

RAILROAD LINE CAPACITY, SCHEDULING, AND DISPATCHING MODELS:  
STATE-OF-THE-ART AND POSSIBLE EXTENSIONS

by

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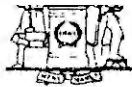
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ABSTRACT

The central thesis of this work is that the current set of models used in railroad capacity analysis, scheduling, and dispatching is such that there exists a gap between the large scale computer based models and sketch planning tools. The concepts of line capacity, train scheduling, and train dispatching are examined and placed in a conceptual framework known as Sequential Problem Solving. The current set of models is examined and evaluated, and it is found that there are no appropriate models for examining complex intersections or critical segments within a line. The system design for an event based simulation model to remedy this problem is presented, which uses alternative train priority schemes, thoroughly probabilistic event timing, and fleet meetable conditions. Conclusions and recommendations for future research are presented.

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I am particularly grateful to the officials in the Transportation Department at the Boston and Maine Railroad, who provided the funding and much of the data for this project. I am especially grateful to Stan Maxwell of that organization for his insistence that the product of the research be useful to practitioners of transportation planning.

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My colleagues and classmates in the Transportation Program provided me with intellectual challenges and good friendship. I value the latter more.

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CHAPTER 1  
KEY CONCEPTS

1.0 INTRODUCTION

Line capacity, train scheduling, and train dispatching are, as we shall see, intimately related processes in the operations of a railroad. Decisions made with respect to one of these processes can have a profound effect on the other two, and a host of general problems in railroad operations can be attacked by modifying one or several of the processes. Because of the important interrelationships among capacity, scheduling, and dispatching, considerable effort has been invested both by railroads and the academic community to developing computer-based models. These models have been relatively sophisticated and varied greatly in their complexity. It is, however, the central thesis of this paper that when the processes of capacity analysis, train scheduling, and train dispatching are placed into a problem-solving framework, a significant gap in the current set of models becomes evident. In particular, the current set of models either incur high costs as measured in staff and computational resources on the user, or their non-probabilistic nature does not reflect the uncertain nature of railroad operations. A possible extension to the current set of models is presented in the form of a system design for a thoroughly probabilistic model which can be run

in a microcomputer environment

The organization of this paper is as follows:

Chapter 1 introduces and defines several key concepts which are used throughout the paper. These include the processes of capacity analysis, schedule development, train dispatching, and sequential problem solving. In defining these concepts and explaining how they are made operational in railroads, the general techniques used to analyze and model them are discussed. Because this chapter draws its examples primarily from the Boston and Maine Railroad, the Chapter is prefaced with a discussion of that railroad's organization and structure.

Chapter 2 extends the the discussion of capacity, scheduling, and dispatching by characterizing the general types of models and categorizing a number of actual models. These categories include a number of basic structural and operational features, the computational characteristics, and whether and how the models are used. Chapter 2 then examines the models in light of the central thesis described above.

Chapter 3 presents and analyzes the system design for a model being developed for use on an Apple computer. The model is designed to employ a number of recent research advances by other modellers and to fill the gap in the current set of models demonstrated in Chapter 2

Chapter 4 presents the conclusions of this research and recommendations for further work to be done on the subject.

## 1 1 ORGANIZATIONAL RELATIONSHIPS ON THE BOSTON AND MAINE RAILROAD

The organizational relationships which govern the processes of capacity analysis, train scheduling, and train dispatching are of significance since, as we shall see, the three are closely related to the successful operation of a railroad. In this section the organizational structure of the Boston and Maine Railroad in 1981 is briefly described in order to make the examples used in the paper more understandable.

The Boston and Maine Railroad (B&M) is organized into various departments along functional lines (see Figure 1). The primary group for coordinating activities of interdepartmental concern is the Service Committee. The Service Committee, organized as part of a M.I.T. research project to improve service and operations planning (14), is composed of representatives of the Engineering, Labor Relations, Marketing, Mechanical, and Transportation Departments (see Figure 2). The Service Committee meets each month, with more frequent meetings scheduled as needed.

Transportation matters requiring intra-departmental coordination are handled on an ad hoc basis by the Transportation Department, either by informal meetings of the relevant officials or through the intervention of senior management of the Department. The organization of the Transportation Department is shown in Figure 3.

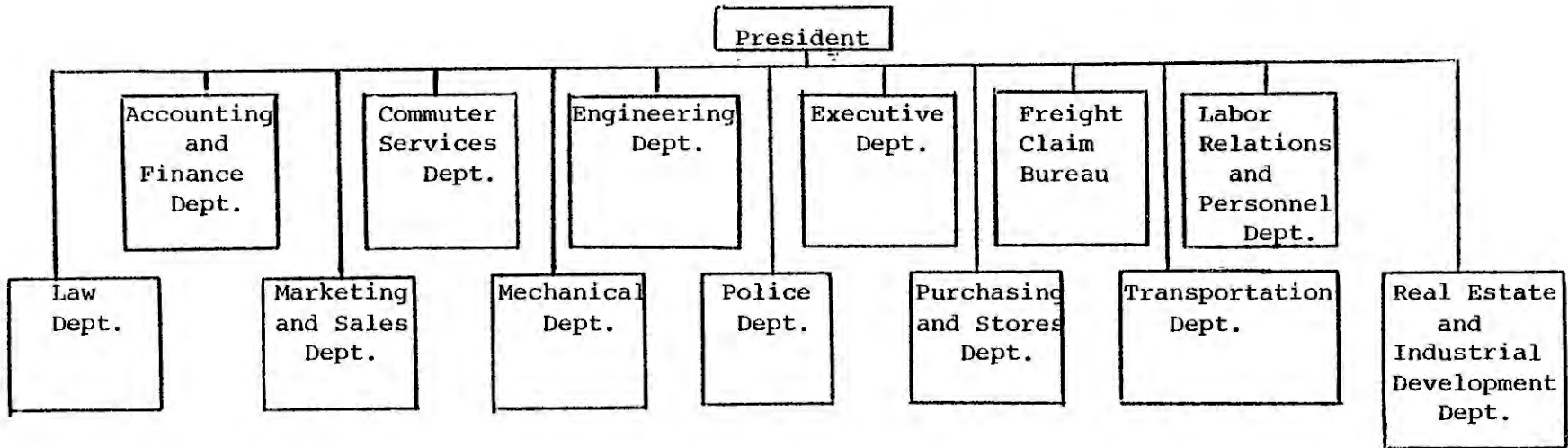


FIGURE 1

ORGANIZATION OF THE BOSTON AND MAINE RAILROAD

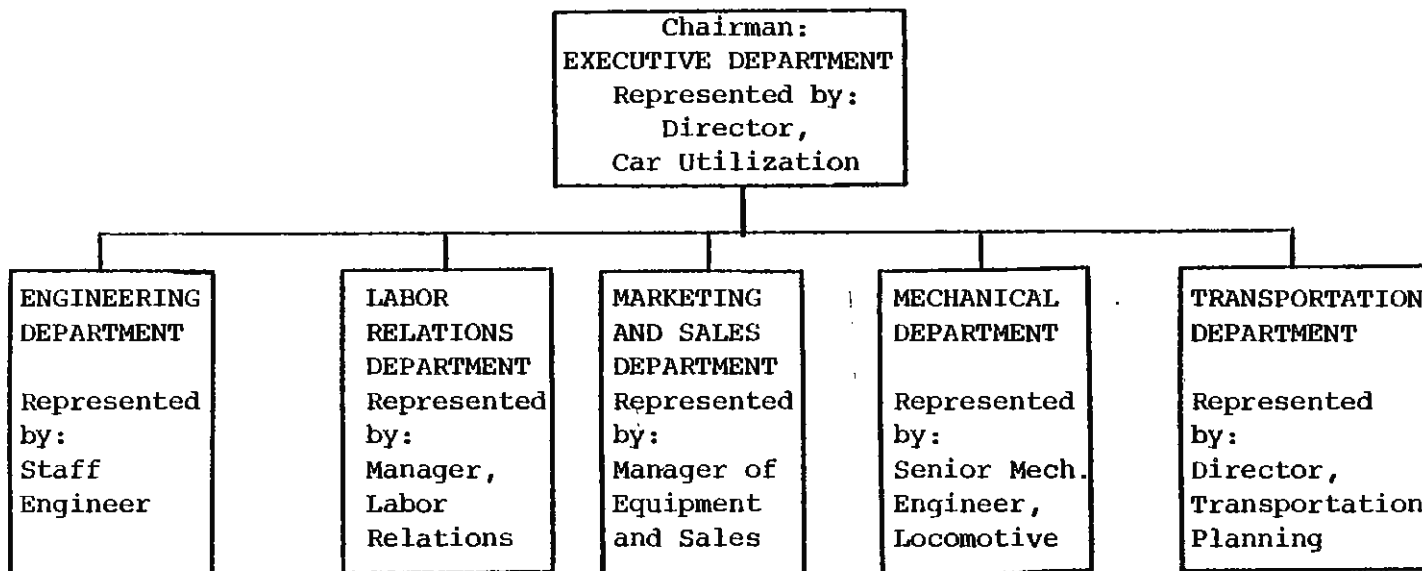


FIGURE 2  
SERVICE COMMITTEE,  
BOSTON AND MAINE RAILROAD

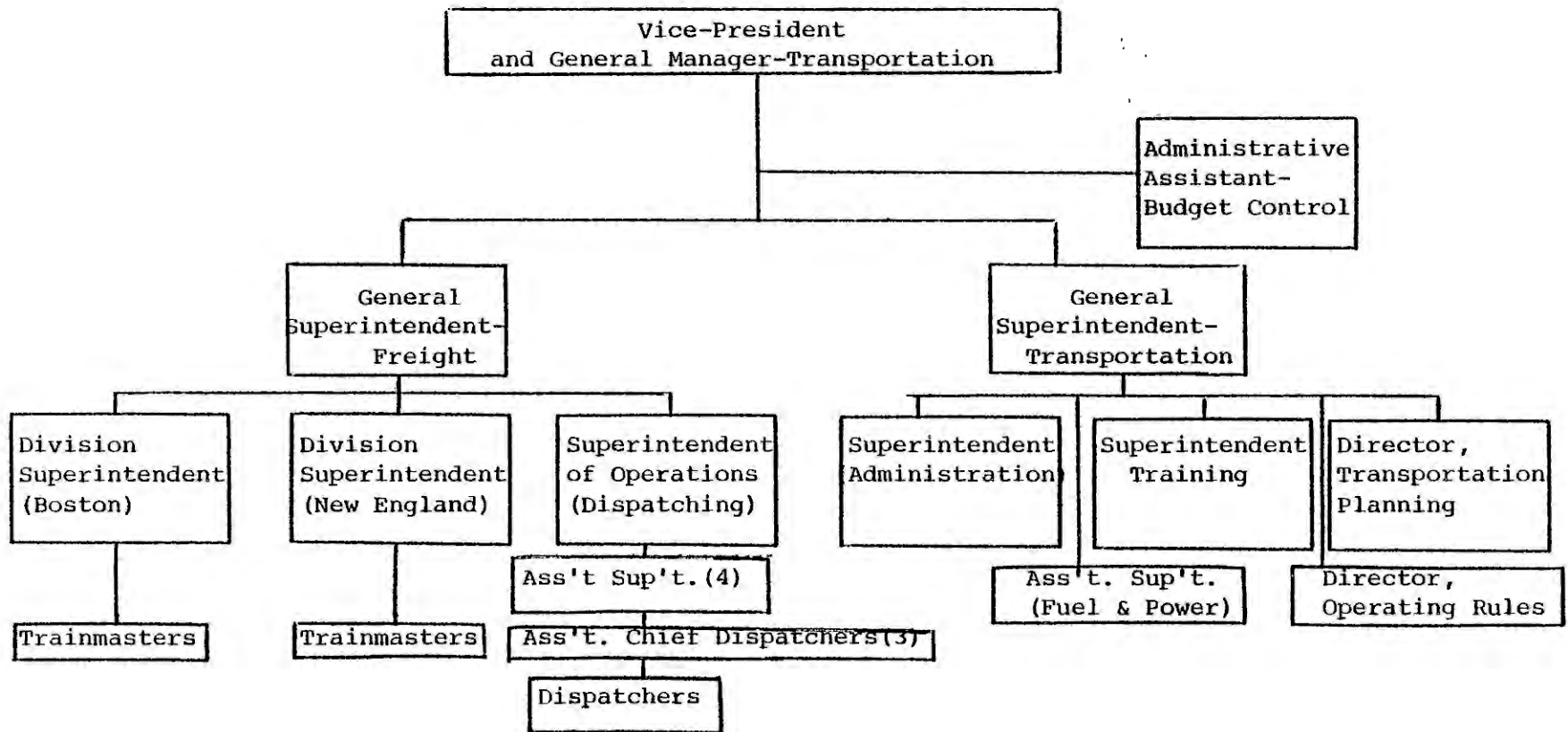


FIGURE 3

ORGANIZATION OF THE B&amp;M TRANSPORTATION DEPARTMENT

## 1.2 LINE CAPACITY

Line capacity, because of the interactions between scheduling, dispatching, and the physical characteristics of the line, can be defined in a number of ways. Akyilmaz (1) defines capacity as the "maximum volume which a link of any transport system can accomodate". Manheim (10) distinguishes between physical capacity, "the maximum number of units (trains) that can be squeezed through the system per unit time", and practical capacity, "a lower level such that delays are in some sense tolerable". Manheim goes on to point out that "although physical capacity is usually a well-defined concept, workable practical definitions of capacity must be related explicitly to levels of delay". Prokopy and Rubin (20) note the distinction between ultimate capacity (i.e. physical capacity), economic capacity, which they define as "an optimal balance between operating costs and capatal costs", operationally stable capacity, such that "a line could recover from a disruption in service of moderate length", and capacity based on "the maximum allowable time for the most delayed train to traverse the line". In the U.S., this latter definition might use the limits imposed by the Federal Hours of Service Law as its upper bound for typical operations.

It should be noted that all the above definitions with the exception of those for physical capacity incorporate some notion of maximum acceptable delay, and as such are operationally dependent upon both a dispatching strategy and

some level of schedule adherence.

Capacity can be viewed as the functional relationship

$$\text{Capacity} = f(\text{train length, speed, headway, distance between sidings, number of trains, communications system}),$$

such that capacity can be increased by increasing speed or train length, or by reducing headways, distance between sidings, or communications times between dispatchers and train crews. A number of authors have attempted to specify this general function with a particular formulation (cf. Martland (13), Morlok (15), Akyilmaz (1)). The logic behind such formulations generally falls into either of two categories: (1) worst section analysis, which recognizes that the practical capacity of a line segment can be no greater than that of the "worst" segment of the link, and (2) link average analysis, in which estimates of capacity are generated statistically by regressing the capacity against the above factors to provide a relationship between volume and level of service. Worst section analysis is particularly useful in understanding the theoretical relationships involved in the capacity of a rail line, since it provides insight into what factors can be changed to increase capacity. By way of example, consider the following formulation (note 1):

$$\begin{aligned} \text{capacity} &\leq 24nm/t[\text{fleet}] \\ &= 24nm(V*e)/((n-1)H+d+nmLc), \end{aligned}$$

where capacity is measured in cars per day,

$n$  = number of trains/fleet,

$t[\text{fleet}]$  = total time for the fleet to move across the single track segment in question,

$V$  = velocity,

$e$  = an efficiency factor incorporating the effective loss in velocity which occurs because of signal response time and dispatcher response time, measured as a decimal fraction (e.g., .95),

$H$  = headway between trains,

$d$  = distance across the single track segment in question,

$m$  = number of cars per train,

$L_c$  = length of an average car.

The formula first tells us that the practical capacity of the single track segment cannot exceed the physical capacity of the segment, but more significantly shows that there are several ways of increasing physical capacity:

1) increasing speed  $V$  (e.g., by using more power);

2) improving the signal or dispatcher response time (i.e. increasing  $e$ );

3) reducing  $H$  (better signals or schedules),

4) reducing  $d$  (i.e. increasing sidings or double tracking part of the segment);

5) increasing  $m$  (train length);

6) increasing  $n$  (trains/fleet).

Formulation of this functional relationship has at its basis the evaluation of a particular single segment (link) within a line. If the link is not the most constraining segment of the line, then estimates of capacity based upon the analysis of the link may be in error. The analysis further assumes that factors such as trains/fleet, headway, and velocity can be summarized by a single value. In many cases these numbers are not appropriate (as when, for instance, trains of radically different velocities are present in the system.) In such cases, simulation models may be more appropriate tools for analysis.

