demand	Low
Low	Customer Service Requirement	High
More Likely	Uncertain Events	Less Likely

Figure 6-1: Key Parameters Affecting Adoption of Different Operating Strategies

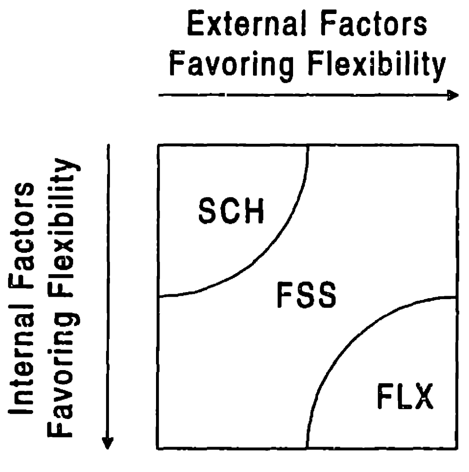

Figure 6-2: Effects of Internal and External Conditions on Different Operating Strategies

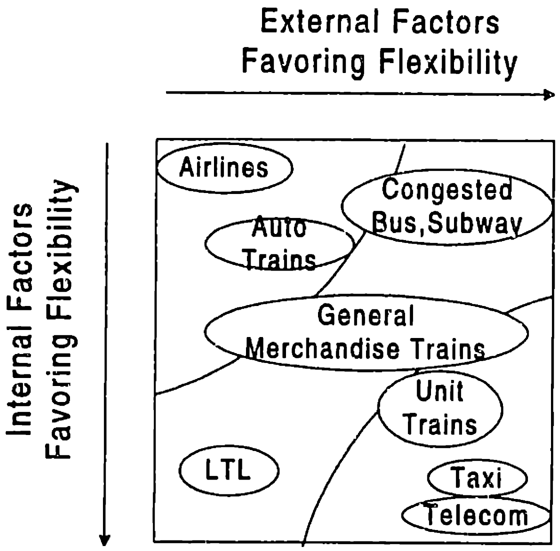

Figure 6-3: Effects of Internal and External Conditions on Use of Different Operating Strategies

- Terminal operations are a major part of railroad operations and are a critical factor in railroad operations. Major service problems often occur at terminals.

- A methodology is developed in this research, which decomposes complicated terminal operations into processes and tasks. The key to modeling and improving terminal operations is to model these processes and tasks and relate them to terminal performance measures.

- Two terminal models are developed applying this methodology, which can be used to evaluate terminal operations under different operating strategies for a day or a shift. The intermediate terminal model (ITM) predicts terminal performance such as average yard time, connection reliability, achievability of terminal operating plans, PMAKE parameters, and operating cost based on given IB train arrival pattern and OB train departure requirements, terminal resources, terminal processing capability, and the specified processing sequencing for the tasks in each process.

  The terminal processing sequencing model system (PSM) determines the "optimal" processing sequencing for each process using a heuristic procedure called potential car hours avoided (PCH) and predicts the terminal performance based on the optimal sequencing in each process and other input in ITM. As decision support tools, these two models were used by several railroads as tools to develop terminal operating plans, estimate and evaluate alternative terminal operating plans and evaluate the trade off between terminal performance and terminal capacity.

- A stochastic terminal model (STM) is developed to estimate train performance under different operating strategies. The model assumes that IB arrivals are stochastic processes and the traffic on each IB train for an OB train is probabilistic. The number of cars for the OB train at any given time is derived as a probability function using the central limit theory and the means and the standard deviations are estimated for the schedule-adherence and the flexible operation strategies. The results from the STM show that for the schedule-adherence strategy, the departure time is very reliable but the traffic volume on trains is variable; for the flexible operation strategy, the departure time is variable but the traffic volume on trains is very stable. The flexible short-run scheduling strategy performs between the parameters of the schedule-adherence and the flexible operation strategies.
- A microscopic terminal simulation model (TSM) is developed based on the methodology implemented in the ITM and the PSM and the results from the STM. Efficient data structure and algorithms are developed in the model to simulate realistic terminal operations for several months in less than a minute. The TSM is used to evaluate terminal operations under different operating strategies and a case study using actual terminal data from a major hump terminal of a Class I railroad is conducted.

6.1.4 Modeling network operations under different operating strategies

As a continuation and extension effort beyond the terminal simulation model, a microscopic network simulation model (NSM) is developed to simulate rail network operations, including operations at hump terminals, intermediate terminals, and line haul segments. The network simulation model is used to evaluate terminal performance, train trip time performance, and crew and power unit availability and utilization under different operating strategies.

Two case studies using two portions of a physical network from a Class I railroad are conducted. Case study one uses a service lane network including two hump terminals, several intermediate terminals, and line haul segments between terminals; case study two uses an area network including three hump terminals, several intermediate terminals, and line haul segments between terminals. The service lane and area networks are often used by railroads to test new approaches and operating strategies.

Each case study, as in the terminal case study, includes a base case, which represents normal internal and external operating conditions, sensitivity analysis, in which some operating conditions or variables are changed to evaluate the effects of these variables on system performance, and scenario runs, in which many cases are designed to represent different operating conditions and to evaluate network operations under different strategies and under these different operating conditions.

6.1.5 Evaluation of different operating strategies

Three comprehensive case studies, one for terminal operations and two for network operations, are conducted using the terminal and network simulation models developed in this research. These case studies are used to evaluate terminal and network operations under different internal and external operating conditions and under different operating strategies. The terminal model generates detailed terminal performance and system level resource utilization measures. The network model generates, besides the performance measures generated by the terminal model, train performance over the network and system level resource (e.g., road crews and power units) availability measures such as delays of trains due to lack of these resources.

The terminal case study treats the terminal as an open system in that road crew and power unit resources can be deadheaded into the terminal in a probabilistic manner.[4] On the other hand, the two network case studies treat the two networks as closed systems in that no crews and power units are deadhead in and out.[5] These case studies are also different in various aspects such as terminal layout, resources, capacity, traffic volume, etc., but *the fundamental conclusions from these case studies are basically the same.* The network results give additional conclusions in terms of train performance over the networks and train delays at hump terminals due to lack of road crew and power unit resources.

The major findings from the evaluation of different operating strategies are summarized in Table 6.1 and explained in detail as follows.