When the formulation is of the link average analysis, what is actually being estimated is the level of service in terms of expected delay. In such cases, the capacity is actually an indirect result from the relationships:

$$\begin{aligned} \text{capacity} &= \text{volume/unit time} \\ &= \text{service rate, and} \\ \text{delay} &= f(\text{arrival rate/service rate}) \end{aligned}$$

That is, practical capacity is viewed as the maximum number of cars which can be handled subject to a delay constraint, and is estimated using a delay model which informs the user of what level of volume results in the delay equalling the constraint. In Chapter 2, the reader will note several models which measure expected delay, and are used primarily as capacity models. Such models are of the type just described. Similarly, when computer-based simulation models are used, the configuration of the line is input, along with

a set of performance characteristics for trains across the line, a schedule, and a dispatching routine (algorithm). The output of such models is a measure of the simulated delay incurred by the system as a whole and the trains within the system. The analyst using these models to measure capacity continues to add trains until the delays incurred become unacceptable.

Each of the notions of capacity is useful, but the most appropriate definition depends on the reasons why a line is being analyzed. For purposes of capital investment decisions, the economic capacity might prove most useful, since it incorporates the trade off between increased capital costs and improved operating efficiencies. For some operations planning purposes, the maximum allowable trip time definition is useful, since schedule planners, as we will see, are particularly interested in avoiding "recrews", i.e. trains forced to stop before they reach their destinations because the crew has worked a full 12 hours. In the Northeastern U.S. the concern with network rationalization prompted by the high costs of track maintenance has led capacity analysts to generally ask the question, "how much excess capacity can be removed without causing undue congestion (delay)?" (See, for example, Harris (5).) Capacity analysis then becomes most useful in determining whether congestion can be expected for a given track configuration and the current schedule and for certain expectable or credible schedule increases. Other railroads,

particularly the coal and grain hauling roads, are concerned not only with the elimination of excess capacity, but the appropriate level of capacity to add to congested or potentially congested links, and are thus concerned with accurate prediction of future traffic levels on the potentially congested links. Akyilmaz states that if "congestion occurs at or near this volume, then information concerning capacity is useful for deciding the level of investment of adding new links to the network of the system or improving the existing links to meet the changed transport demand."

On the B&M, the Engineering Department performs capacity analyses, although in a study of any significance the output would so affect other departments that the study would be coordinated and managed through the Service Committee. (B&M has not undertaken a major capacity analysis since 1976, which was before the formation of the Service Committee. Since that time, all major capital projects, e.g., yard improvements, etc., have been managed through or coordinated with the Committee.)

### 1.3 TRAIN SCHEDULING

Train scheduling is the process by which the set of train schedules, or timetable, is developed. Generally for freight operations the schedule takes the form:

- departure time from origin station;
- blocks carried from origin station;
- arrival time at intermediate stops;

- work to be performed at intermediate stops;
- departure time from intermediate stops;
- arrival time at destination station;
- crew change points (if any).

A sample page of a timetable is shown in Figure 4.

Of considerably more interest is the process by which such schedules are actually developed. In the case of the Boston and Maine, the schedules are generated by the Transportation Planning Department after coordination with the Service Committee. In the following sections we will examine the process from the perspectives of:

1. Initiation of the schedule changing processes, i.e., who initiates it and why;
  2. The schedule acceptance process, which is an overall corporate level process involving several departments; and,
  3. The schedule development process, the selection of particular times and work assignments for particular trains.
- These processes, as we shall see, are actually interrelated.

### 1.3.1 Initiation of the Scheduling Processes on the B&M (Note 2)

In general, the processes are initiated either by senior operations management or by senior management from non-operating departments. Operations management seeks changes in schedules as a response to changes in traffic levels (in which case the initiator tends to be the Vice-President Transportation), or because of an obvious

MELA-A

MELA-A

Mechanicville to Lawrence

<u>DAILY</u>		<u>DAY</u>
Mechanicville	LV 1100	1
E Deerfield	SO 1400	1
Lowell	SO/PU 2000	1
Lawrence	AR 2100	1

Mechanicville

Take cars classified

- 1 E Deerfield (To include Groveton Oil & EDWH cars)
- 2 Nashua
- 3 Manchester
- 4 Concord
- 5 Montvale
- 6 Boston
- 7 W Cambridge
- 8 TOFC/COFC

E Deerfield

Set Off Block #1

Ayer - (Connect to EDCO)

Set off Blocks #2, 3, 4

Lowell

Set off Blocks #5, 6, 7, 8 (Connect to NABO)  
Take cars classified  
9 Lawrence

Revised 12/80

FIGURE 4

EXAMPLE OF A TIMETABLE PAGE

SOURCE: B&M

inefficiency, such as regularly missed connections or trains recrewing frequently. In this case the initiator is usually the Division Superintendent where the inefficiency occurs, or the General Superintendent-Freight.

Non-operations management initiates the schedule changing processes when there is a matter which requires coordination between several departments and acts through the Service Committee. They are likely to intervene in matters such as:

- significant changes in the corporate or network structure (e.g., mergers, acquisition of new lines, etc.);

- service related initiatives generated outside the Transportation Department (e.g., special piggyback trains);

- track maintenance requirements, which occur during warm weather months and necessitate that line segments under repair be removed from service for 8-10 hours per day.

Regardless of who initiated the processes, however, the schedule acceptance and schedule development processes are essentially standardized, with variations occurring in the degrees of emphasis placed on interdepartmental coordination.

### 1.3.2 The Schedule Acceptance Process

This process consists of six steps, which are capable of being iterated a large number of times:

1. The schedule changing processes are initiated.

2. A preliminary schedule is developed by the

Transportation Planning Department (see Section 1.3.3, The

Schedule Development Process, below).

3. The preliminary schedule is coordinated within the Transportation Department (General Superintendent, Superintendent-Transportation, Ass't. Superintendent-Power, Division Superintendents, Trainmasters in affected territories). Note that the Superintendent-Dispatching is not generally included in the list of actors consulted.

4. The schedule is modified in accordance with the input from the above consultations.

5. The schedule is submitted to the Service Committee and altered as necessary to meet any significant objections.

6. The new schedule is implemented upon its publication in a Bulletin.

The process is diagrammed in Figure 5.

This process as described is somewhat idealized in that many minor schedule changes are implemented by the various superintendents without going through the entire process, and in cases where the change is purely technical the consultation with the Service Committee often takes place after the change has already been implemented.

### 1.3.3 The Schedule Development Process

The process by which the actual times of departure, workloads, and crew change points are assigned to particular trains consists of ten steps. As in the schedule acceptance process, certain steps can be iterated several times until an acceptable result is found. The basic process is:

1 The current train schedule is "charted out". That is,

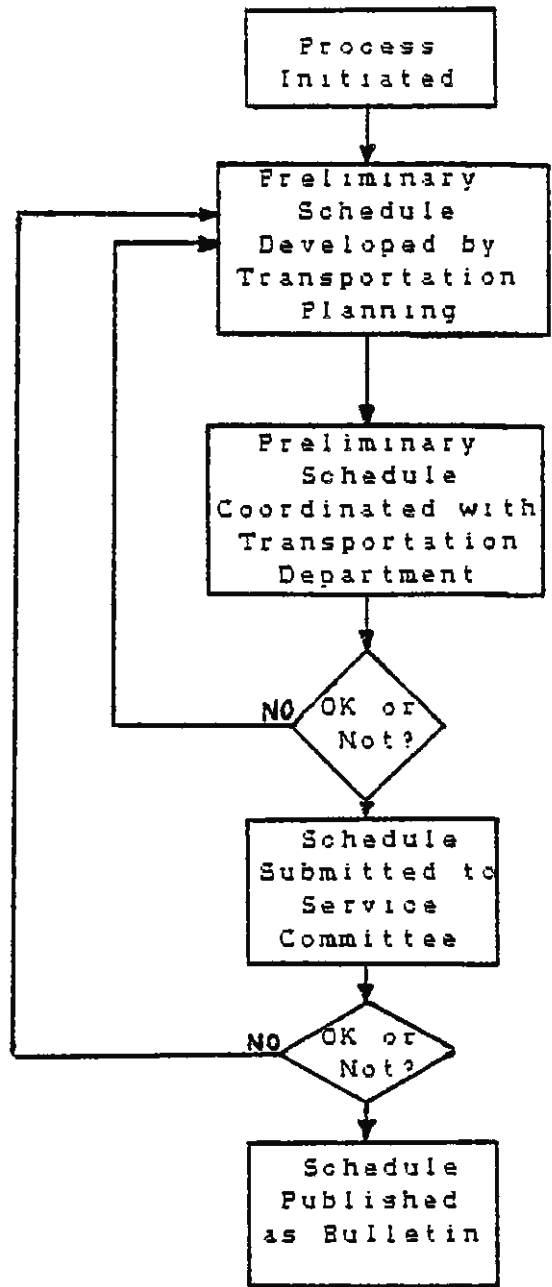


FIGURE 5  
THE SCHEDULE ACCEPTANCE PROCESS

the current timetable is updated with information derived from Bulletins published since the last publication of the timetable. This information is then organized into several large charts to permit easy inspection of current schedules. This step is not actually so obvious nor so simple as it may at first appear, since a large number of minor changes may have occurred since the previous use of the full schedule development process.

2. Trains are segregated into those expected to be changed or to be significantly affected, and those expected to be unaffected.

3. If the change is addition of a train, then an attempt is made to simply fill an existing gap or to evenly schedule the trains doing similar work. If, for example, there are trains leaving at 0800 hrs. and 1600 hrs., an attempt is made to place the third train at 2400 hrs.

4. If a train is to be deleted, then an attempt is made to avoid "schedule bunching" with large unserved gaps. It is generally undesirable to have two trains scheduled to operate over the same route within a few hours of one another with no other departures throughout the schedule day (e.g., 0800 hrs. and 1000 hrs. departures with no other service scheduled).

5. Critical locations and service requirements are noted (e.g., early morning congestion in Boston due to commuter trains), and if necessary, schedules are "backed out" from critical points.

6. A preliminary schedule is drawn up which meets the concerns noted in steps 3-5.

7. The preliminary schedule is tested for crew and power turns. Questions asked include:

-How long before power can be used again on another train?

-Is there adequate time for servicing power?

-How long are the crew layovers before crews can return to their home terminal? The time must be greater than 8 hours, but should be relatively short beyond that.

-Where should home terminals be located?

8. If the preliminary schedule is acceptable on the above grounds, then the schedule is tested for operational efficiency. On some railroads the test is performed using computer-based models such as those described in Chapter 2, while on other railroads the test is performed using manual techniques such as "eyeballing", which relies on the experienced judgement of participants in the process, or development of stringlines. Stringlines plot the path of trains across a track segment as a function of time. Since two trains cannot traverse single track segments in opposite directions during the same time frame, significant delays due to train meets are made apparent by substantial horizontal line segments in the plots. Some of the computer-based simulation models currently in use produce stringlines as outputs. An example of such a computer generated stringline is shown in Figure 6. On the B&M,

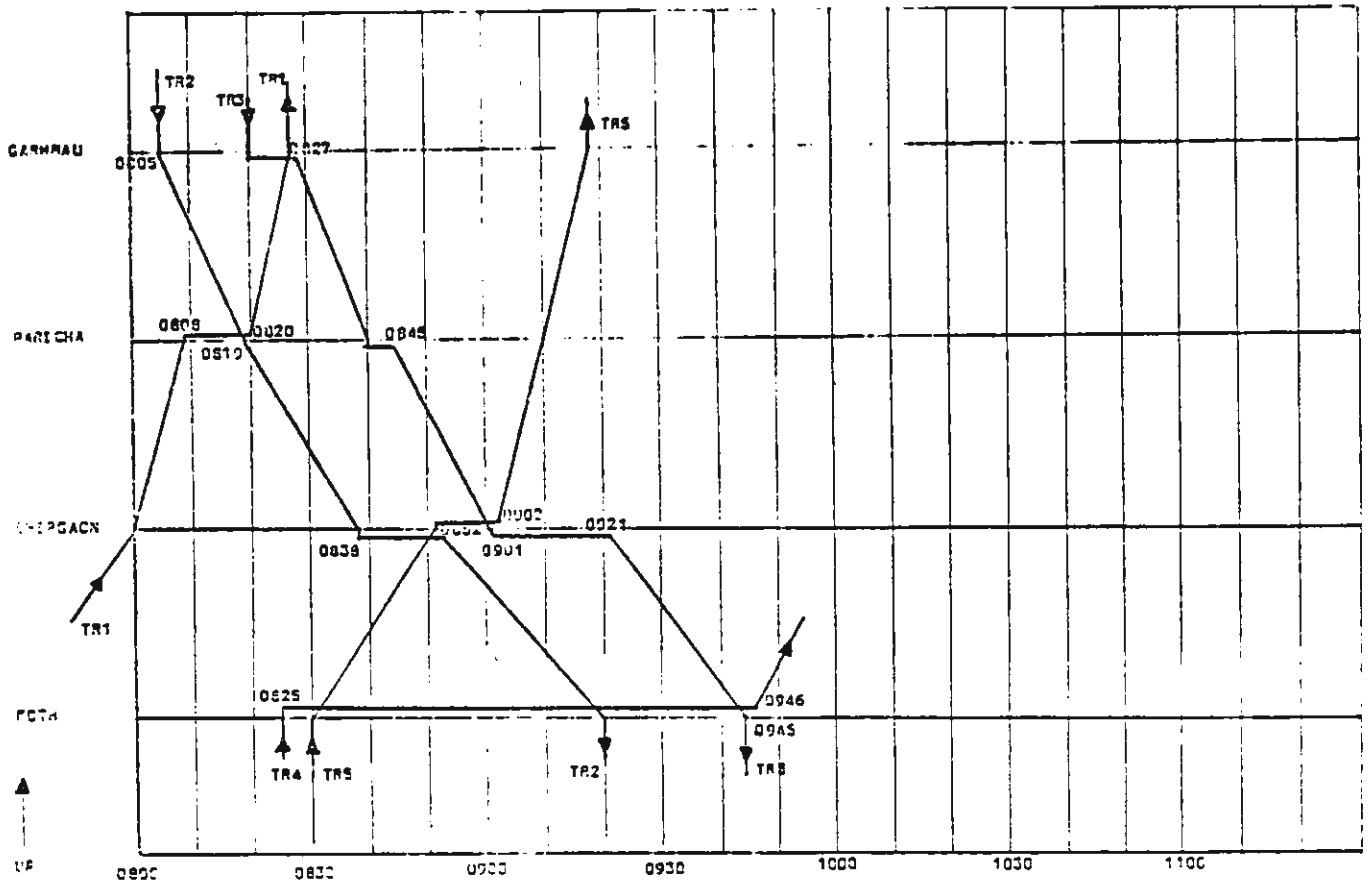


FIGURE 6

EXAMPLE OF A COMPUTER GENERATED STRINGLINE

SOURCE: Kant (8)

schedules are tested both by "eyeballing" and through use of manually drawn stringlines. Note that if manual techniques are used, then any uncertainty which is incorporated into the process comes about either through the ability of the planner/analyst to gauge uncertainty in an intuitive manner, or through building "fat" into the schedule, that is, by allowing more time between stations than can be expected under normal conditions. The use of "fat" in schedules was found to be common in schedule development on both the B&M and the Maine Central Railroad, and is believed to be widely used throughout the industry (Note 3).

9. The schedule is adapted if particularly troubling results occur in step 8, such as an inordinate number of trains arriving at the same place at the same time, or if trains cannot be expected to complete their runs without recrews, or if undesirable train connections result (This can be viewed as an iteration to Step 6.)

10. The schedule is finalized and written up in timetable form.

The process is diagrammed in Figure 7.