- No operating strategy achieves the best performance for all the major performance measures (used in this research). No single operating strategy dominates the others. Each operating strategy has its advantages and disadvantages;
- The schedule-adherence strategy (SCH) provides the best customer service performance, measured by connection performance and OB train on-time performance. It has the highest level of crew and power unit availability and the fewest OB train delays due to lack of crews and power units. It also has very high levels of crew and power unit utilization, measured by average crew and power time, especially when traffic volume is low. But it tends to use the most resources, such as road crews and power units, and run more trains to maintain a high level of service. A large buffer time is added in the operating plan under this operating strategy to deal with internal and external conditions which may prevent the operating plan being achieved. The addition of the buffer time is good for making the operating plan achievable but not good for achieving large terminal through put. Operating railroads under this operating strategy requires the highest level of crew and power unit resources and capacity in terminals and line segments as buffers, and hence incur the largest resource and

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[4] This is realistic in terminal operations. See Chapter 4 on page 127 for discussions.

[5] For a service lane or an area network, it is generally the case except very limited exchanges of crews and power units with other parts of a larger network. See Chapter 5 on page 151 for discussions.

Performance Measures or Attributes	Schedule-Adherence (SCH)	Flexible Short-Run Scheduling (FSS)	Flexible Operation (FLX)
Customer Service:	Good	Fine	Poor
conn. perf.	good	fine	poor
OB train on-time	good	fine	poor
Crew and Power Availability:	High	Low	Lower
# delays	few	many	more
avg delay	small	large	larger
Crew Utilization:	Higher	High	Low
avg crew time	smaller (esp. traffic low)	small	large
Power Utilization:	Higher	High	Low
avg power time	smaller (esp. traffic low)	small	large
Train Cost:	Large	Small	Smaller
# trains run	large	small	smaller
Car Utilization:	High	Higher	Low
Car Cost:	Small	Smaller	Large
avg yard time	small	smaller	large
Train & Car Costs	Small	Smaller	Large (car cost high)
Ability to Handle Traffic Increase	Weaker	Weak	Strong
Resources & Capacity as Buffers?	Yes (higher)	Yes (high)	No (low) (very robust)

Table 6.1: Summary Conclusions from Evaluation of Different Operating Strategies

capacity related investment and costs; the return of the largest costs is the best customer service and savings of car utilization cost compared with the flexible operating strategy (FLX).

SCH works best to keep its goal of schedule-adherence when there are extra resources, such as crews and power units, and capacity available as buffers. When road crew and power unit resources are in a limited supply, the schedule-adherence strategy tends to incur large delays for a large number of OB trains and the average yard time and other performance measures quickly worsen;

- The flexible short-run scheduling strategy (FSS) provides the best car utilization, measured by average yard time. The car cost is the smallest and terminal through put is the largest under this operating strategy. FSS also provides better system level resource utilization, measured by average crew and power time, than FLX, which is often worse than SCH. The customer service performance, measured by connection performance and OB train on-time performance, is also better than FLX and worse than SCH. The availability of road crews and power units are lower than SCH and higher than FLX. Even though the level of system resources, such as road crews and power units, required may be less than that under SCH, this operating strategy also requires additional resources and capacity as buffers, especially when traffic level is high.

  This operating strategy often provides the smallest car and train costs. But the level of customer service is worse than SCH. When the road crew and power unit resources are in a limited supply, it tends to incur large average yard time, more and larger OB train delays, and lower connection performance quickly;

- The flexible operation strategy (FLX) runs fewest OB trains and hence provides the largest savings in train cost, which is one major part of railroad operating cost in railroad budget. It does not require additional crew and power unit resources and capacity as buffers. This operating strategy works very well when there is limited supply of system level resources, such as crews and power units. Under this condition, it is very robust in that it can still achieve reasonably good performance on all the performance measures while the SCH and the FSS cannot. But customer service performance, under FLX, is the worst. It often has the largest average yard time, the worst connection performance and OB train on-time performance, and lowest resource utilization, measured by average crew and power time. The FLX can sometimes cause unbalanced road crew and power unit resources at different part of a network due to unscheduled operations under this operating strategy;

- The answer to the question of which operating strategy is the best really depends on which performance measure(s) is the most important one(s) to railroads and the degree to which they can compromise other performance measures.

Railroads do not have enough system level resources, such as road crews and power units, enough system capacity, and urgent need and incentive to apply the schedule-adherence strategy for all traffic priorities. The cost to maintain a high level of customer service is too high to apply this strategy in all cases. They may not have enough system level resources and capacity to apply the flexible short-run scheduling strategy for all the traffic priorities, even though this operating strategy has the minimum car and train costs. If they had enough system resources and capacity to apply this operating strategy, it would be still difficult to provide satisfactory service for customers with very high service requirements. For the flexible operation strategy, since it provides the largest train cost saving and train cost saving is still a major concern from railroad budget point of view, railroads still have incentives to run their operations under FLX as much as possible. This may explain some of the current railroad operations, which run many trains according to FLX. But higher competition and customer service requirements no longer allow railroads to run by FLX rules, especially for high priority traffic.

It seems that different operating strategies should be applied to different traffic priorities to achieve the best performance and results. For high priority traffic with high service requirement, such as auto and intermodal traffic, the schedule-adherence strategy can be used to achieve desired service and enough system resources and capacity should be reserved for this priority traffic.

For middle priority traffic such as general merchandise traffic, the flexible short-run scheduling strategy should be applied to take advantage of the level of service and car and train cost savings it provides, which can satisfy customer service requirement and achieve the largest operating cost savings. Enough system resources and capacity should also be reserved for this type of traffic.

For low priority traffic with low service requirement, such as coal unit trains, the flexible operation strategy should be applied to utilize the remaining resources and capacity whenever possible to achieve train cost savings while service performance is not a major concern.

Service differentiation already exists at railroad operations.[6] Applying different operating strategies is potentially a very effective way to support service differentiation and improve railroad operations and performance.

6.2 Contributions

An improved perspective on modeling and evaluating different railroad operating strategies is developed in this thesis. As with any complex systems, railroads have been seeking effective and efficient operating strategies to improve service, resource utilization, and cost. Finding the best operating strategy for a given set of operating conditions is very useful for railroads trying to achieve their goals. The findings and conclusions of this research are also useful to other complex systems in which different operating strategies must be evaluated and the best one must be applied to their day-to-day operations. The contributions in this thesis are three fold.

Clarifying the Debate About Operating Practice Three fundamental operating strategies were clearly and carefully defined for the first time and the major

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[6] See, for example, [51] for detailed discussions.

characteristics of these operating strategies were analyzed. This is very useful for the rail industry. It can help to clarify the confusion caused by different meanings of their terminology, which prevent them from effectively debating the merits of various operating strategies. When all parties agree on the definitions of these operating strategies, the debate can be very useful.

Developing an Efficient Modeling Framework A modeling framework, a methodology, and a set of models were developed to evaluate different operating strategies at the terminal and network level. The microscopic terminal and network simulation models are developed using the methodology and efficient data structures and algorithms are developed and applied to these models to easily simulate realistic terminal and network operations for several months in less than a minute. The models not only provide comprehensive average performance measures but also the variances of these measures, which are important for statistically sound estimates of these performance measures.

Choosing the Best Operating Strategies for Various Operating Conditions Using actual data from a Class I railroad, three comprehensive case studies were conducted and the conclusions were drawn from the model results, regarding which operating strategies were best for which internal and external operating conditions. To respond to the question of which operating strategy is the best, which is the major issue we seek to address in this research, we showed the operating conditions under which each operating strategy is best, which depends on available railroad resources, traffic priority, and other internal and external conditions.

6.3 Future studies

Several areas for future study are suggested as follows.

- The definitions of railroad different operating strategies are not very concrete in a sense that only the major ideas of each operating strategy is defined and discussed. In the future, more railroad practice can be incorporated in the definitions of these different operating strategies. Specifically, how to develop short-run plans under the flexible short-run scheduling strategy, what is the time frame for developing these short-run plans, and who should be involved in developing these plans need to be addressed in future studies;

- Apply the terminal simulation model in a study of a particular terminal. The terminal study can be conducted to validate the variables representing different aspects of terminal operations, to validate the model so that it can simulate detailed terminal operations and generate the same or very similar results as the actual terminal performance, and to find the best operating strategy under the given operating conditions to achieve the best performance for the terminal. The terminal study can also generalize the model so it can be used in studies of different terminals;
- Apply the network simulation model in a study of a particular network. In the future, data, including the operating plan, of a reasonably large network can be collected and used to conduct the network study to validate the model and provide more complete conclusions in terms of which operating strategy is the best for the given operating conditions for a large network.

6.4 A final comment

Railroads have been seeking effective and efficient operating strategies to improve their operations and performance. Specifically, in recent years, there have been discussions about operating a railroad according to a plan, with a focus on running trains according to schedules. Some railroad experts advocate a scheduled approach, which allows considerable flexibility in operations; some emphasize the importance of the operating plan on railroad operations and service performance; some think flexible operation is critical to take into account such matters as stochastic demand, extreme weather conditions, accidents, etc. Different operating strategies reflect different philosophies in terms of how a railroad should be operated. It involves the *degree of schedule-adherence* in railroad operations. It also related to the issue of *global* vs. *local* control or *centralized* vs. *decentralized* control in railroad operations.

This thesis defines three fundamental operating strategies, which is very useful for the rail industry to clarify the confusions caused by different meanings of their terminology, identifies major factors affecting which operating strategy is the best by reviewing practice and research in complex systems, including other transportation systems, and develops terminal and network models to evaluate railroad operations at terminal and network levels under different operating strategies for a given set of internal and external operating conditions represented by the identified factors. It demonstrates that choosing an appropriate operating strategy allows a railroad to improve its service performance and resource utilization and to achieve great operating cost savings. It also shows that each operating strategy has its advantages and disadvantages and railroads can applying different operating strategies to different traffic priorities to take advantage of customer service requirements and better utilize railroad available capacity and resources.

Applying most appropriate operating strategies in railroad operations is potentially a very effective strategy to improve railroad operations and performance. It is hoped that this thesis can be useful to the rail industry in applying different operating strategies to its operations.

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Appendix A

Terminal Simulation Model Input and Output Files

A.1 Terminal simulation model input files

A.1.1 IB train schedule file

IB train schedule file lists all the IB trains that are scheduled to arrive at the terminal each day from the operating plan. It includes the train name, the scheduled arrival time, the number of blocks on the train, the average number of cars on the train, the name of each block, and the average number of cars of each block. The form of the IB train schedule is shown by the following example:

```
R111   01:00   22   100
AAL 9    AAB 2    BBL 5    BBP 2    BBN 7    ...
```

where, the **R111** is the IB train name, **01:00** is the scheduled arrival time, **22** is the number of blocks this IB train carries, **100** is the average number of cars on the train. It then lists the 22 blocks with the name and the average number of cars for the block.

R111	01:00	22	100									
	AAL	9	AAB	2	BBL	5	BBP	2	BBN	7	BBB	8
	BBC	5	CCN	6	DDU	4	HHM	4	HHB	7	JJM	3
	JJP	2	LLU	4	MMN	7	MMA	2	NNS	7	RRT	6
	SSS	3	SSV	3	SSR	2	WWN	2				
R222	01:30	17	88									
	BBL	2	BBQ	4	CCL	5	CCG	5	FFC	2	JJE	4
	JJX	8	KKM	2	MMA	6	MMG	10	OOK	11	OOL	6
	SSF	2	TTM	7	TTO	4	VVL	4	WWN	6		
Q111	04:30	8	100									
	AAL	20	BBN	12	BBB	15	BBC	13	CCL	13	CCN	10
	FFL	11	MMN	6								
R333	07:00	14	83									
	AAL	6	AAB	2	BBP	2	BBI	5	CCG	3	DDU	6
	HHM	8	JJE	5	MMG	10	OOL	10	RRT	5	SSF	3
	SSW	8	WWN	10								
Q222	08:45	25	99									
	AAB	2	BBL	5	BBP	2	BBQ	3	BBN	4	BBB	3
	BBC	6	CCG	2	DDU	4	FFC	2	FFL	3	JJE	3
	JJM	3	JJX	2	KKM	3	LLU	4	MMN	6	MMA	4
	OOK	17	OOL	1	RRT	2	SSR	4	TTO	5	VVL	6
	WWN	3										
Q333	10:00	11	84									
	CCG	5	FFC	7	JJX	7	KKM	12	MMA	6	MMG	6
	OOL	8	SSV	6	SSI	9	TTM	5	WWN	13		
R444	10:01	18	101									
	AAL	5	AAB	3	BBL	5	BBN	5	BBB	11	BBC	11
	CCG	3	CCN	9	CCW	3	CCR	2	CCS	5	HHM	2
	LLU	9	MMN	6	NNS	9	RRT	9	SSF	2	SSV	2