A few remarks concerning the above process are in order here. First, the reader will note that the process as described seeks to find an acceptable schedule, not an optimal one. One could argue that the ongoing process of making minor schedule changes under the prompting of the Transportation Department managers moves the schedule toward optimality, but a careful examination of this claim is

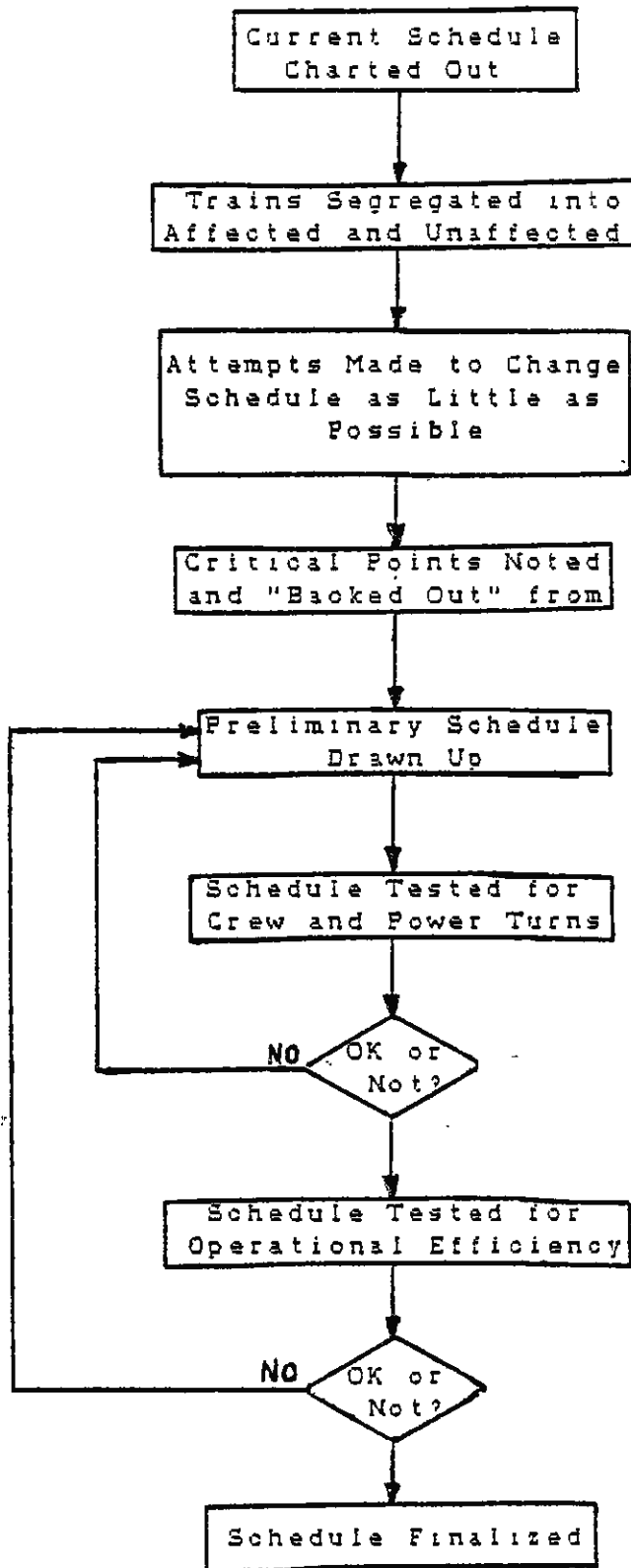


FIGURE 7  
THE SCHEDULE DEVELOPMENT PROCESS

beyond the scope of this paper. Second, the process described may appear to the reader to be rather slow and even laborious. In fact, it has been my observation that experienced schedulers can develop schedules which modify as many as three trains in a few hours. In larger modifications, as in that caused by the proposed "run-through" service between the B&M and the Maine Central, the majority of the three weeks spent in developing schedules acceptable to the management of both railroads was spent in determining what the constraints were and in negotiating what level of service was actually desirable. The actual assignment of times and workloads was accomplished in less than 3 days by a combined planning group of 6 persons. The actual impacts of the schedules developed, however, have yet to be tested under actual conditions (see Note 4).

#### 1.4 TRAIN DISPATCHING

Train dispatching is the process by which decisions are made about which train may occupy a particular segment of track at a given time. The dispatching decision begins with a request by either a yardmaster or trainmaster for permission for a train to enter a line segment (exit a terminal). This request may be relayed via a tower operator to the dispatcher with authority over that segment. If the line segment which the train seeks to enter is clear, the dispatcher approves the request. This message is forwarded to the train crew, usually both by radio communication and

by changing the signal facing the train to yellow or green. Once the train has entered the line, a similar process continues throughout the journey to the final destination. The train will face signals at key points such as changes from double to single track, at intersections with other lines, at major sidings, at the entrance to yard facilities, and throughout long sections of track where there is a possibility of overtaking another train. The primary concern of the dispatcher is to guarantee the safe operation of trains in his territory, with the secondary goal of avoiding unnecessary delays. As such, the dispatching decision is most critical when congestion is high and there are substantial numbers of physical changes (such as those described above). These conditions can be expected to result in large numbers of train meets, wherein two or more trains arrive at a segment of single track at the same time and one may proceed and the other must be held until the line is clear. Congestion effects can also result in overtakes, in which a train operating at a higher permitted speed (e.g., passenger trains) comes up behind a train with a slower speed. In this instance the dispatcher seeks to permit the faster train to safely pass the slower one so that it will not be needlessly delayed. The dispatchers generally are held responsible for recrows, and are therefore concerned also with minimizing delay incurred by trains at or near the 12 hour limit.

The procedure generally used to decide which train will

be delayed and which will not is the assignment of priorities. Priority allocation is a managerial decision, based on such factors as:

- type of train (passenger vs freight);
- size of train;
- traffic being carried (obviously, revenue traffic is generally given priority over empty car movements);
- distance to be travelled by the train;
- significance of connections the train must make.

On the B&M, priorities are assigned as follows (Note 5):

1. Passenger trains
2. Westbound through trains
3. Southbound through trains
4. Eastbound through trains
5. Northbound through trains
6. Westbound local trains
7. Eastbound local trains
8. All other trains.

This set of priorities is, however, subject to change in practice when circumstances dictate. A good example is the recent institution of a special piggyback train from Brattleboro Vt. to Boston. Because the Marketing Department was convinced that this train could only be effective if it arrived in Boston before 10:30 a.m., it was given priority over all non-passenger trains during the marketing test period. Similarly, the dispatchers frequently override the priorities if they believe that following them will result

in unnecessary delays for large numbers of trains or if there is a real possibility of a recrew. This is because management has been observed to intervene with criticism in cases of re crews or substantial delays by several trains.

The process is managed by a Superintendent who oversees four Ass't. Superintendents who supervise the actual work of the dispatchers. (On some railroads the Ass't. Superintendents' function is performed by a Chief Dispatcher.) The Superintendent-Dispatching reports to the General Superintendent-Freight. It is not surprising, then, that communications between individual dispatchers (who are in a position to have first-hand knowledge of how well a particular schedule is performing) and the persons with responsibility for developing schedules and capacity analyses should be limited. This situation is exacerbated by the environment in which the dispatcher works. Generally the dispatcher is found in a room surrounded by electronic equipment producing an almost constant flow of communications between himself, train crews, tower operators, and yard officials. As such, the dispatchers tend to be out of sight performing work of great complexity which most senior managers are not at all certain how to do. The selection process for dispatchers, in which the best clerks are chosen to become tower operators, and the best tower operators become dispatchers, coupled with the very great responsibilities conspire to convince most managers that as long as there are no serious problems (accidents or large

numbers of recrews) then the dispatchers should be left alone. On a small railroad such as the B&M, informal structures may exist which permit communications to flow in spite of the many potential barriers. In a larger corporation, communications failures such as these could easily result in unrealistic schedules or inefficient dispatching strategies. So long as the results are not catastrophic, such inefficiencies might continue indefinitely.

#### 1.5 SEQUENTIAL PROBLEM SOLVING

Many of the problems faced by railroad management can be viewed more accurately as problem solving processes than as direct implementations of the processes described in Sections 1.2-1.4. It is only when some symptom of a deficiency in the operations of a railroad has appeared that managers can reasonably be expected to invoke these processes. Consider, by way of example, the case of excessive recrews. The fact that a railroad is experiencing an unacceptable number of crews exceeding the Hours of Service Law is not, on the face of it, clear evidence that capacity of the link is too low, nor that the current schedule is faulty, nor that the dispatching strategy is wrong. It is only after an appropriate analysis of the current situation has been made that managers can conclude which, if any, of the processes are in need of change. The analysis of the current situation with an aim to correcting deficiencies or improving operations has been studied

extensively as a "problem solving process".

The general problem solving process has been characterized by Simon (in 19A, p.89) as consisting of three phases:

1) Intelligence phase: the definition of the problem and collection of relevant data;

2) Design phase: the generation and analysis of alternatives;

3) Choice phase: the selection of the best alternative from among those developed in the design phase.

This framework has been applied in a railroad environment by Philip in his study of car distribution decision support systems (19A). The applicability of this conceptual framework to capacity, scheduling, and dispatching related problems can be shown using the example mentioned in the first paragraph of this section. Consider again the case of a railroad incurring what it considers an unacceptable number of re crews. The intelligence phase might simply consist of defining the problem as: reduce the number of re crews without disrupting service or increasing overall expenses. Data collection might take the form of gathering together the "train sheets" (dispatching records) for the past several months. In the design phase a number of alternatives might be considered:

-split the trains experiencing the most re crews into two trains or crew assignments with an evenly distributed workload,

-improve signal systems on the line segments most prone to recrews;

-alter the dispatching priorities of trains along the relevant line segments;

-increase the number of sidings along the line segment;

-increase the level of supervision of train crews experiencing recrews."

After examining these and perhaps other alternatives, the decision maker may find that several of the choices might achieve the desired objective. The choice phase would consist of an application of experienced judgement to select the alternative which is viewed as "best".

Unfortunately, in the design phase of problem solving processes, the analysis of the various alternatives is not generally costless. This fact has led to an extension of the general problem solving process known as Sequential Problem Solving (SPS). Manheim (11) examined and applied SPS to the highway location decision process.

SPS differs from the general problem solving process in that the decision maker faces two choice sets:

1) Action set: the alternatives developed during the design phase, as above; and

2) Experiment set: a set of possible "experiments", or information generating activities, which attempt to reveal the consequences of the members of the action set. The members of the experiment set need not be limited to experiments in the classical scientific sense, but may

include items such as hiring consultants to undertake a study, executing a computer program, conferring with professional colleagues, and undertaking actual members of the action set on a limited basis (e.g., pilot projects) Members of the experiment set incur a cost, and generate a benefit to the decision maker in the form of better information in making his choice from the action set. The costs and benefits of any particular experiment need not (and probably will not) be linked in a correspondence

The decision maker in this case is faced with a sequence of choices: (1) whether or not to select any member of the experiment set; (2) if so, which experiment to undertake; (3) if not, which member of the action set to select. Item (3) is identical with the choice phase in the general problem solving process.

Presumably, a good manager will balance the costs and benefits of an experiment against the importance and permanence of the final decision. Thus we would expect to find a greater willingness to spend money for studies in support of a decision on whether and where to build a new line than for a decision on whether or not to alter the departure time of a local train by one hour. Figure 8 provides examples from capacity, scheduling, and dispatching related problems and the levels of analysis (a proxy for the experiment set). Figure 9 generalizes from the examples in Figure 8. Note that as the level of importance and permanence increases, the number of tools suitable for

LEVEL OF EXPENSE OR PERMANENCE			
	HIGH	MEDIUM	LOW
<u>CAPACITY</u>	BUILDING A NEW RAIL LINE	CONVERTING A SECTION OF TRACK FROM SINGLE TO DOUBLE	ADDING A SIGNAL TO A SINGLE LOCATION
ANALYSIS LEVEL	-DEMAND FORECASTS -ENGINEERING STUDIES -LAND STUDY -FINANCIAL STUDIES -CAPACITY STUDIES	-CAPACITY STUDIES (MODELS) -CONSULTATION WITH OPERATIONS DEPT.	-HISTORICAL REVIEW -SIGNALLING MODELS -CONSULTATION WITHIN DEPT
<u>SCHEDULING</u>	REVISING ALL SCHEDULES IN RESPONSE TO SEASONAL CONDITIONS	ADDING OR DELETING A SINGLE THRU FREIGHT TRAIN	CHANGING THE TIME ON A SINGLE TRAIN BY A SMALL AMOUNT
ANALYSIS LEVEL	-DEMAND FORECASTS -CONSULTATION WITH OTHER DEPTS. -SIMULATION MODELS -SERVICE PLANNING PROCESS	-STRINGLINE DIAGRAMS -CONSULTATION W/ MARKETING DEPT. -CONSULTATION WITH TRAIN-MASTERS IN AFFECTED AREA	-HISTORICAL REVIEW -CONSULTATION WITH DIVISION SUPERINTENDENT
<u>DISPATCHING</u>	INTRODUCING CENTRALIZED TRAFFIC CONTROL	ADDING A NEW SIGNAL TO A KEY LOCATION	ALTERING PRIORITIES FOR A FEW TRAINS
ANALYSIS LEVELS	-COST/BENEFIT STUDIES -REVIEW OF OTHER RR'S EXPERIENCES -CONSULTATION WITH UNION & OTHER DEPTS. -SIMULATION MODELS	-SIGNALLING MODELS -CONSULTATION W/ENGINEERING AND OPERATIONS DEPTS. -CONSULTATIONS WITH TRAIN-MASTER IN AREA AFFECTED	-HISTORICAL REVIEW

FIGURE 8  
LEVELS OF DECISIONS AND LEVELS OF ANALYSIS  
(EXAMPLES)

Level of Expense  
or Permanence

TOOLS	HIGH	MEDIUM	LOW
Historical Review	✓	✓	✓
Manual Calculations	✓	✓	✓
Intra-Departmental Coordination	✓	✓	✓
Inter-Departmental Coordination	✓	✓	
Pilot Programs	✓	✓	
Use of Outside Experts	✓		
Computer-Based Analysis	✓	(✓)	
Coordination With Outside Parties (e.g. Gov't, Financial, Shippers)	✓		

FIGURE 9  
RELATIONSHIP OF LEVEL OF EXPENSE AND METHODS OF ANALYSIS

analysis also increases.

Implicit in the use of such a framework such as SPS is that the experiment set is not empty. If the experiment set is empty or very sparsely populated, the decision maker may be reduced to making decisions without full information, or with information acquired only at an excessive cost. The question of whether the tools which exist are adequate for capacity, dispatching, and scheduling can only be properly addressed after the current state of the art is examined. That is the subject of Chapter 2.

## CHAPTER 2

### REVIEW OF MODELS

#### 2.0 CHAPTER STRUCTURE

In this chapter the analytic tools available for capacity analysis, train schedule development, and analysis of dispatching strategies are examined. Section 2.1 presents an overview of the characteristics of the 5 general types of models. Section 2.2 examines the features of the particular models in use in the industry. The chapter concludes with an examination of the models in light of the central thesis of this paper, namely that the current set of tools (i.e. models) has a gap which can be filled by the development of a new model.

The models and techniques selected for inclusion in this chapter reflect the author's concern with line models, and for this reason models which examine rail operations and schedules but do not explore performance across the actual line segment are not included. No reflection on the quality of any model is intended by its exclusion.

#### 2.1 GENERAL CLASSES OF ANALYTIC TOOLS

In order to provide an overview of the current analytical tools in use, it is useful to group them into general categories. The categories used in this section are:

1. Aggregate capacity and delay/volume models (single

equation models);

2. Optimization models;

3. Thoroughly deterministic simulation models,

4. Random entry, deterministic movement simulation models;

5. Thoroughly probabilistic models.

Members of the first two categories have perhaps the least in common, but there are enough similarities within the groupings that there is value in grouping the models.

For each of the categories the following format is used:

-definition of the category

-example

-strengths

-restrictions on use

-conclusions.

#### 2.1.1 Aggregate Capacity and Delay/Volume Models (Single Equation Models)

1) Aggregate capacity and delay/volume models are those models which are characterized by one or at most a few equations which specify the relationship between the capacity of a line and the level of service across the line (measured in terms of expected delay or the number of trains of a given size). As was stated in Section 1.2, such models generally are built around the average characteristics of the line. Frequently the models are the result of an analysis of the current delays on a given line segment,

using regression analysis or a similar estimation technique

2) Example: Akyilmaz formulation,

$$D = (aXPd) / (1-bXd),$$

where:

D : delay over a line segment, measured in time/train-km.

X : volume, measured in trains per day,

d : distance between sidings, measured in km,

P : number of priority trains per day,

a,b : constants in D,X,P space.