Q444	10:15	8	83									
	CCG	8	FFC	13	MMA	6	OOL	18	SSF	7	SSI	7
	TTM	7	WWN	17								
R555	13:00	18	98									
	AAL	8	AAB	2	BBL	7	BBP	3	BBN	6	BBB	10
	BBC	5	CCN	6	CCR	2	HHM	3	LLU	8	MMN	6
	MMA	3	NNS	14	RRT	4	SSS	3	SSV	4	SSR	4
A111	13:01	19	100									
	AAL	7	AAB	2	BBL	2	BBM	3	BBP	3	BBQ	3
	BBC	6	CCN	13	CCS	4	FFC	7	KKM	3	LLU	6
	MMG	2	NNS	3	RRT	12	SSV	10	TTM	3	TTO	4
	WWN	7										
A222	15:00	12	90									
	BBC	15	CCG	4	CCW	5	CCR	7	DDU	6	EEW	2
	FFO	4	JJX	9	LLU	9	NNS	12	RRT	11	SSR	6
Q555	15:30	16	86									
	AAB	2	BBL	4	BBH	3	CCG	3	JJM	9	JJX	6
	MMA	3	MMG	5	NNS	11	OOL	13	SSV	4	SSR	4
	SSI	4	TTM	4	TTO	7	WWN	4				
Q666	21:00	19	92									
	AAB	3	BBL	3	BBC	5	EEW	3	JJE	5	JJM	7
	JJX	2	KKM	3	MMA	3	MMG	10	OOL	7	SSF	4
	SSS	2	SSV	3	SSR	3	SSI	4	TTM	3	VVL	8
	WWN	14										
Q777	21:30	22	99									
	AAL	6	AAB	4	BBN	5	BBB	9	BBC	9	CCL	5
	CCG	3	CCN	8	CCW	2	CCS	3	FFL	5	HHM	3
	LLU	9	MMA	2	NNS	3	RRT	3	SSV	6	SSR	2
	SSI	3	SSW	2	TTO	4	WWN	3				

R666	21:31	20	100									
	AAL	7	AAB	2	BBL	5	BBP	2	BBN	6	BBB	8
	BBC	7	CCN	6	FFC	4	HHM	3	JJE	3	JJM	7
	LLU	6	MMA	3	MMG	5	NNS	7	RRT	6	SSS	2
	SSV	8	SSI	3								
Q888	22:01	25	100									
	AAL	5	BBL	6	BBP	3	BBQ	2	BBR	2	BBN	5
	BBC	8	CCN	7	CCW	2	CCC	5	DDU	2	FFC	2
	JJE	5	JJX	2	KKM	2	LLU	8	MMA	1	MMG	2
	NNS	5	OOK	11	OOL	2	TTM	2	TTO	4	VVL	5
	WWN	2										
A333	22:02	27	98									
	AAL	5	BBL	4	BBP	2	BBQ	2	BBN	3	BBB	11
	BBC	7	CCG	2	CCN	11	CCW	2	CCR	2	CCS	3
	CCC	4	EEW	2	FFC	2	FFO	1	LLU	6	MMN	2
	MMA	2	MMG	2	NNS	4	RRT	3	SSV	3	SSR	2
	SSI	3	TTO	3	WWN	5						
A444	22:03	10	98									
	AAB	7	BBP	4	CCG	5	CCO	4	FFC	12	FFO	3
	HHB	9	RRT	40	SSV	7	TTO	7				
R777	23:00	19	99									
	AAL	7	AAB	3	BBN	7	BBB	9	BBC	9	CCG	2
	CCN	9	CCW	6	CCS	4	HHM	2	LLU	13	MMN	4
	MMG	3	NNS	8	RRT	4	SSF	2	SSS	3	SSV	2
	VVL	2										
R888	23:30	18	92									
	BBL	5	BBH	3	FFC	4	FFL	8	JJE	3	JJP	3
	JJX	3	KKM	3	MMA	4	MMG	4	OOK	13	OOL	4
	SSV	7	SSI	4	TTM	10	TTO	5	VVL	3	WWN	6

A.1.2 OB train schedule file

OB train schedule file is almost the same as IB train schedule file except that the order of the blocks in the OB train represents the order of preference. The sequence of the blocks is in the order of pulling operation to assemble the OB train.

A001	00:01	4	89									
	VVL	28	TTO	36	DDU	9	WWN	16				
Q001	01:00	5	102									
	JJE	28	JJX	39	AAB	20	JJM	9	OOL	6		
R001	02:00	2	92									
	CCN	85	TTO	7								
R002	02:30	4	92									
	MMG	37	TTM	14	WWN	35	BBL	6				
R003	05:00	4	98									
	CCO	4	HHM	25	SSI	37	CCG	32				
R004	05:01	2	97									
	BBN	60	MMN	37								
A002	05:02	6	102									
	FFO	8	KKM	28	BBH	6	EEW	5	FFC	41	SSR	14
A003	07:00	2	90									
	WWN	41	RRT	49								
Q002	08:30	5	92									
	CCW	20	CCC	9	SSF	20	BBC	30	CCG	13		
R005	09:00	4	101									
	CCL	23	OOK	45	FFL	20	DDU	13				
R006	11:00	1	85									
	AAL	85										
R007	13:30	4	102									
	OOL	63	JJP	5	JJM	20	FFC	14				
Q003	14:00	5	104									
	SSS	13	SSW	10	EEW	2	SSV	65	AAB	14		

R008	14:01	3	85									
	MMA	45	TTM	27	SSR	13						
A004	14:02	2	92									
	HHB	16	BBC	76								
Q004	18:00	3	101									
	NNS	83	OOK	7	BBB	11						
Q005	18:30	1	80									
	LLU	80										
Q006	19:30	5	100									
	BBI	5	CCR	13	CCS	19	RRT	56	FFL	7		
Q007	20:00	7	94									
	BBM	3	BBP	23	BBQ	14	BBR	2	BBL	47	MMG	3
	LLU	2										
R009	23:00	2	92									
	BBB	73	MMG	19								

A.1.3 Track and block to track assignment file

Track and block to bowl track assignment file first lists the number of receiving tracks, the number of bowl tracks, and the number of departure tracks. It then lists the receiving track identification number and the length of the track in terms of the number of cars it can hold. It then lists bowl track information as follows: bowl track identification number, the length of the bowl track in terms of the number of cars it can hold, the *status* of the bowl track, the number of blocks assigned to this track, and the names of these blocks. The status can have three values: 0 means that the track can hold only *high priority* cars[1], 1 means that the track can hold *medium* and *low priority* cars, and -1 means that the track can hold high, medium, and low priority cars. Finally, the file lists the departure track identification number and length information.[2]

12	52	10
1	120	
2	120	
3	120	
4	120	
5	110	
6	110	
7	110	
8	110	
9	100	
10	100	
11	100	
12	100	

---

[1] Cars belonging to this block *and* whose traffic priority is *high* can be assigned to this track

[2] Although only a static block to track assignment is implemented in the model, the *dynamic* block to track assignment can also be easily implemented as follows: Each block to a track assignment will have a preference number associated with it. For a block with the same priority, multiple tracks are assigned to it with different preference. When a car is humped, it will go to its first preferred bowl track (specified by its block and traffic priority) if the track is not full. Otherwise it will go to its second preferred track if this track is not full. ...etc.

1	45	1	1	BBC		
2	45	0	1	BBC		
3	45	1	1	RRT		
4	45	0	1	RRT		
5	40	-1	3	CCS	CCR	BBI
6	40	1	1	WWN		
7	40	0	1	WWN		
8	40	1	3	SSV	SSS	SSW
9	40	0	3	SSV	SSS	SSW
10	40	1	1	AAL		
11	40	0	1	AAL		
12	45	1	1	CCN		
13	45	0	1	CCN		
14	45	1	1	BBB		
15	45	0	1	BBB		
16	45	1	1	NNS		
17	45	0	1	NNS		
18	45	1	1	LLU		
19	45	0	1	LLU		
20	40	1	1	OOL		
21	40	0	1	OOL		
22	40	1	1	BBN		
23	40	0	1	BBN		
24	40	1	1	MMN		
25	40	0	1	MMN		
26	40	1	1	MMG		
27	40	0	1	MMG		
28	40	1	1	FFC		
29	40	0	1	FFC		
30	40	1	1	BBL		
31	40	0	1	BBL		
32	40	1	1	OOK		
33	40	0	1	OOK		
34	45	-1	3	CCW	SSF	CCC
35	45	-1	1	CCG		

36	45	-1	1	MMA			
37	45	-1	1	TTO			
38	45	-1	3	KKM	FFO	BBH	
39	45	-1	4	BBP	BBQ	BBM	BBR
40	45	-1	1	TTM			
41	40	-1	1	JJX			
42	40	-1	1	SSI			
43	40	-1	2	HHM	CCO		
44	40	-1	1	AAB			
45	40	-1	1	JJM			
46	40	-1	1	JJE			
47	40	-1	1	VVL			
48	40	-1	1	FFL			
49	40	-1	1	SSR			
50	40	-1	1	CCL			
51	40	-1	1	DDU			
52	40	-1	3	EEW	HHB	JJP	
1	120						
2	120						
3	120						
4	120						
5	120						
6	120						
7	110						
8	110						
9	110						
10	110						

A.1.4 Terminal resource file

Terminal resource file includes the number of IB and OB inspection teams, hump crews, assembly crews, available units of road power units and crews.

IB_INSP	OB_INSP	HUMP_CRW	PULL_CRW	PWR_POOL	CRW_POOL
4	4	1	3	20	7

A.1.5 Train capacity file

Train capacity file includes the number of cars each (IB or OB) train can have for a given number of road power units. We assume that the maximum number of power units is 5 for each OB train. A single unit can draw 40 cars, and each additional unit can draw another 40 cars.

$$\begin{aligned} \textit{train capacity} &= f(\textit{power units}) \\ &= 40 * \textit{units} \end{aligned} \tag{A.1}$$

Also, the file contains the minimum and maximum number of cars that an OB train must have for the flexible operation strategy. For flexible short-run scheduling strategy, these two numbers are the estimated minimum and maximum cars on each train. For schedule-adherence strategy, there is no requirement for the number of cars.

TRN_CAP1	TRN_CAP2	TRN_CAP3	TRN_CAP4	TRN_CAP5
40	80	120	160	200
MIN_OB_CARS	MAX_OB_CARS			
80	160			

A.1.6 Terminal processing time file

Terminal processing time file includes the fixed time (e.g., fixed in the following formula) and variable time (var) for each process. The processing time unit is in minute.

$$\begin{aligned} processing\ time &= pf(min\ processing\ time, max\ processing\ time) & \text{(A.2)} \\ &= pf(fixed - var + f(cars), fixed + var + f(cars)) & \text{(A.3)} \end{aligned}$$

where pf is any continuous probability function and $f(cars)$ is a time function for the process. For IB and OB inspection, and hump operations, this function is a function of number of cars (e.g., 1 minute each car for IB and OB inspection and 0.5 min for hump). For assembly operation, this function is a function of number of blocks pulled (e.g., 15 min per block). For IB arrival, brake test and departure, this function is 0 since the process time for these operations is usually not directly related with number of cars or blocks.

YARD_TRN	INSP_TRK	INSP_PER_CAR	HUMP_TRK	HUMP_PER_CAR
40	40	1	25	0.5
PULL_TRK	PULL_PER_BLK	TEST		
40	15	40		
VAR_YARD	VAR_INSP	VAR_HUMP	VAR_PULL	VAR_TEST
5	10	10	10	5

A.1.7 Cutoff time file

Cutoff time file includes cutoff time (in minutes) for different traffic priority. Cutoff time is the time that an IB train will arrive late (compared with the train schedule) but is still scheduled to make its first connections. In the file, **Q** means the Q train[3], **R** means the R train, and **O** means other train.

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[3] A train whose first character of its name is Q

Q_CUTOFF	R_CUTOFF	O_CUTOFF
1200	1200	1200

A.1.8 Road power unit preparation time file

Road power unit preparation time file includes road power unit's **long**, **medium**, and **short** preparation times (in minutes), the **probability** of long and medium time preparations, and the **variable** preparation time parameters. A random (real) number is generated to determine if a long, medium, or short time preparation is to be conducted for the road power unit under consideration. For example, if the random number belongs to long time preparation category, then a long time preparation is needed. The actual preparation time is:

$$actual\ prep.\ time \quad = \quad f(fixed * VAR\_PWR1, fixed * VAR\_PWR2) \quad (A.4)$$

where *fixed* is the fixed preparation time for long, medium, or short preparation.

PWR_REST_L	PWR_REST_M	PWR_REST_S	PWR_L_PROB	PWR_M_PROB
480	180	120	0.1	0.2
VAR_PWR1	**VAR_PWR2**			
0.875	1.125			

A.1.9 Road crew rest time file

CRW_REST_L	CRW_REST_S	CRW_L_PROB	VAR_CRW1	VAR_CRW2
480	120	0.3	0.875	1.125

A.1.10 Terminal queuing strategy file

Terminal queuing strategy file includes the *terminal* operating strategies to deal with queues at each process. For IB processes (e.g., arrival, IB inspection, and hump), the available strategies are: *FIFO*, *LIFO* (last in first out), *PRIORITY* (e.g., the more high priority cars, the less time for waiting in the queue), and *CONTRIBUTION* (e.g., the "contribution" of the cars in the IB train or receiving track to all the OB trains to be assembled. If an OB train's traffic is already at the bowl track, then the contribution of the cars for this OB train is 0). Their values are 1, 2, 3, and 4, respectively. For assembly, the available strategies are: *FIFO*, *LIFO*, *MORE_CARS* (e.g., the more cars to assemble, the less time to waiting in the assembly queue), and *MORE_BLOCKS* (e.g., the more blocks to assemble, the less time to wait). Their values are 1, 2, 3, and 4, respectively. For OB inspection process, the available choices are: *FIFO*, *LIFO*, *PRIORITY* (e.g., the more high priority cars, the less time to wait in the OB inspection queue), and *MORE_CARS*. Their values are 1, 2, 3, and 4, respectively. For brake test process, the available strategies to deal with the queues are: *FIFO*, *LIFO*, *PRIORITY*, and *MORE_CARS*. Their values are 1, 2, 3, and 4, respectively. For departure process strategy, there are two choices: depart whenever the OB train is ready (with value 1) and depart when the scheduled departure time is reached (with value 2). *All the combinations of these choices constitute all the possible terminal operating plans*. In other words, we can treat each combination of these choices as one simplified terminal operating plan.