3) Strengths: The three greatest strengths of models of this type are found in the ease of use, computational efficiency, and strong theoretical underpinnings. The user of such a model need only gather recent data on the line in question to calibrate the model, and can perform the computations on a pocket calculator. The strong theoretical foundations are of particular note, since the formulation can, depending on which factors are incorporated into the model, provide some insight into the relative value of various strategies.

4) Restrictions: The models of this category have a number of characteristics which restrict the uses to which they can be usefully applied. The models assume that the past dispatching strategies will continue to be followed on the line, since the dispatching strategy is essentially ignored. The models also assume that the line segment in question is relatively homogeneous, such that sidings are uniformly spaced, trains are uniformly timed, and conditions

do not vary from day to day. The output of the models do not provide any information on the location of train delays or of the particular trains which experience delays. If the user seeks information on these matters it is advisable to use a model from another category.

5) Conclusions: Models of this type are most useful as sketch planning tools in which the uncertainty of day to day operations are not a matter of concern, and in which a number of simplifying assumptions are not troubling

#### 2.1.2 Optimization Models

1) This category includes those models which attempt to optimize rail system operations by minimizing train delays or minimizing a cost function which trades off between various operating costs and capital costs. A set of constraints is given which might include the configuration of the lines, maximum train lengths, train arrival and departure "windows", which yards must be serviced by which trains, etc. The result is an "optimal" schedule which meets the constraints. In practice, models which incorporate constraints which are realistic rapidly become very difficult to solve. Those "models" which are essentially attempts to apply various operations research techniques in an extremely simplified or stylized network or train schedule (e.g. Frank (4)), but have not found application in the North American railways are not examined. They would, however, properly form a subset of this class of models, and the author notes that the techniques explored in their

development have been used in some of the models in this class.

2) Example: Peterson and Merchant (17)

3) Strengths: When models of this type are adequately specified, a number of solution techniques developed for other disciplines and other problems can be applied. This is particularly true of developments in Operations Research and Management Science. Thus a breakthrough in a field other than transportation can be exploited by the developer of a model in this category. Recent advances in related disciplines and in computer technology are rapidly expanding the size and structure of problems which this type of model can solve. Even in their present state, models in this category can provide an analyst with insight into what a desirable schedule or network configuration might look like, thus giving the analyst a potentially better starting point for the iterative processes described in Chapter 1.

4) Restrictions: Models of this sort tend to become increasingly difficult to solve as the constraints become more realistic, so the user must either sacrifice realism or computational ease. The models also tend to require a high level of sophistication on the part of the analyst with respect to operations research techniques and methodologies. The models generally output a schedule and service strategy, but do not incorporate the uncertainties of day to day operations, and as such are wholly dependent on the accuracy and representativeness of the data embodied in the

constraints. Models of this sort provide no information on the expected delay by train or location other than that input as constraints

3) Conclusion: Models in this category are likely to be of most use to railroads with analytic staffs with a high degree of familiarity with operations research, but even in these cases, the outputs of the models are more likely to serve as a starting point than to provide actual schedules.

### 2.1.3 Thoroughly Deterministic Simulation Models

1) These models are those which use standard discrete event simulation techniques to "move" a scheduled set of trains across a given network in accord with a set of logical operations rules. Such models have as inputs a set of train schedules and priorities, a line configuration, and a dispatching algorithm, or group of rules for deciding which train may move at any given time. The inputs may also include a group of engineering based rules for computing the velocities of trains dependent upon the size, weight, and power consist of the train. As the trains are "moved" by the computer, the results are recorded and reported to the user in the forms of statistics and, in some cases, stringline diagrams. In the thoroughly deterministic case all trains leave at the scheduled time, the travel time for a given train across each track section is fixed, and the priorities assigned to the trains are held fixed throughout the run of the model. Thus a single run of the model tells the user as much as could be learned from multiple runs of the same

schedule

2) Example: Train Simulation/Capacity Model, by  
Transportation Data Systems

3) Strengths: Because of the thoroughly deterministic nature of the routines this type of model tends to be extremely computationally efficient and simple to use. The computational efficiency permits the models, in principle, to produce relatively sophisticated output while still keeping computer usage relatively low. Such models can generally be upgraded to those described in Section 2.1.4 with ease. Models of this category provide at least as much information as manually drawn stringline diagrams in far less time.

4) Restrictions: The thoroughly deterministic nature of the models precludes them from capturing any of the uncertainty which characterizes rail operations in the U.S. If the user is concerned with the implications of a schedule or line configuration under conditions other than the "ideal" (i.e. strict adherence to schedule at originating terminals), this group of models will not provide such information.

5) Conclusion. Computational efficiency makes these models potentially very useful for sketch planning or for replacing manually drawn stringlines. The failure to capture uncertainty would make it difficult for the user to have a great deal of confidence that the results represent day to day performance of a schedule or line configuration under

actual conditions.

#### 2.1 4 Random Entry, Deterministic Movement Simulation Models

1) These models are virtually identical to those described in Section 2.1.3 except that they attempt to capture the uncertainty by allowing departure times from the origin station to vary according to a probability distribution. In at least one case, the re-entry into the system from intermediate stops can also be randomized. The actual movement across any track segment and the dispatching routines are thoroughly deterministic.

2) Example: ICC RSPO Line Capacity Model

3) Strengths: at least some of the uncertainty of rail operations is captured. When properly designed, the models in this category retain much of the computational efficiency of the models in Category 3. Further, models of this sort are already in use or in the process of being applied at a number of railroads, so staffs within the industry are comparatively familiar with them.

4) Restrictions: Not all of the uncertainty faced in rail operations is attributable to the departure onto the track segment from a station. The models in this category vary greatly in their ability to handle levels of congestion, in their computational requirements, and in the degree of usage they have received.

5) Conclusions: Some of the models of this category have shown themselves to be very useful in line capacity analyses. The presence of staffs capable of utilizing the

models on the various railroads represents a considerable "sunk cost" and suggests that these models will continue to be widely used in the rail industry. The failure to capture the randomness in the movement of trains suggests that the analyst be careful in using them to analyze a particular intersection or short segment within a larger network, particularly under peak congestion conditions

### 2.1.3 Thoroughly Probabilistic Simulation Models

1) This category actually consists of only one model at this time, but can be expected to expand with computational resources available to rail staffs. The model extends the random entry characteristic of the models in Section 2.1.4 to include randomness in virtually every aspect of operations. In addition to specifying schedules, dispatching routines, and line configuration, the user inputs probability distributions for almost all the events, including yard work times, link travel times, etc. The model selects from the distributions each time an event occurs, and the events take on a randomness which is very similar to reality.

2) Example: Train Meet Calculator, by St. Louis San Francisco Railway

3) Strengths: The model goes considerably further in capturing the stochastic nature of reality than any of the other models described, and is capable of providing the statistical likelihood of many of the events which the other models must take for granted.

4) Restrictions: The models requires large amounts of information to accurately generate the probability distributions for the various events. This can result in high costs to set up the model in a way which approximates reality. The fact that so many events are simulated in probabilistic terms also implies fairly high computation requirements. Finally, because of these restrictions the network that can be simulated is considerably more restricted than those modelled less realistically.

5) Conclusion: This type of model is an extremely promising development, particularly as computational capabilities are improved. The user must be aware that the information requirements and the skill levels needed to use the model effectively may exceed the capabilities of some railroads. Similarly, the current burdens may exceed the scope of the problem to be analyzed in many cases.

## 2.2 PARTICULAR MODELS

In this section the various features of actual models in use by North American railroads are examined. Because the purpose of this section is to provide a basis for evaluating the central thesis of the paper, the models are examined in light of the following criteria:

1) Primary function of model (i.e. capacity analysis, train scheduling, dispatching analysis).

2) Probabilistic elements (if any): What features or elements are used to capture or model uncertainty?

3) Size of network handled/use of actual configuration.

What is the maximum size of the network which the model is capable of analyzing; if available, the largest known application is referenced. if the actual configuration of the line is used, it is so specified.

4) Maximum number of trains handled: As above, if available, the largest known application is referenced.

5) Time frame generally modelled: one day, one week, one month, etc.

6) Is the model in use? If so, by whom, with any relevant details of the application.

7) Computer language used.

8) Dispatch logic: 2 aspects of the dispatch logic are examined, conflict resolution and priority allocation. Conflict resolution is the means by which the model determines whether or not a move is feasible, and whether or not the move will result in a line blockage. The three methods for avoiding line blockages are:

1. Move all the highest priority trains first and then "fill in" the remaining available "slots" with lower priority trains. This includes "first in, first out" schemes in which all trains have equal priorities, de facto.

2. Multiple look aheads- The model examines the next several segments of track to determine whether or not a higher priority train will conflict with the proposed train move. This method is the most commonly used, but the computation time grows rapidly with the number of look aheads used. The trade off is that the likelihood of line

blockages is reduced as the number of segments looked ahead to is increased.

3. Fleet meetable conditions: This method, developed by Peterson and Taylor (18), tests the network for sufficient conditions for a move's feasibility without inducing a line blockage. Basically, the opposing fleet of trains relative to the proposed move is tested for their ability to complete their route. It has been implemented in a computationally efficient way, but cannot guarantee that the dispatch selected is an "optimal" one.

Priority allocation is the means by which priorities are assigned to trains as the simulation progresses. If the train priorities are set throughout the simulation at the level assigned initially by the user, the allocation is static. If the program is capable of increasing the priority in response to changed circumstances, the priority allocation is considered dynamic.

9) Cost per run (if available): Measured in either cpu time or dollars. Whenever possible, a benchmark of a 100 mile line segment with 20 sidings and 24 trains per day has been used.

10) Cost of acquisition (if available).

11) Comments: Any particular features which might distinguish the model from other models in the same class. Where available, remarks concerning the experience of users are included.

To facilitate the examination of the models, I have

sorted them into the categories defined in Section 2.1.

1. Aggregate capacity and delay/volume models (Figure 10),
2. Optimization models (Figure 11);
3. Thoroughly deterministic simulation models (Figure 12);
4. Random entry, deterministic movement models (Figure 13);
5. Thoroughly probabilistic models (Figure 14).

## 2.3 STATE-OF-THE-ART AND THE CENTRAL THESIS

The central thesis of this paper as outlined in Section 1.0 is that there exists a gap in the techniques and tools available to the analyst who examines issues of capacity, scheduling, and dispatching, and that this gap can be filled by the development of a new model. The reader will recall the charts presented in Section 1.5, which matched the tools and techniques with the various levels of importance and permanence attached to managerial decisions. For significant investments in capacity, major changes in schedules, and substantial capital investments to improve train dispatching, there are a number of types of analysis available. These range from the sketch planning tools discussed in Section 2.1.1 to the various simulation models in Sections 2.1.3-5. The costs also carry a wide range, as measured both in computational burdens and information requirements. Presumably, for an investment of several millions of dollars or affecting the level of service for an

NAME/ SOURCE REFERENCE	PRIMARY FUNCTION	PROBABIL. ELEMENTS	TYPE & SIZE OF NETWORK		NUMBER OF TRAINS	TIME FRAME	DISPATCH LOGIC			COST PER RUN	IN USE?	COMMENTS
			USE OF ACTUAL CONFIG. ? (YES/NO)				CONFLICT RESOLUTION TYPE	PRIORITY ALLOCATION	COMPUTER LANGUAGE			
AKYILMAZ FORMULA (1)	DELAY (CAPACITY)	NONE	SINGLE LINE NO LIMITS (NO)		NO LIMITS	1 DAY	NONE	NONE	STATIC	NOMINAL	YES, IN TURKISH RAILWAY STUDY	DELAY=F(#OF TRAINS,# OF PRIORITY TRAINS,# OF SIDINGS)
LANG FORMULA (6)	TRAVEL TIME (CAPACITY)	NONE	SINGLE LINE NO LIMITS (NO)		NO LIMITS	1 TRAIN TRIP	NONE	NONE	NONE	NOMINAL	NO	TOTAL TRIP TIME= UNOBSTRUCTED TRIP TIME+ AVG.DELAY/ MEET * NO. OF MEETS
MARTLAND FORMULATION (13)	EXPECTED DELAY	PROBABILITY THAT A SIDING WILL BE AT CAP- ACITY	SINGLE LINE NO LIMIT (NO)		NO LIMITS	1 SCHEDULE DAY	NONE	NONE	NONE	NOMINAL	NO	EXPECTED TOTAL DELAY = NUMBER OF SIDINGS * PROB(IN USE) + EXPECTED DELAY IF MEET
FEAT, MARWICK MITCHELL PARAMETRIC ANALYSIS (16,20,NOTE 1)	CAPACITY	NONE	SINGLE LINE (CAN BE SUMMED FOR NETWORK) (NO)		NO LIMITS	1 DAY	PL/1	NONE	NONE	UNKNOWN	HAS BEEN USED FOR FRA STUDY	USES AVG. SIDING SPACING, AVG. SPEEDS, AVG. TRAIN SIZE AVG. DELAY/ MEET

CATEGORY 1 MODELS  
SINGLE EQUATION MODELS

FIGURE 10

NAME/ SOURCE REFERENCE	PRIMARY FUNCTION	PROBABIL. ELEMENTS	TYPE & SIZE OF NETWORK		TIME FRAME	COMPUTER LANGUAGE	DISPATCH LOGIC			COST PER RUN	IN USE?	COMMENTS
			USE OF ACTUAL CONFIG.? (YES/NO)	NUMBER OF TRAINS			CONFLICT RESOLUTION TYPE	PRIORITY ALLOCATION				
OPERATIONS PLANNING MODEL/ SOU. PACIFIC RR. (3,21,NOTE 2)	SCHEDULING	NONE	140 LINKS, 20 SIDINGS/ LINK (YES)	200 TRAINS	1 DAY	FORTRAN	HIGHEST PRIORITY TRAINS FIRST	STATIC		UNKNOWN, SAID TO BE 8 P. "SLOW", WHICH IMPLIES HIGH CPU COSTS	YES, BY MOPAC AND (SEVERAL TIMES PER YEAR)	RUNS A DET- ERMINISTIC SIMULATION AND ADDS POWER TO MAINTAIN SCHEDULE, THEN OPT- IMIZES POWER USE.
OVER THE ROAD SIM- ULATION/ MISSOURI PACIFIC RR. (3,21)	CAPACITY	NONE	SINGLE LINE NO LIMITS (YES)	NO LIMITS	1-30 DAYS	FORTRAN	SEEKS MIN. DELAY CHOICE BY TRYING THE POSSIBLE MOVES	DYNAMIC		7 DAYS OF BENCHMARK TOOK 5 MIN CPU TIME ON AN IBM 370	YES, BY MOPAC AND SOUTHERN	USES DETER- MINISTIC SIMULATION THEN TRIES TO REDUCE DELAY BY ALTERNATE MEET/OVER- TAKE OPTION USED IN EVALUATING SIDINGS & CTC CHANGES
PETERSON & MERCHANT MODEL (17)	EXPECTED DELAY	NONE	SINGLE LINE (NO)	SEE COMMENTS	1 DAY	N.A.	N.A.	N.A.		UNKNOWN	TESTED ON A CANADIAN RAILROAD	DETERMINES # OF TRAINS TO RUN, NOT TIMETABLE; COMPUTATION TIME GROWS RAPIDLY W/ # OF TRAINS
G.W. ENGLISH MODEL (2)	EXPECTED DELAY	COMPUTES PROB. OF DELAYS OCCURRING & DURATION	SINGLE LINE (YES)	NO LIMITS EXPRESSED	1 DAY	N.A.	N.A.	STATIC		UNKNOWN	NO	

CATEGORY 2 MODELS  
OPTIMIZATION MODELS

NAME/ SOURCE REFERENCE	PRIMARY FUNCTION	PROBABIL. ELEMENTS	TYPE & SIZE OF NETWORK		NUMBER OF TRAINS	TIME FRAME	COMPUTER LANGUAGE	DISPATCH LOGIC		COST PER RUN	IN USE?	COMMENTS
			USE OF ACTUAL CONFIG.? (YES/NO)					CONFLICT RESOLUTION TYPE	PRIORITY ALLOCATION			
MULTIPLE TRACK TERMINAL SIMULATION MODEL/ CN (21)	CAPACITY	NONE	HANDLES MULTIPLE TRACK ENT- RANCES TO YARDS (YES)		UNKNOWN	1 DAY	UNKNOWN	UNKNOWN	STATIC	UNKNOWN	YES, BY CN	USED TO EXAMINE SWITCH AND SIGNAL SYSTEMS AT ENTRANCE TO YARDS
TRAIN DISPATCHING SIMULATION MODEL/ PMM (20,NOTE 3)	CAPACITY	NONE	SINGLE LINE NO KNOWN LIMITS (YES)	NO SET LIMITS, SOME USERS EXPRESSED PROBLEMS W/ >30 TRAINS PER DAY		1-30 DAYS	PL/1	MULTIPLE LOOK AHEADS	STATIC	UNKNOWN	YES, IN FRA STUDY AND BY CP	PMM HAS UPGRADED TO AN IMPROVED VERSION
TRAIN SCHEDULE AND NETWORK SIMULATOR/ CN (21,NOTE 4)	YARD ANALYSIS, SCHEDULING	NONE	SINGLE LINE, NETWORKS, YARDS, NO SET LIMITS (YES)		UNKNOWN	1 DAY	UNKNOWN	N.A.	STATIC	UNKNOWN	YES, BY CN	USES AVG. DELAY/MEET PRODUCES STATS AND STRINGLINES

CATEGORY 3 MODELS

DETERMINISTIC SIMULATION MODELS

FIGURE 12 A

NAME/ SOURCE REFERENCE	PRIMARY FUNCTION	PROBABIL. ELEMENTS	TYPE & SIZE OF NETWORK		TIME FRAME	COMPUTER LANGUAGE	DISPATCH LOGIC			COST PER RUN	IN USE?	COMMENTS
			USE OF ACTUAL CONFIG.? (YES/NO)	NUMBER OF TRAINS			CONFLICT RESOLUTION TYPE	PRIORITY ALLOCATION				
N LATION/ CITY L/ SPORTATION SYSTEMS NOTE 5)	CAPACITY	NONE	SINGLE LINE NO SET LIMITS (YES)	NO SET LIMITS	1 DAY	FORTRAN	FIRST IN FIRST OUT	STATIC	BENCHMARK FOR 1 DAY ON DEC-10 COST \$10 ON TIME SHARE SYSTEM	NO		
RAC/ ,22)	CAPACITY, DISPATCHING STRATEGIES	NONE	SINGLE LINE 1000 MILES (YES)	MORE THAN 40 TRAINS PER DAY MAY CAUSE JAMMING	10 DAYS	SIMSCRIPT	MULTIPLE LOOK AHEADS	STATIC	UNKNOWN	YES, BY CN	USES 2 PRE- PROCESSORS AND TRAIN PERF. CALC. PRIOR TO ACTUAL SIM. OUTPUTS INCLUDE STATS & STRINGLINES	
LE K WAY LATION L/ RALIAN AU OF SPORT OMICS 2)	CAPACITY, SCHEDULING	NONE	SINGLE LINE NO SET LIMITS (YES)	HAS BEEN RUN WITH 64 TRAINS PER DAY.	1-2 DAYS	PL/1	COMPLEX SCHEME OF FEASIBILITY CHECKS, MULT- IPLE LOOK AHEADS AND PRIORITY BASED SEL- ECTION.	DYNAMIC	BENCHMARK W/ 41 TRAINS PER DAY USED 25 SEC CPU TIME ON IBM 360	UNKNOWN	PRODUCES STATS AND STRINGLINES	

CATEGORY 3 MODELS  
DETERMINISTIC SIMULATION MODELS

FIGURE 12 B

TYPE & SIZE  
OF NETWORK

DISPATCH LOGIC

NAME/ SOURCE REFERENCE	PRIMARY FUNCTION	PROBABIL. ELEMENTS	USE OF ACTUAL CONFIG.? (YES/NO)	NUMBER OF TRAINS	TIME FRAME	COMPUTER LANGUAGE	CONFLICT RESOLUTION TYPE	PRIORITY ALLOCATION	COST PER RUN	IN USE?	COMMENTS
RSPO CAPACITY L/ RSTATE ERCE MISSION OTE 6)	CAPACITY	RANDOM ENTRY FROM ORIGIN AND INTERMEDIATE YARDS, IF CONGESTED	SINGLE LINE UP TO 220 MILES (YES)	NO SET LIMITS (SEE COMMENTS)	1-30 DAYS	SIMSCRIPT 2.5	MULTIPLE LOOK AHEADS	STATIC	7 DAYS OF BENCHMARK USED APPROX 25 MIN. CPU TIME ON AN IBM 370/165	YES, BY B&M, BN, AND SCL	SAID TO HAVE PROBLEMS AT HIGH # OF TRAINS
CITY LATOR/ INGTON HERN RR OTE 7)	CAPACITY	RANDOM ENTRY FROM ORIGIN, RANDOM REMOVAL OF TRACK SEC. FROM SERVICE	SINGLE LINE 100-300 MI CAN RUN ) 500 MILES (YES)	80 TRAINS PER DAY (40-60 DAYS RECOMMENDED)	UP TO 1 YEAR (40-60 DAYS RECOMMENDED)	SIMSCRIPT 2.5	FIRST IN FIRST OUT	DYNAMIC	BENCHMARK FOR 1 YEAR ESTIMATED AT 15 MIN. CPU TIME ON IBM 370	YES, BY BN AND BCL	PROTECTS AGAINST JAMMING AT HIGH TRAIN DENSITIES
PERSON FLOR NOTE 8) TESTING	CAPACITY, SCHEDULE TESTING	RANDOM ENTRY FROM ORIGIN	SINGLE LINE 200 SEGMENTS UP TO 4 TRACKS PER SEGMENT (YES)	2000 TRAINS	1-30 DAYS, 30 DAYS RECOMMENDED	FORTTRAN	FLEET MEETABLE CONDITIONS	STATIC	BENCHMARK NETWORK W/51 TRAINS PER DAY USED 3 07 SECONDS CPU TIME ON IBM 3033	UNDERGOING TESTS ON CN BY CICGT	EXCEPTIONAL COMPUTATION TIMES FROM CLEVER DISPATCH ALGORITHM

CATEGORY 4 MODELS

RANDOMENTRY SIMULATION MODELS

FIGURE 13

ME/ RCE ENCE	PRIMARY FUNCTION	PROBABIL. ELEMENTS	TYPE & SIZE OF NETWORK		NUMBER OF TRAINS	TIME FRAME	COMPUTER LANGUAGE	DISPATCH LOGIC		COST PER RUN	IN USE?	COMMENTS
			USE OF ACTUAL CONFIG. ? (YES/NO)					CONFLICT RESOLUTION TYPE	PRIORITY ALLOCATION			
MEET ATOR/ JIS- ANCISCO ( CO. (NOTE 9)	CAPACITY	MAXIMUM USE OF RANDOM VARIABLES, INCLUDING DEPARTURES, TRAVEL TIMES, YARD TIMES.	SINGLE LINE 36 SIDINGS (YES)		20/DAY	1-98 DAYS, 30 DAYS RECOMMENDED	UNKNOWN	MULTIPLE LOOK AHEADS	STATIC	UNKNOWN, ONE SOURCE INDICATED VERY HIGH COST FOR BENCHMARK RUN	YES, BY BN	EXTRA TRAINS CAN BE GENERATED, EXTENSIVE STATISTICAL OUTPUT

CATEGORY 5 MODELS

THOROUGHLY PROBABILISTIC SIMULATION MODELS

FIGURE 14

entire rail system, the high costs of some of the tools would not be a bar to their use so long as the decision maker is convinced they would impart valuable information. Unfortunately, an examination of less permanent decisions, such as altering the time of a single local freight train, or altering a train's priority, or deciding whether to extend a siding by several hundred feet, and the concomitant tools does not reveal a similar range of experimental options. If we assume managers will match the choice of experiments (techniques) to the importance or permanence of the decision under consideration, then for the lower level of decisions, the experiment set must be restricted to the low-cost easily operated models. This limits the choices to all the members of Category 1 (except the PMM model), none of the members of Category 2, and only a few of the models in Categories 3 and 4 (Train Simulation/Capacity Model, Australian Single Line Simulator, Peterson and Taylor (19), and ICC RSPO Capacity Model). Each of the other models either has a high purchase cost, high information requirements, a high staff skills requirement, is not generally available, or is simply not applicable to small-scale decisions. The models of Category 1, however, provide no information on the particular location of delays or of delays by trains, and include no variables which replicate the small-scale dispatching decisions. Further, their aggregate nature suggests that many of the small scale issues, such as when to add a train, or what its impacts

will be on the most congested section of a line are outside the scope of the models. Similarly, the models which are available from Categories 3 and 4 either assume that trains always depart on schedule or that random schedule variations occur only on the departure from station stops. This means that if the analyst wishes to examine a critical intersection or junction (such as those "backed out" from in the schedule development process described in Section 1.3.3), the models will not permit it. Indeed, if the analyst is willing to capture all the uncertainty at the station stops, the models still must be run for time frames of 30 days to properly capture even these random variations. As is shown in Figures 12 and 13, runs of this size can result in costs in excess of \$300 per schedule or line configuration tested. Thus if the analyst is forced to examine 4 or 5 alternative schedules, the cost of the experiments may outweigh the benefits of performing them. Such models also do not permit the analyst to even examine matters such as altering train priorities for a limited section of the line, nor modelling complex intersections where several lines converge into a single line. The result is that for a great many of the problems reflecting small scale decisions, there are no models which provide sophisticated analysis for low cost. This is precisely the gap claimed in the central thesis.

Having established the need for a low-cost, easily used model capable of analyzing critical intersections or line

segments in an uncertain operating environment, the question arises, "Is such a model feasible?" That issue is addressed in Chapter 3

## CHAPTER 3

### SYSTEM DESIGN FOR MICSIM

#### 3 0 STRUCTURE OF CHAPTER

The previous chapter, after a careful examination of the features of the current set of models, found there was a gap between the large scale simulation models and the sketch planning tools available to the analyst of capacity, scheduling, and dispatching. This gap could be of great importance to the analyst who wishes to study either a complex intersection in great detail, or a "critical location" in the manner described in Section 1.2. This chapter provides the system design for a model to fill this gap. Section 3.1 outlines the goals of the model and some of the design considerations used in developing the model. Section 3.2 presents the general structure of the model including the basic network to be adapted into a particular configuration desired by the user. Section 3.3 explains the data requirements of the model and the input preprocessor (PREMIC) which allows the user to input the data. Section 3.4 presents the detailed design for the main program (MICSIM). The output processor (DUMPSTATS) is described in Section 3.5. A hypothetical scenario for using the model is presented in Section 3.6.

### 3.1 DESIGN CONSIDERATIONS

New models which are designed to fill the gap in user tools available for small scale problems of capacity, scheduling, and dispatching must satisfy a number of goals. In particular, the goals of such models are to provide, at a reasonable cost, capabilities that are lacking in existing models:

- Analyze the "worst locations" in a rail network, as an analyst might choose to define them.

- Perform the analysis of a user specified location in a manner which adequately captures the uncertainty found in the actual operating environment.

- Be compatible with the current planning and analysis processes; that is, capable of being iterated through several configurations, schedules, and strategies in reasonable times at a reasonable cost.

These goals led to the specification of specific design criteria for the particular model presented in this chapter

The design criteria used are:

- The model must be capable of modelling both complex intersections and conventional short track segments.

- The model must be fully probabilistic with respect to start times, travel times, work times in yards and stations, and signal response times.

- The model must be designed so that alternative dispatching strategies can be developed and tested, both

through dynamic priority allocation and through user assignment of priorities throughout the train's simulated journey.

-The model must operate in a reasonable range of computer environments, or at least be structured so that the concern of the analyst can be directed to the specification of the rail operations problems rather than the state of relations with the Information/Computer Systems Department.

Based on the above goals and design considerations, it was decided to develop a thoroughly probabilistic simulation model (see Section 2.1.5) which is capable of running on an Apple II microcomputer. Microcomputers are coming into increased use in the railroad industry, are capable of handling higher-level programming languages, and allow the modeller to transfer a model from one railroad to another without an extensive study of the information systems capability of either (Van Dyke (24)). It was decided to design to program the model in a structured programming language (PASCAL), so that users could modify particular sections to meet their own needs without having to redevelop other parts of the program. Similarly, researchers could test alternative algorithms for dispatching or randomizing events without having to alter the basic model, and if successful could distribute results easily. Using a structured programming language also meant the model could use the "overlying" abilities of the computer and language, that is, the machine could switch sections of the model

between the computer's memory and the disk storage device. Use of this feature reduced the need for extensive core memory by the computer

### 3.2 GENERAL STRUCTURE OF THE MODEL

In this section the basic network configuration and the general structure of the actual model are presented and explained.

#### 3.2.1 The Basic Network

In order to satisfy the constraints of handling complex intersections, short line segments, and fully probabilistic events, it was decided to design the model around a basic configuration, or framework, which the analyst could alter to replicate the actual intersection or line segment. The basic configuration was chosen to permit the analyst to examine critical locations or complex intersections, not the entire network or rail line. The framework selected is shown in Figure 15. The user selects the nodes he wants to use, and specifies the characteristics of the nodes and the links which connect them. By judicious selection of the nodes and links to be used, the analyst can adapt this framework to a number of standard line and intersection configurations, including a short single track line segment with two sidings (Figure 16), and entrance and exit tracks surrounding a yard (Figure 17). The network can also be adapted to model a number of non-standard track sections, including the convergence of two lines into one (Figure 18). The advantage of the general framework is that the user needs to become

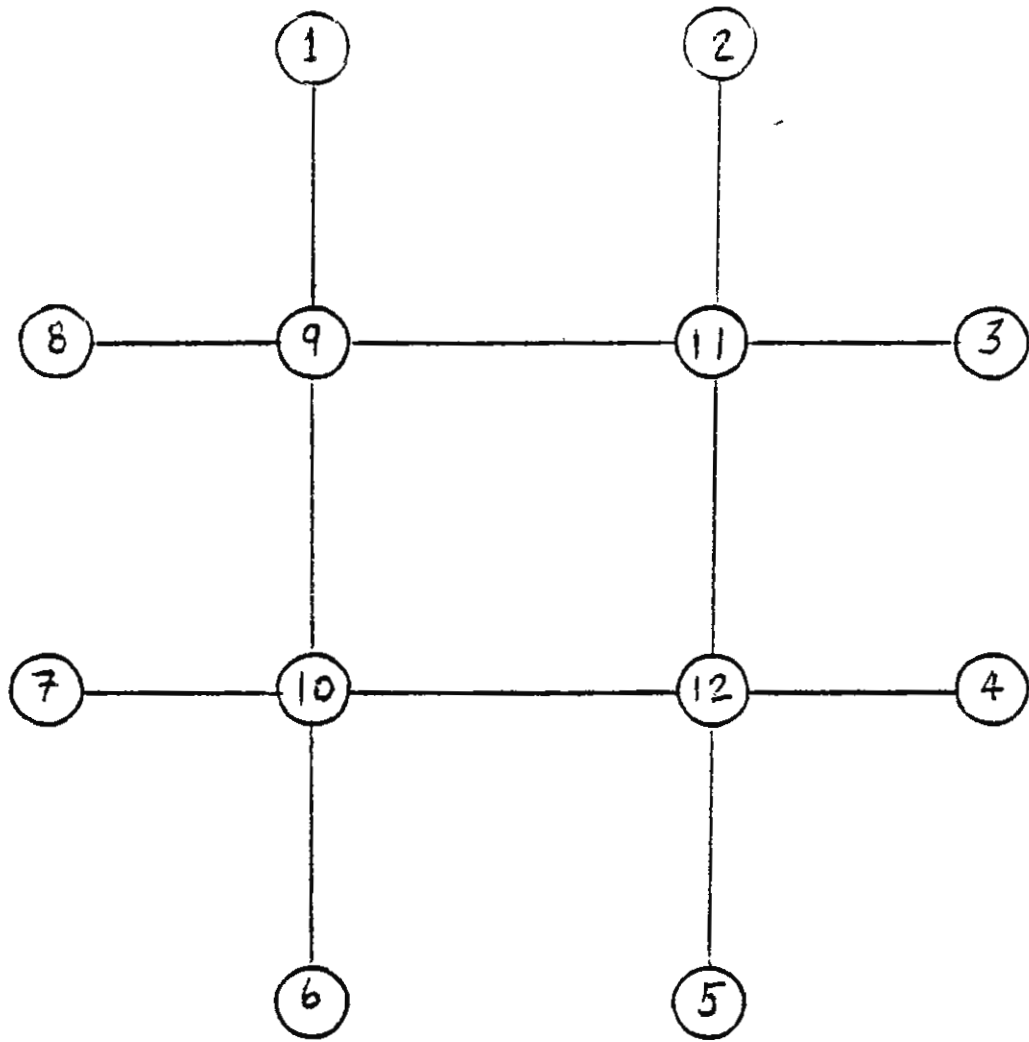


FIGURE 15  
BASIC NETWORK



CORRESPONDS TO

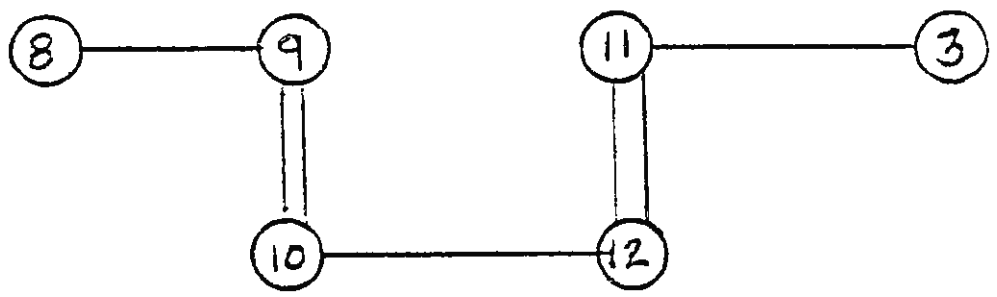
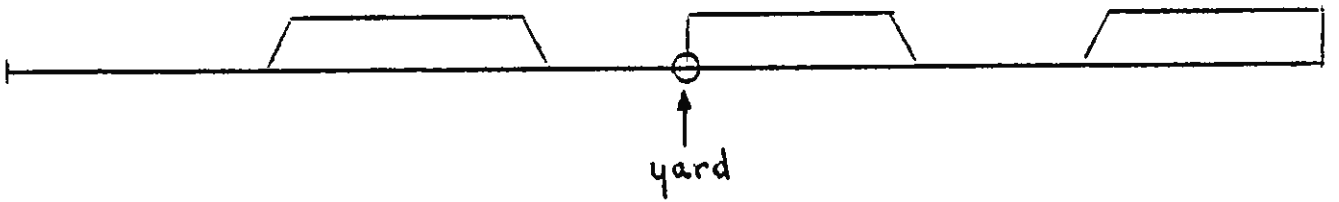