ARR_STR	IB_INSP_STR	HUMP_STR	
1	1	1	
ASSM_STR	OB_INSP_STR	TEST_STR	DEPT_STR
1	1	1	1

A.1.11 Other parameter file

Other parameter file includes many parameters for the simulation model. These parameters show, in some degree, the capability of the simulation. The meaning of these parameters are listed below.

- **PULL_FIX** the amount of time (in minutes) an OB train is assembled before its scheduled departure time. This parameter is only used by schedule-adherence and flexible short-run scheduling strategies. **OUTPUT_DETAIL** is a parameter whose value is either 0 or 1. If its value is 1, then detailed output file (for each IB and OB train including all the cars in the train, and each activity performed with the major resource involved), and is printed out.

- **VAR_IB_CARS_MIN1** and **VAR_IB_CARS_MAX1** are the two parameters to determine IB train traffic volume for *schedule-adherence* strategy.

  $$IB\ cars = pf(c * VAR\_IB\_CARS\_MIN1, c * VAR\_IB\_CARS\_MAX1) \quad \text{(A.5)}$$

  where, c is the number of cars for the IB train from the operating plan (e.g., from IB train schedule file). pf is any probability function with a minimum value of $c * VAR\_IB\_CARS\_MIN1$ and with a maximum value of $c * VAR\_IB\_CARS\_MAX1$.

- **SCH_ARR_RANGE**, **FLX_ARR_RANGE**, and **FSS_ARR_RANGE** are parameters used to determined the actual IB train arrival time for schedule-adherence, flexible operation, and flexible short-run scheduling strategies, respectively. That is,

  $$arrival\ time = pf(sch\ arr\ time - RANGE/2, sch\ arr\ time + RANGE) \quad \text{(A.6)}$$

  where, *sch arr time* is the scheduled arrival time of the IB train from the operating plan. The *RANGE* is the parameter in the file. The reason for IB trains to arrive more likely late (e.g., the factor that the earliest arrive time is time-RANGE *divided by 2*) is due to the fact that IB trains are more likely to arrive late based on the historical statistics. In the base case study, the uniform distribution is used for pf. To simulate a realistic arrival distribution of IB trains by different day of the week, another *week factor* term[4] is added to both term in equation A.6. The actual arrival peak by the day of the week is usually on Tuesday, Wednesday, and Thursday, with off peak on Sunday, Monday, Friday, and Saturday. The arrival pattern is like a bell shape. The value of the week factor is positive for Sunday, Monday, and Tuesday, negative for Thursday, Friday, and Saturday, and zero for Wednesday.

- **ON_TIME_ARR** and **ON_TIME_DEPT** are parameters used to determine if an IB train is arrived at the terminal on time or if an OB train departed from the terminal on time. If the actual arrival or departure time is within the specified time (in minutes) of its scheduled arrival or departure time (from the operating plan), the train is considered as on time. Otherwise the train is not on time.

- **PROB_DELAY**, **MIN_DELAY**, **MAX_DELAY**, and **PROB_UNSCH_ARR** are parameters to determine if an IB train is delayed (due to bad weather, unscheduled maintenance, or accident), the minimum delay (in minutes), the maximum delay (in minutes), and the probability of a unscheduled train arrival, respectively.

- **INVT_LEVEL**, **CAR_L_PROB**, **CAR_M_PROB**, **INSP_LEVEL**, and **DB_OVER** are the parameters of the percentage of total cars from the operating plan that is to be initialized to the bowl tracks *before* the simulation model runs, the probability of a car whose traffic priority is low, medium, the percentage of a receiving track capacity that is full with cars to inspect the track, and the percentage of track capacity to conduct major double over operation, respectively.

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[4] This term is defined in the program rather than in the file.

- **VAR_IB_CARS_MIN2** and **VAR_IB_CARS_MAX2**, and **VAR_IB_CARS_MIN3** and **VAR_IB_CARS_MAX3**. They have the same meaning and usage as in Equation A.5, but they are used for flexible operation strategy and flexible short-run scheduling strategy, respectively.

- **DEADHEAD** is a parameter which is used to determine if deadhead in and out road crews and power units are allowed. If the value is 1, the deadhead is allowed. If the value is 0, it is not allowed. If the value is 2, partial deadhead is allowed.[5] The deadhead probability is specified by the parameter **DH_PROB**. If the road power units and crews are allowed to be deadheaded out, the following two parameters, **FIX_PWR_OUT** and **FIX_CRW_OUT**, specify the power units and crews that can be kept at the terminal without being deadheaded out. When the available units of road power units is greater than FIX_PWR_OUT, the extra units will be deadheaded out with later OB trains. When the available units of crews is greater than FIX_CRW_OUT, extra units of crews will be deadheaded out with later OB trains.

- **ADD_RES** determines if the terminal can add extra terminal resources. If the value is 1, then the terminal can add terminal resource at a fixed amount of time (3 hours in this case) before each shift. Otherwise no more terminal resource can be added. The criteria for adding terminal resource is specified by the following parameters: **Q_IBINSP**, if there are more than Q_IBINSP receiving tracks are waiting for IB inspection, then an additional IB inspection team is added; **Q_Hump**, if there are more than Q_HUMP inspected receiving tracks waiting for hump, an additional hump engine and crew is added;[6] **Q_ASSEMBLY**, if there are more than Q_ASSEMBLY OB trains waiting for assembly, an assembly engine and crew is added; and **Q_OBINSP**, if there are more than Q_OBINSP OB trains waiting for OB inspection, an additional OB inspection team is added.

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[5] It is true that when a terminal manager asks for some system resource, he or she is sometimes satisfied and yet sometimes is not satisfies.

[6] The effect of adding a hump engine and crew will reduce the fixed hump time, since the added hump engine can help the other engine move a string of cars toward to hump, hence reducing the fixed pushing time.

For the added terminal resources, if the next shift does not satisfy the congestion criteria, then the added resource is removed from the terminal operation.