FIGURE 16

MICSIM CONFIGURATION CORRESPONDING TO  
A SINGLE LINE WITH 2 SIDINGS



CORRESPONDS TO

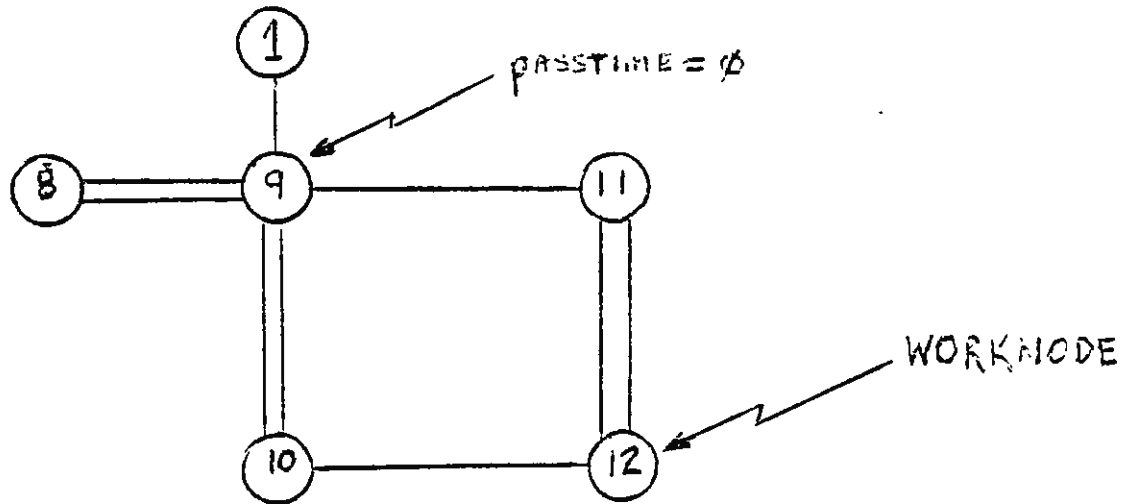
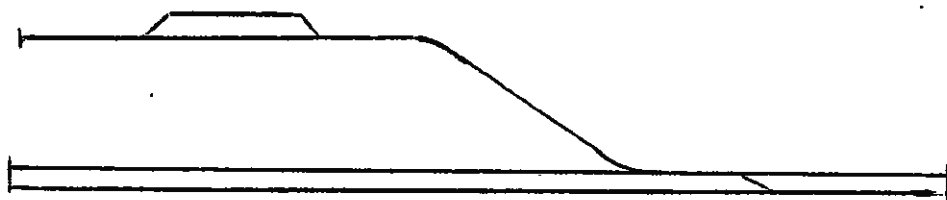


FIGURE 17

MICSIM CONFIGURATION CORRESPONDING TO  
A COMPLEX ENTRANCE TO A YARD



CORRESPONDS TO

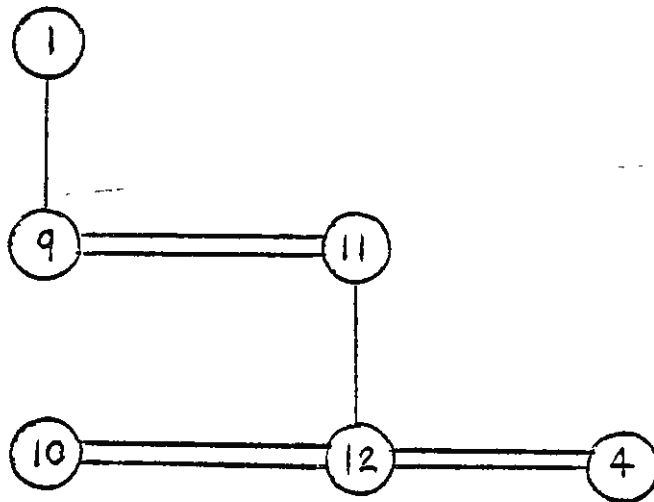


FIGURE 18

MICSIM CONFIGURATION CORRESPONDING TO  
CONVERGENCE OF A SINGLE TRACK LINE AND  
A DOUBLE TRACK LINE

familiar with only one method of organizing the data to configure a number of possible line structures, and needs to learn only one method of entering the data into a form usable by the model

### 3.2.2 The General Structure of the Model

The model is composed of three computer programs, an input preprocessor (PREMIC), the main program (MICSIM), and an output processor (DUMPSTATS). The input preprocessor (PREMIC) is an interactive program which permits the user to select the particular network configuration, the train schedules, the priority allocation routine, and the probability distributions to be used in the simulation executed by the main program. PREMIC is also designed to permit the user to simply alter one of the input files, so that matters such as the addition of a single train can be analyzed without a laborious process. PREMIC permits the user to specify any of three types of priority allocation schemes: static priorities, dynamic reallocation, and user specified dynamic allocation. The static option retains a train's initially assigned priority throughout the simulation. Dynamic reallocation examines a train's accumulated delay after each delay is incurred and determines whether the train's priority should be increased in response to the level of delay accumulated thus far. User specified dynamic allocation permits the user to input a specific priority level for each segment of its scheduled route. The main program (MICSIM) simulates the movement

of trains across the network using an event-based simulation routine. At the end of each simulated train trip the level of delay incurred by that train is compared with the simulated runs for that train for all preceding days of the simulation. If the level of delay is lower than for all other simulations of that particular train, the run is considered a "best case", and the details of that train's trip are recorded in a file. A similar test is made to determine if the train's run is a "worst case". In this way, when the analyst examines the results of the simulation (using DUMPSTATS), he not only receives summary and statistical information, but also information of what events seem to lead to very good or very bad performance across the network. The general structure of the model is shown in Figure 19. The details of PREMIE, MICSIM, and DUMPSTATS are provided in Sections 3.3-3.5

### 3.3. INPUT PREPROCESSOR (PREMIE)

The input preprocessor (PREMIE) permits the user to input data concerning the network configuration, the train schedules, the priority allocation routines, and the probability distributions. PREMIE is designed to permit the user to edit any of the existing files and data structures so that if, for example, the user simply wants to change one train's schedule, or one aspect of the line configuration he need not re-enter the entire data base. The data entry routine is shown in Figure 20. The reader will note that this routine calls any of six procedures for creating new