PULL_FIXED	OUTPUT_DETAIL		
300	0		
SCH_ARR_RANGE	FLX_ARR_RANGE	FSS_ARR_RANGE	
60.0	240.0	120.0	
ON_TIME_ARR	ON_TIME_DEPT		
50	180		
PROB_DELAY	MIN_DELAY	MAX_DELAY	PROB_UNSCH_ARR
0.10	60	360	0.05
VAR_IB_CARS_MIN1	VAR_IB_CARS_MAX1		
0.90	1.10		
VAR_IB_CARS_MIN2	VAR_IB_CARS_MAX2		
0.98	1.02		
VAR_IB_CARS_MIN3	VAR_IB_CARS_MAX3		
0.95	1.05		
INVT_LEVEL	CAR_L_PROB	CAR_M_PROB	INSP_LEVEL
0.20	0.20	0.40	0.50
DB_OVER			
0.50			
DEANHEAD	DH_PROB	FIX_PWR_OUT	FIX_CRW_OUT
0	0.5	30	10
ADD_RES	Q_IBINSP	Q_HUMP	Q_ASSEMBLY
1	5	5	5
Q_OBINSP			
5			

A.1.12 Flexible short-run scheduling strategy file

This file specifies the **fixed time** period (in minutes) for planning purpose (e.g., what is the time period for developing the short-run plan) and the estimated **IB processing time** in minutes. The IB processing time is used to estimate the time required from an IB train's arrival until its end of hump thus the traffic from this IB train is available for OB connections.

FIXED_TIME	IB_PROC_TIME
480	300

A.2 Terminal simulation model scenario design

A.2.1 Define variables and their values

- IB traffic
  - Traffic volume (average number of IB trains/day)

l	20
m	22
h	24

  - IB arrival pattern (U(T-x/2, T+x), U: uniform distribution, T: scheduled arrival time, x: cell value in hours in the table)

	sch	fss	flx
l	1.0	2.0	4.0
m	2.0	3.0	5.0
h	3.0	4.0	6.0

  - Probability of IB train delays (amount delay = U(1, 6) hours)

l	0.05
m	0.15
h	0.25

  - IB traffic variation (U(N*(1-x), N*(1+x)), N: # cars from plan)

	sch	fss	flx
l	0.10	0.05	0.02
m	0.15	0.10	0.07
h	0.20	0.15	0.12

- Terminal capacity

	receiving tracks	departure tracks
l	10	8
m	12	10
h	14	12

- Terminal processing time
  - Fixed processing time (in minutes)

	yarding	insp	hump	pull	pull/blk	brk test
l	35	35	20	35	10	35
m	40	40	25	40	15	40
h	45	45	30	45	20	45

  - Processing time variation (U(T-x, T+x), T: processing time)

	yarding	insp	hump	pull	brk test
l	3	3	7	7	3
m	5	5	10	10	5
h	8	15	15	15	8

- Cutoff time (in hours)

	cutoff time
l	18
m	20
h	22

- Terminal queuing strategy FIFO, LIFO, Priority rule, Contribution rule

- Road crew and power inventory

	crews	power units
l	5	15
m	7	20
h	9	25

- Capability of deadheading road crews and power units

l	0.0(not allowed)
m	0.3(30% time allowed)
h	0.6(60% time allowed)

- Road crew rest time distribution (short time 2 hours and long time 8 hours)

	prob_short
l	0.6
m	0.4
h	0.2

- Road power preparation time distribution (short time 2 hours, middle 3 hours, and long 8 hours)

	prob_short	prob_middle
l	0.3	0.4
m	0.2	0.3
h	0.1	0.2

A.2.2 Define scenarios

See Table A.1

A.3 Terminal simulation model major output

A.3.1 Train statistics

IB_trns: Number of IB trains received;

Scenario	Terminal Parameter Variables									System Resource Variables			
	IB Traffic Variables				Processing Time Var		Terminal Queuing Str	Terminal Capacity	Cutoff	Pool	Deadhead	Crew Rest	Power Prep
	volume	arrival	delay	cars var	fixed time	variation							
Case 1	l	l	l	l	l	l	Contribution	h	l	h	h	h	h
Case 2	l	l	l	l	m	m	FIFO	m	m	m	m	m	m
Case 3	l	l	l	l	h	h	LIFO	l	h	l	l	l	l
Case 4	m	m	m	m	l	l	Priority	h	l	h	h	h	h
Case 5	m	m	m	m	m	m	FIFO	m	m	m	m	m	m
Case 6	m	m	m	m	h	h	Contribution	l	h	l	l	l	l
Case 7	h	h	h	h	l	l	FIFO	h	l	h	h	h	h
Case 8	h	h	h	h	m	m	Priority	m	m	m	m	m	m
Case 9	h	h	h	h	h	h	LIFO	l	h	l	l	l	l

Table A.1: Terminal Simulation Model Scenario Design

IB_On_time_trns: Number of IB trains arrived on time compared with the operating plan (e.g., train schedules) for scheduled and flexible operations and with the short-run plan (e.g., modified train schedules) for the flexible short-run scheduling (fss) operation;

IB_On_time_trns_fss: Number of IB trains arrived on time for flexible short-run scheduling operation compared with train schedules;

IB_trns_waited: Number of IB trains waited outside the terminal before entering the terminal;

OB_trns: Number of OB trains departed from the terminal;

OB_On_time_trns: Number of OB trains departed on time compared with the operating plan;

IB_trns_p_Sun to **IB_trns_p_Sat:** Number of IB trains planned to arrive from Sundays to Saturdays;

IB_trns_a_Sun to **IB_trns_a_Sat:** Number of IB trains actually arrived from Sundays to Saturdays;

A.3.2 Car statistics

IB_cars: Number of IB cars arrived at the terminal;

IB_on_time_cars: Number of IB cars arrived on time;

IB_on_time_cars_fss: Number of IB cars arrived on time for fss operation;

IB_h_cars: Number of high priority IB cars received;

IB_m_cars: Number of medium priority IB cars received;

OB_cars: Number of OB cars departed;

OB_h_cars: Number of high priority OB cars departed;

OB_m_cars: Number of medium priority OB cars departed;

Ms_cars: Number of OB cars missed their first connections;

Ms_h_cars: Number of high priority OB cars missed their first connections;

Ms_m_cars: Number of medium priority OB cars missed their first connections;

IB_cars_p_Sun to **IB_cars_p_Sat:** Number of IB cars planned to arrive from Sundays to Saturdays;

IB_cars_a_Sun to **IB_cars_a_Sat:** Number of IB cars actually arrived from Sundays to Saturdays;

A.3.3 Road power statistics

IB_pwrs: Number of IB locomotive units arrived (including deadhead in power units);

OB_pwrs: Number of OB locomotive units departed (including deadhead out power units);

DH_in_pwrs: Number of deadheaded IB locomotive units arrived;

DH_out_pwrs: Number of deadheaded OB locomotive units departed;