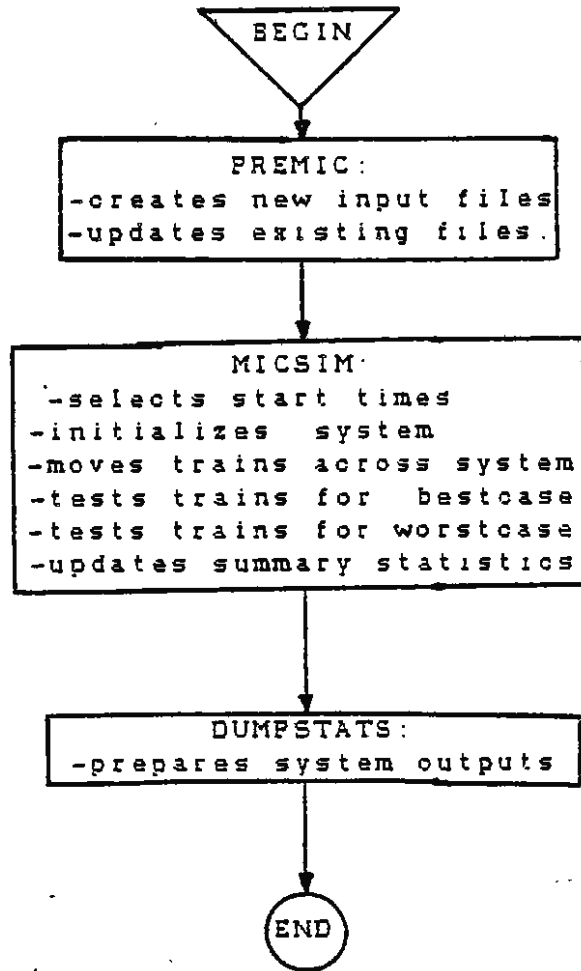


FIGURE 19  
GENERAL STRUCTURE OF THE MODEL

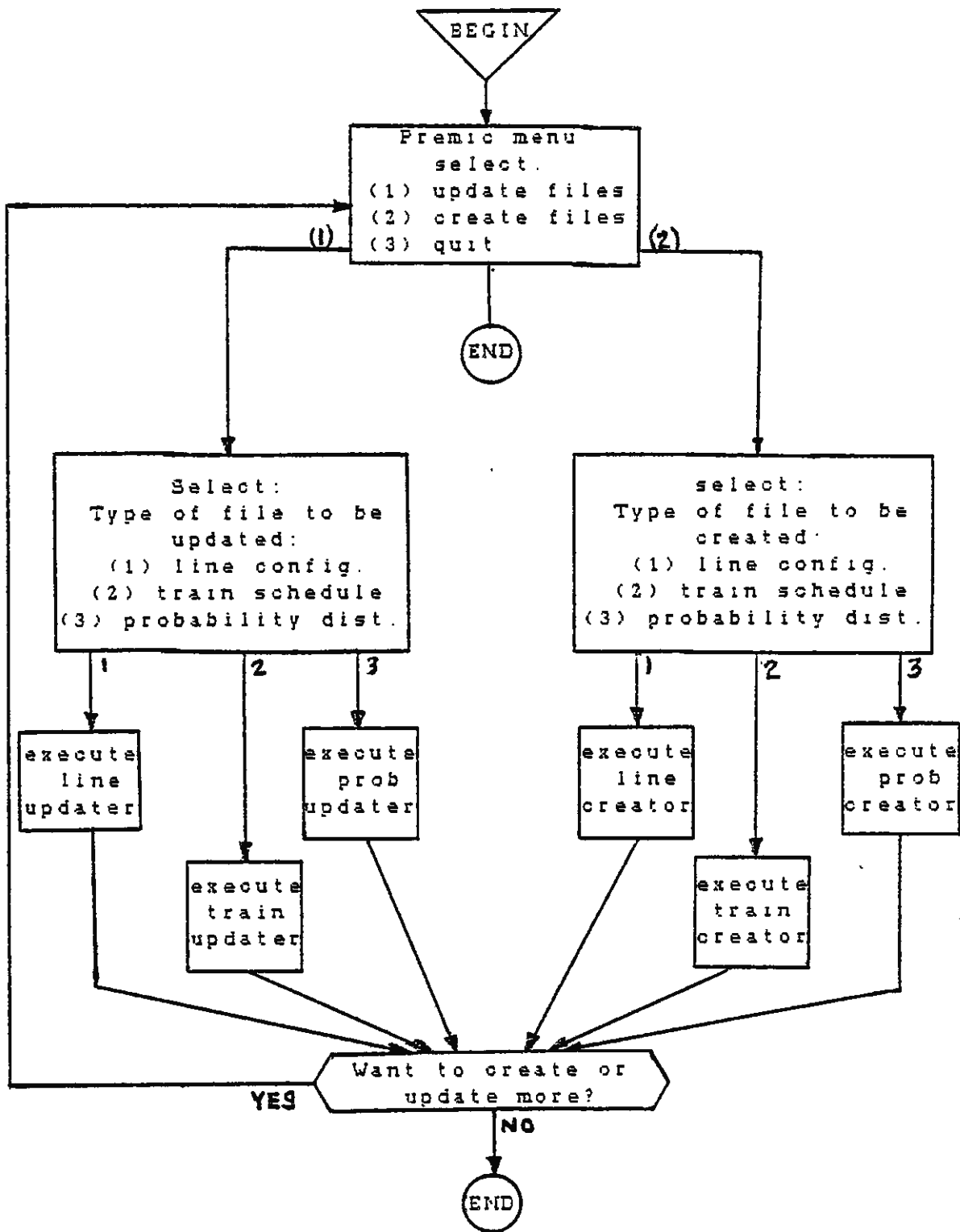


FIGURE 20  
PREMIC

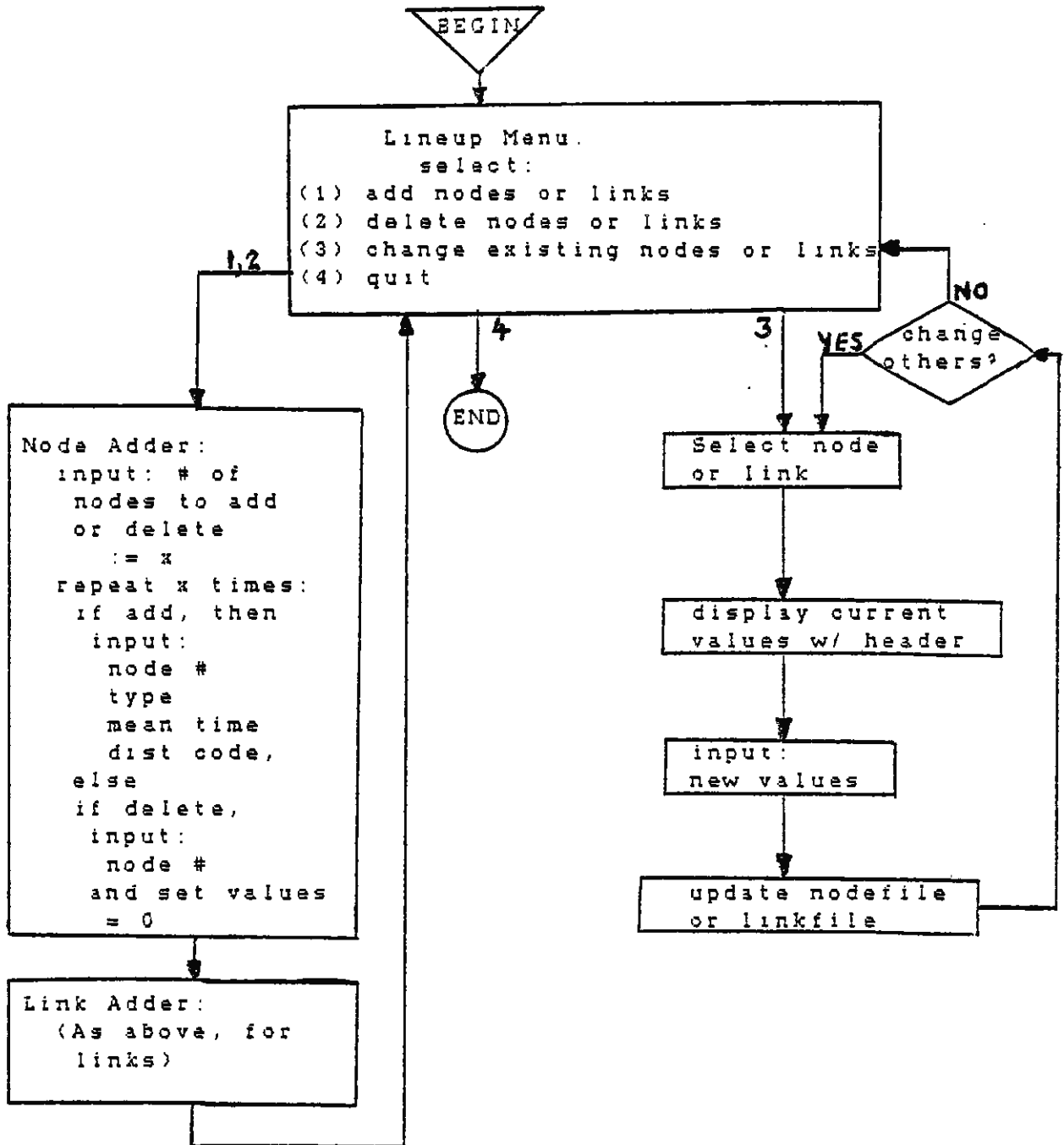


FIGURE 21  
LINK UPDATER

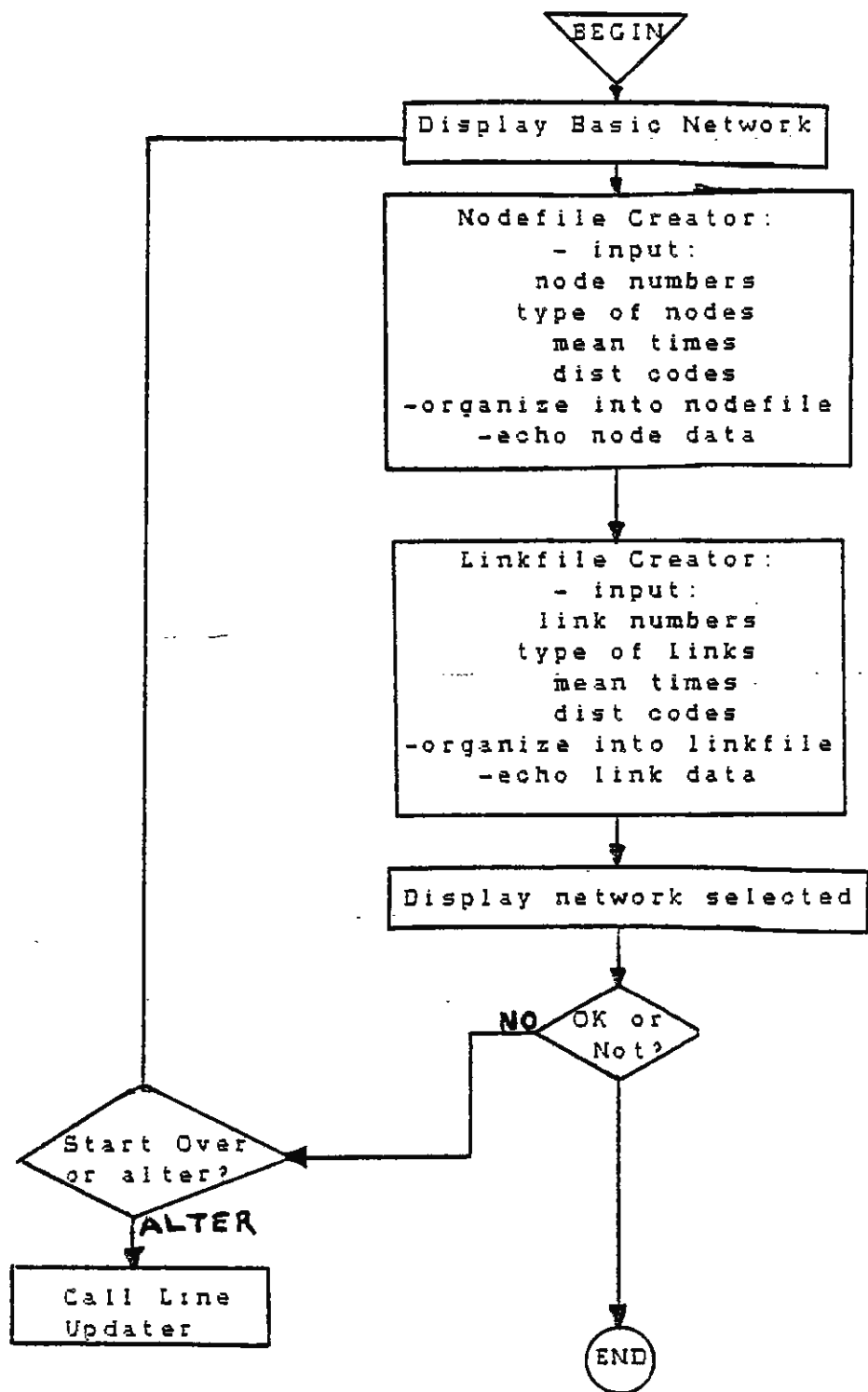


FIGURE 22  
LINEFILE CREATOR

files or altering existing ones. Figures 21 and 22 provide examples for creating and updating line configurations. The train schedule and probability distribution procedures are similar in logic and design. After the data is entered by the user, PREMIEC converts the information into usable formats for computer manipulation (e.g. conversion of minutes into hundredths of hours). PREMIEC creates or alters four types of files:

- Node Files, which specify which nodes are in use, whether a node is a crossover from single to double track (passnode) or a yard (worknode), the mean time a train spends crossing or working in the node, and what the distribution of work times is in particular yards.

Example:

NODE #	TYPE	MEAN TIME	DIST. CODE
----	----	----	-----
1	W	45	2

The procedure converts the mean times from minutes into decimal based hours. (In this example, 45 minutes would be converted into .75 hours.)

- Link Files, which specify which particular line segments are active, whether the segment is single or double tracked (Note 1), the mean travel time across the segment, and the probability distribution about the mean travel time.

Example:

LINK #	TYPE	MEAN TIME	DIST. CODE
----	----	----	-----
3	S	30	4

Again, the procedure converts the travel time into hundredths of hours.

- Train Files, which specify the train name, the train's priority, the train's route, its scheduled departure time from its initial node, the distribution about the scheduled start time, and the speed multiplier. (The user specifies at an earlier point whether the priority allocation is static, dynamic, or user specified. Depending on which allocation scheme has been selected, the train's priorities are either input as a single number (the initial priority), or an array in which the priority corresponds to each link of the route.)

Example (static priority allocation):

TRAIN NAME	PRIORITY	SKED TIME	DIST. CODE	SPEED MULT.	ROUTE
MEPO	2	2230	3	1.8	8-9-1-0

The route is specified as a series of nodes, and is concluded with a '0'. The conversion scheme mentioned above is used.

- Probability Distribution Tables, which specify the correspondence between a given probability and the distribution of times about a mean. These are the Distribution Codes referenced in the other files. These tables are input as percentages and values and are converted into a format which the main program can check random numbers against

### Example

PERCENTAGE	VALUE		RANDOM NUMBER	VALUE
25	-30		00-24	-30
25	-15		25-49	-15
10	0	BECOMES	50-59	0
25	30		60-84	30
10	60		85-94	60
5	90		95-99	90

Thus, if this particular distribution were being used to examine the start times for a particular train, the main program would generate a random number, determine the corresponding value, and add that to the scheduled start time.

### 3.4 MAIN PROGRAM (MICSIM)

The main program is called MICSIM (for MICRo SIMulator). MICSIM is an event based simulation which "moves" trains across the network according to the schedule and line configuration specified in PREMIEC. The program initializes the various workfiles used in the program, dispatches the trains across the network, records delays by train and location, and updates the information which is organized into statistical output by DUMPSTATS. The program is currently designed to allow several train priority allocation schemes, and uses the Peterson and Taylor simple meetable conditions (see Section 2.2 and Figure 24). The general structure and logic of MICSIM is shown in Figure 23. Section 3.4.1 describes the initial conditions and some of the structures used by MICSIM. Section 3.4.2 examines the time related characteristics of the model, Section 3.4.3

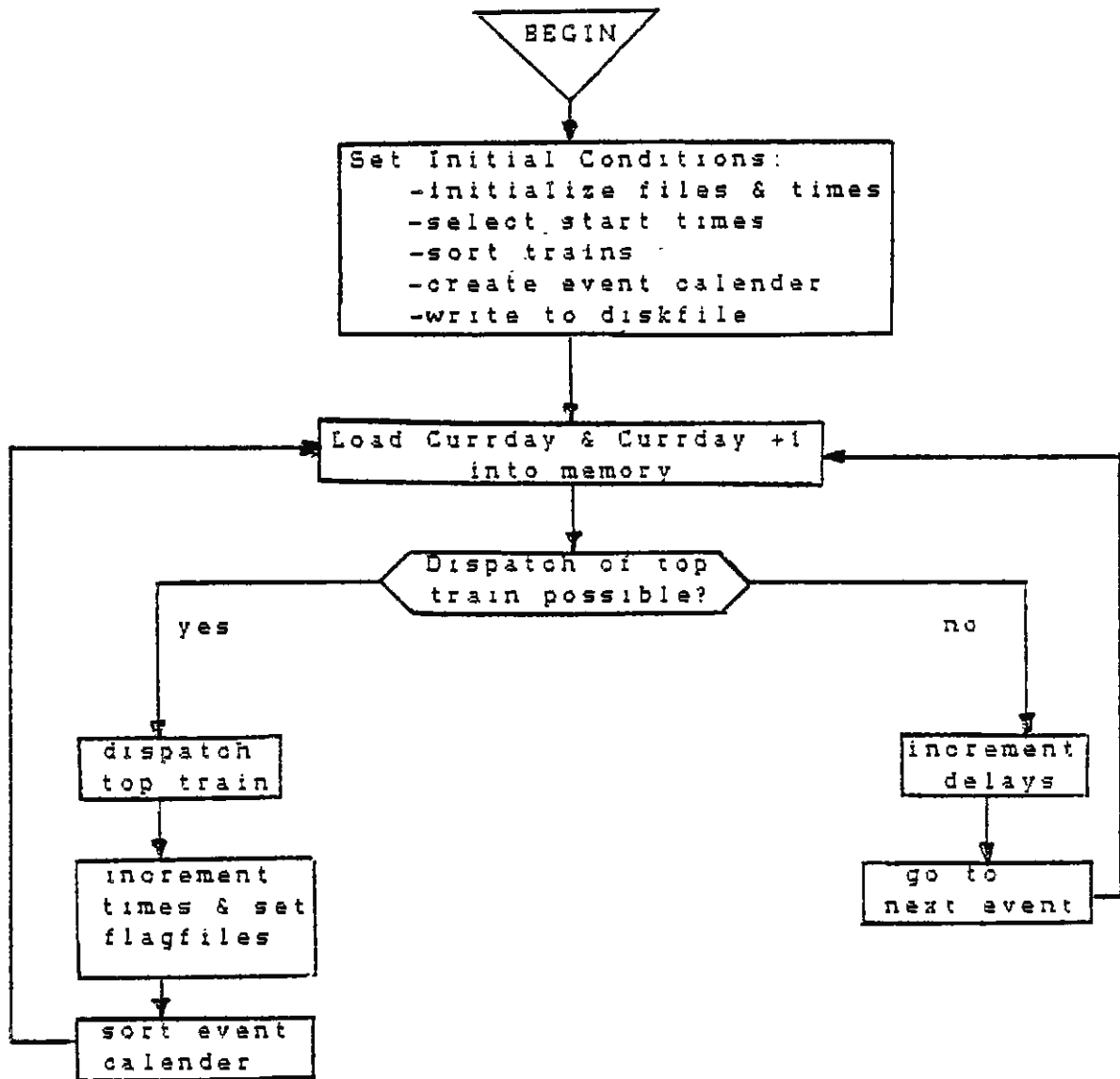


FIGURE 23  
GENERAL STRUCTURE OF MICSIM

### Peterson and Taylor Meetable Conditions

When a train move is being considered, it is important to determine whether the move will block the line, and avoid such moves. If the move is such that all other trains can be arranged to complete their journey, the train is considered "meetable". If the other trains cannot be arranged to reach their destination, the train is "non-meetable" (i.e. a line blockage will follow from the move). To implement the meetable test, create a variable, counter, and set counter = 1. At the train's next event after the one under consideration, set

$$\text{counter} = \text{counter} +$$
$$\left\{ \begin{array}{l} 1, \text{ if double track, occupied same direction;} \\ 1, \text{ if single track, occupied either} \\ \text{direction;} \\ 0, \text{ if single track unoccupied;} \\ -1, \text{ if double track, unoccupied, or} \\ \text{occupied opposite direction.} \end{array} \right.$$

Repeat through the train's remaining journey until counter = 0, or the destination station is reached. If counter = 0, then the train is simple meetable. If the destination is reached and counter = n, the train is n-th order meetable. Constraining moves to simple meetable ones insures computational efficiency; Electing for n-th order meetable moves may permit more sophisticated dispatch moves, but also increases computation time.

FIGURE 24

presents the dispatching routine used by the program.

### 3.4 1 Initial Conditions and Data Structures

In order to run a simulation of several days on a microcomputer, it is necessary to set initial conditions in such a way that no events are overlooked and computer memory is preserved. It is also necessary to create an easy means to test whether a single track line segment is occupied by a train so that line blockages are avoided and other trains travelling in the same direction as the initial occupier of the line may follow the train into the line segment without overtaking the initial train. In order to perform these functions, several data structures are used by MICSIM:

-Flagfile: This is a binary file for each "event location" on the network, that is, for each node and each link in each possible direction. Thus if the network is comprised of the network shown in Figure 16 (single line with 2 sidings), the Flagfile would be comprised of 16 members: nodes 8, 9, 10, 11, 12, and 3, and the links 8-9, 9-8, 9-10, 10-9, 10-12, 12-10, 11-12, 12-11, 11-3, and 3-11. Note that there is a binary variable for each link in each direction. This is so that if a train crosses a single track segment the flag for trains in the opposite direction can be set while allowing the flag for trains following in the same direction to remain unset. The initial condition for the Flagfiles is unset (false).

-Followflags: This is a binary file identical to the Flagfile, which is used to indicate whether any train has



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were not included in the copy of the  
thesis deposited in the Institute Archives  
by the author:

p 80, p 81

event to the next, and so long as the event calender has been properly updated, consider all the decisions which a dispatcher would have to address. Next event timing also permits dynamic priority allocation to be easily implemented

Minimum positive event time is defined as the smallest increment of time in which any event in the simulation can occur (i.e. cross a node, travel across a link, etc ) For the purposes of MICSIM, the minimum time is selected from the mean times input in PREMIC. The minimum positive event time becomes significant in cases where a train is forced to delay entrance into a node or link, since it is the smallest amount of delay that a train can accrue in such a case. While it is possible that a train could accrue less delay in practice, the minimum positive event time is a useful logical construct which permits considerable simplification of the dispatching routine, since any train which is delayed can be simply advanced by this amount, returned to the event calender, and the simulation continued. The construct is particularly useful in cases where the next event to occur has the same event time as the delayed train and a lower priority. Consider the case where train a of priority 1 is scheduled to enter link i-j at 1130, and train b of priority 2 is scheduled to vacate the link at 1130. If we simply move the next event time of train a to the next event time on the event calender, we can end up in an endless loop incrementing the next event time by zero and always finding

the priority 1 train being considered ahead of the priority 2 train. By always assigning some nominal amount of delay we insure that such a loop will be escaped after one pass. The tradeoff is that if the next significant scheduled event is 30 minutes later and the minimum positive event time is 10 minutes we must make 4 attempts to move the delayed train before we actually move it. This disadvantage is not viewed as significant at this time.