Pwr_pool: Number of available locomotive units at terminal at the end of simulation;

Pwr_srv: Number of serving locomotive units at terminal at the end of simulation;

Avg_pwr_time: Average locomotive yard time in hours;

A.3.4 Road crew statistics

IB_crws: Number of IB crews arrived (including deadheaded in crews);

OB_crws: Number of OB crews departed (including deadheaded out crews);

DH_in_crws: Number of deadheaded in crews;

DH_out_crws: Number of deadheaded out crews;

Crw_pool: Number of available crews at the terminal at the end of simulation;

Crw_srv: Number of serving crews at the terminal at the end of simulation;

Avg_crw_time: Average crew time in hours;

A.3.5 Terminal resources added

IB_insps_added: Number of IB inspection teams added during the simulation;

Hump_crws_added: Number of hump crews added;

Assmbl_crews_added: Number of assembly crews added;

OB_insps_added: Number of OB inspection teams added;

A.3.6 Average yard time performance

Avg_yd_time: Average yard time in hours;

Avg_yd_time_h: Average yard time for high priority cars in hours;

Avg_yd_time_m: Average yard time for medium priority cars in hours;

Avg_yd_time_l: Average yard time for low priority cars in hours;

Yd_time_less_30_hrs: The percentage of departed cars that spend less than 30 hours in the terminal;

A.3.7 Yard processing time performance

Yarding: Average yarding time in minutes;

IB_insp: Average IB inspecting time in minutes;

Humping: Average humping time in minutes;

Assembl: Average assembling time in minutes;

OB_insp: Average OB inspecting time in minutes;

Depting: Average testing and departing time in minutes;

A.3.8 Connection performance

Conn: Average connection performance compared with operating plan for schedule-adherence and flexible operations strategies and with short-run plan for flexible short-run scheduling strategy;

Conn_h: Average connection performance for high priority cars;

Conn_m: Average connection performance for medium priority cars;

Conn_l: Average connection performance for low priority cars;

Conn_plan Average connection performance for flexible short-run scheduling strategy compared with operating plan;

Conn_h_plan: Average connection performance of high priority cars for fss operation compared with operating plan ;

Conn_m_plan: Average connection performance of medium priority cars for fss operation compared with operating plan;

Conn_l_plan: Average connection performance of low priority cars for fss operation compared with operating plan;

Appendix B

The Major Input[1] and Output of the Network Simulation Model

B.1 Service lane network input file

B.1.1 Service lane network node file

ID	Type	Capacity	Arr_period	Dep_period	Fix_time	Var_time	Time_per_car
A	1	15	5.0	5.0	30.0	10.0	5.0
B	1	15	5.0	5.0	30.0	10.0	5.0
d	2	5	10.0	10.0	30.0	10.0	5.0
c	2	5	10.0	10.0	30.0	10.0	5.0
e	2	5	10.0	10.0	30.0	10.0	5.0
f	2	5	10.0	10.0	30.0	10.0	5.0

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[1] Terminal input files in the terminal simulation model are part of the network input but are not included here. The input files listed here are for the service lane network.

B.1.2 Service lane network arc file

ID	IB_nd	OB_nd	Length	IB_cap	OB_cap	Arr_prd	Dep_prd	IB_spd	OB_spd
101	c	A	100	10	10	10.0	10.0	45.0	45.0
102	d	c	50	5	5	10.0	10.0	45.0	45.0
103	e	d	50	5	5	10.0	10.0	45.0	45.0
104	f	e	40	4	4	10.0	10.0	45.0	45.0
105	B	f	60	6	6	10.0	10.0	45.0	45.0

B.1.3 Service lane network capacity for scenario runs

- Road crews and power units

	crews	power units
l	35	110
h	40	120

- Node capacity and arrival and departure time requirements

	int_cap	hump_cap	int arr_ & dep_period	hump arr_ & dep_period
l	4	12	12.0	7.0
h	7	15	8.0	4.0

- Line capacity and arrival and departure time requirements

	capacity	arr_period	dept_period
l	h value - 1	12.0	12.0
h	1 train/10 miles	8.0	8.0

- Line segment travel speed

	speed
l	40
h	50

B.2 Area network input file

B.2.1 Area network node file

ID	Type	Capacity	Arr_period	Dep_period	Fix_time	Var_time	Time_per_car
A	1	15	5.0	5.0	30.0	10.0	5.0
B	1	15	5.0	5.0	30.0	10.0	5.0
e	2	5	10.0	10.0	30.0	10.0	5.0
d	2	5	10.0	10.0	30.0	10.0	5.0
f	2	5	10.0	10.0	30.0	10.0	5.0
h	2	5	10.0	10.0	30.0	10.0	5.0
i	2	5	10.0	10.0	30.0	10.0	5.0
g	2	5	10.0	10.0	30.0	10.0	5.0
C	1	15	5.0	5.0	30.0	10.0	5.0

B.2.2 Area network arc file

ID	IB_nd	OB_nd	Length	IB_cap	OB_cap	Arr_prd	Dep_prd	IB_spd	OB_spd
101	d	A	60	6	6	10.0	10.0	45.0	45.0
102	e	d	40	4	4	10.0	10.0	45.0	45.0
103	B	e	100	10	10	10.0	10.0	45.0	45.0
104	A	f	80	8	8	10.0	10.0	45.0	45.0
105	f	g	50	5	5	10.0	10.0	45.0	45.0
106	g	h	60	6	6	10.0	10.0	45.0	45.0
107	h	C	60	6	6	10.0	10.0	45.0	45.0
108	B	i	60	6	6	10.0	10.0	45.0	45.0
109	i	C	50	5	5	10.0	10.0	45.0	45.0

B.2.3 Area network capacity for scenario runs

- Road crews and power units

	crews	power units
l	40	110
h	50	130

- Node capacity and arrival and departure time requirements

  same as in service lane network;

- Line capacity and arrival and departure time requirements

  same as in service lane network;

- Line segment travel speed

  same as in service lane network;

B.3 The major output[2]

For each origin destination pair, the major output are as follows:

#_trns: The number of trains run over the network during the simulation.

int_yard: The average yard time (in hours) each train spends at *intermediate* terminals during the simulation.

avg_line: The average line haul movement time (in hours) during the simulation.

avg_trip: The average trip time (in hours) of the trains from one hump terminal to another hump terminal during the simulation, which is the sum of the corresponding int_yard and avg_line.

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[2] The terminal output from the terminal simulation model is part of the output but is not included here.

#_delays: The number of trains delayed due to lack of road power units or crews before departing the hump terminals during the simulation.

avg_delay: The average delay (in hours) of the trains waited for road power units or crews before departing the hump terminals during the simulation.