The other time related characteristic that should be mentioned is the routine for loading new days into the event calender. After each event the next event is tested for the train at the top of the event calender. If this is scheduled to occur in a day later than Currday, then Currday is incremented to Currday plus one, and the event calender for Currday plus one is loaded into memory. Thus the largest size the event calender within memory can become is 3 times the number of scheduled trains per day. (in fact, the number could, under a very peculiar set of probability distributions and with a very high number of scheduled trains per day actually exceed this number, but this possibility is so remote as to be practically non-existent.) In practice, the event calender in memory will be smaller than this most of the time, since trains which have terminated are removed from the event calender.

These time related routines and characteristics are believed sufficient to operate MICSIM fully within standard simulation techniques

### 3 4 3 Dispatching Routine

As stated earlier, MICSIM incorporates both dynamic priority allocation and the Peterson and Taylor simple meetable conditions. Thus the dispatching routine can be characterized by the following logic:

1) Select the top item from the event calender and advance Currtime to the time of this event.

2) Test the event against Flagfile to determine whether the move is feasible (i.e. whether the proposed move would block a single track segment of the line). If the move is not feasible, increment the appropriate times and delays by the minimum positive event time, update the train's priority (if dynamic reallocation is in use), sort the event calender, and return to step 1).

3) If the move does not cause an immediate blockage, test the move for simple meetability using the Peterson and Taylor counters. (See Section 2.2 for a general description, see Peterson and Taylor (18) for a detailed theoretical description, and Peterson and Taylor (19) for a mathematical implementation.) Figure 24 presents the logic used in implementing the counters. If the move is not found to be simple meetable, the appropriate times and delay are incremented by the minimum positive event time, the train's priority is tested for changes (if dynamic reallocation is in use), the event calender is resorted, and the program is returned to step 1.

4) If the move is simple meetable, the train's travel

time is computed, the event calender is updated, the appropriate Flagfiles or Followflags are set, the train's priority is tested for changes (if user specified priorities are in use), the event calender is resorted, and the dispatch routine moves on to the next event on the event calender

The dispatching routine is shown in Figure 25.

When a train reaches its terminal destination (next scheduled event = .0), the train is tested against the best and worst cases for other days' simulations of that train. The test for best and worst cases for a train is the following:

Best case:

accumulated delay(train) < accumulated delay (train,  
bestyet),

Worst case:

accumulated delay(train) > accumulated delay (train,  
worstyet).

If the accumulated delay is neither less than "bestyet", nor greater than "worstyet" for that train, the information on that train is simply incorporated into the summary information operated upon by DUMPSTATS. If the train's performance indicates that it is either a best or worst case, the particular statistics are recorded in the bestcase or worstcase files.

### 3 5 Output Processor (DUMPSTATS)

The output processor is a menu driven program, which,

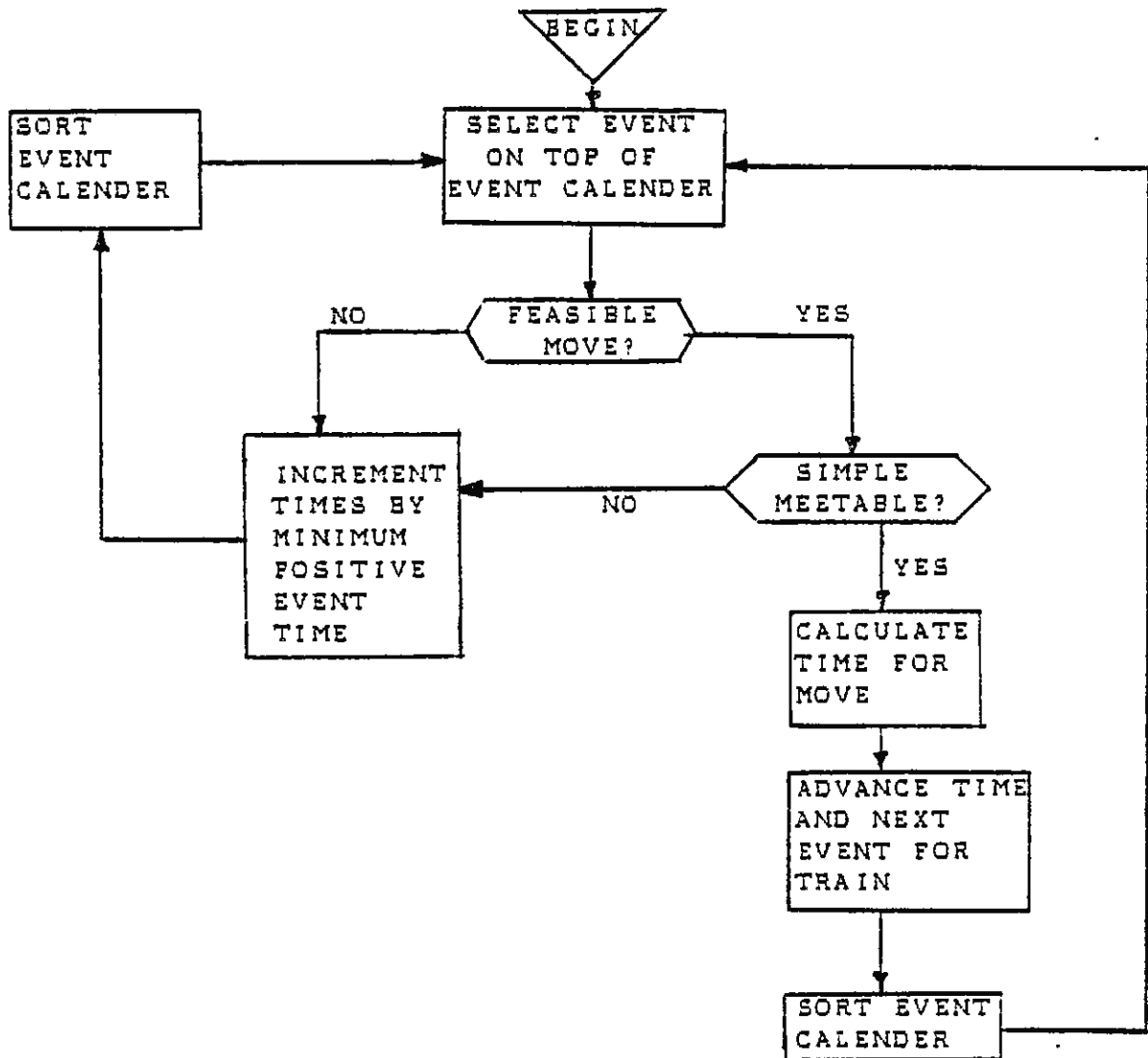


FIGURE 25  
DISPATCH ROUTINE FOR MICSIM

upon completion of the simulation permits the user to generate reports concerning system performance during the simulation. The various records are maintained throughout the simulation and are available to the user as disk files at the end of the program. The records for generating the statistics are stored in files of arrays, which are accessed by MICSIM whenever certain types of events occur. If, for example, a train is delayed at a location, then the system total delay file is accessed for that day, the location file is accessed for that day, and the train file is accessed for that day. Thus the computational routine, Statprocessor, can be developed which computes the mean and standard deviation of the values of any of these arrays.

The statistics available are:

- 1) average accumulated delay per train (mean and std deviation),
- 2) average daily delay by train (mean and std. deviation),
- 3) average accumulated delay per day (mean and std. deviation),
- 4) average delay by location per day (mean and std. deviation),
- 5) best case performance for each train- includes train name, day and time train originated and terminated, accumulated delay, train's initial priority, train's final priority,
- 6) worst case performance for each train- includes train

name, day and time train originated and terminated, accumulated delay, train's initial priority, train's final priority

Thus if a user is only interested in what percentage of the delays occur at a particular location on average, he can simply compute and print out the average accumulated delay per day and the average delay by location. A simple division provides the desired answer.

The general structure of DUMPSTATS is shown in Figure 26.

### 3.6 HYPOTHETICAL SCENARIO FOR USING THE MODEL

This paper has argued throughout that the tools used for analyzing problems should be matched to the importance and permanence of the problem. In this section a hypothetical case is examined in which the appropriate tool is the model presented in Sections 3.1-3.5. The case is drawn from a situation which confronted the B&M in the Spring of 1982, but is modified slightly for purposes of demonstration.

Consider a rail line such as that shown in Figure 27(a). The railroad operated both commuter and freight service across the line, with commuter trains operating from points 1 to 4 and returning to 1, while the freight service operates between 1 and 6, 6 and 1, 6 and 7, and 7 and 6. The commuter trains are given the highest priority, and are marked by a high degree of schedule adherence. The freight trains vary widely from their scheduled times. The commuter

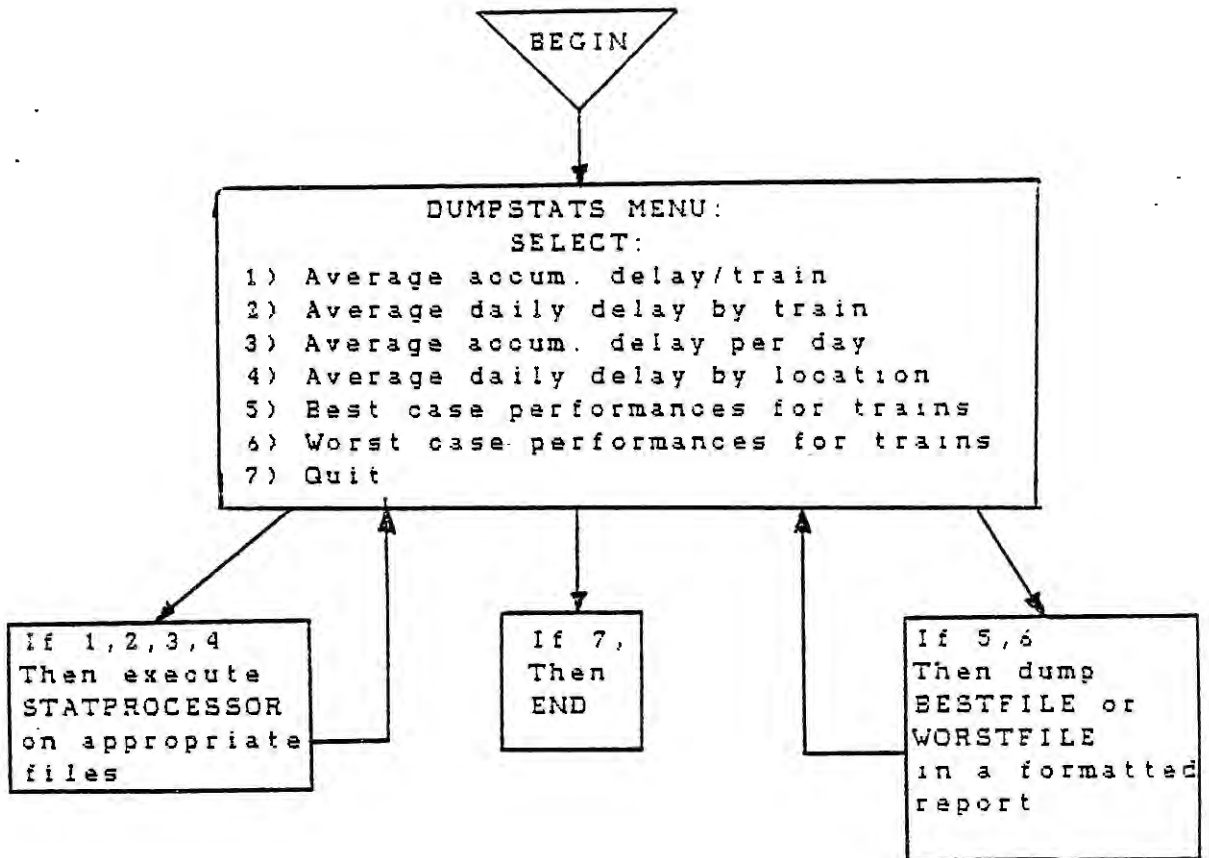


FIGURE 26  
GENERAL STRUCTURE OF DUMPSTATS

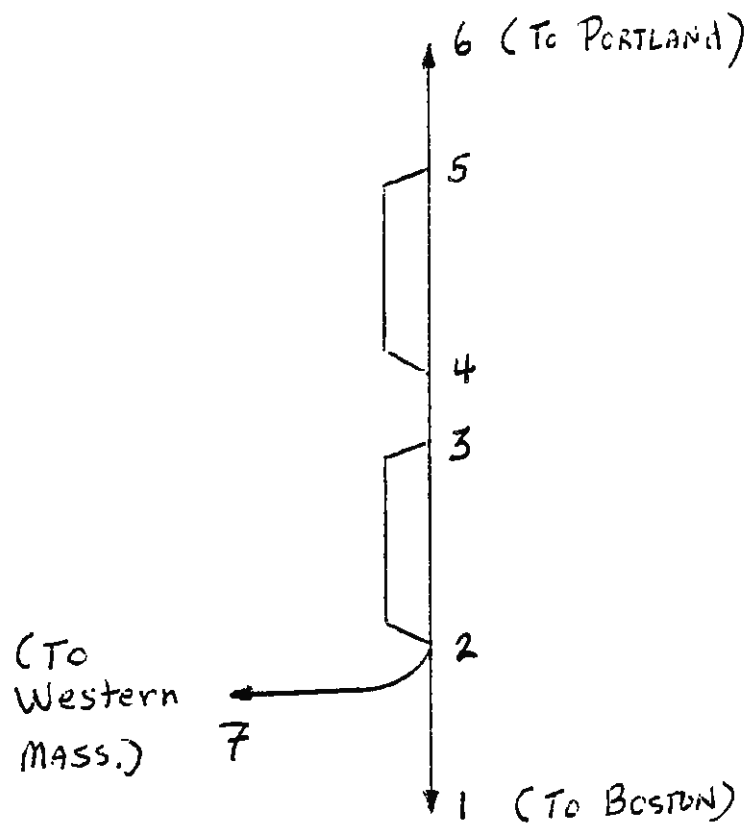


FIGURE 27(a)  
CORRESPONDS TO

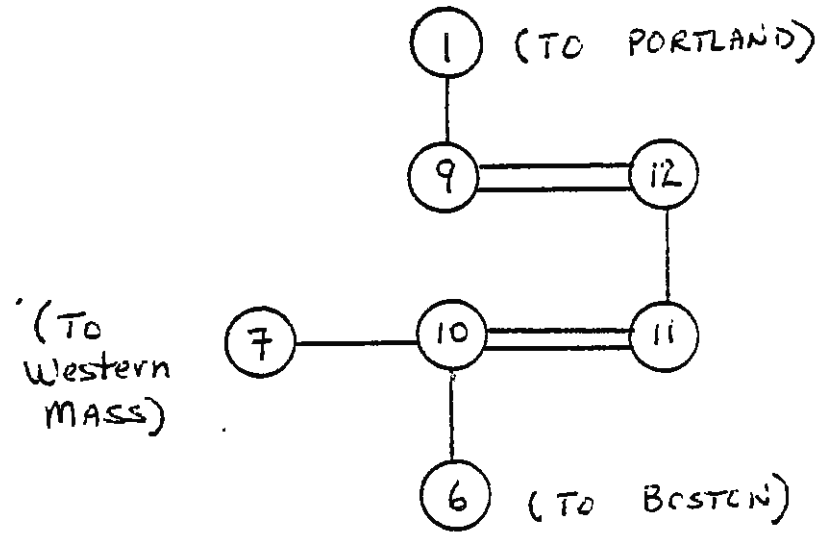


FIGURE 27(b)

CONFIGURATION OF LINE AND MICSIM NETWORK  
FOR HYPOTHETICAL SCENARIO

service has decided to extend service to point 5. The question confronting the freight operations planning group are:

1) Will freight trains encounter unacceptable levels of delay because of the extension of the commuter service?

2) Can the freight schedule be altered slightly to alleviate delays?

3) Is there some preferred time for the freight service to operate such that the schedules are not changed radically which minimizes delays?

Clearly, use of an aggregate delay model will provide no insight into questions 2 and 3. Simulation models which assign delay to the origin stations will not capture the uncertainty in trains turning around at stations 4 or 5, and will have difficulty modelling the turnout to Western Massachusetts. Thoroughly probabilistic models are necessary to capture this set of circumstances, but because the problem is small, an inexpensive model is most appropriate.

Figure 27(b) shows how the line might be modelled using the basic network in MICSIM. By selecting the probability distributions surrounding nodes 9 and 12, the variability in times for commuter trains to execute their turnarounds is captured. By running the model first with the current variety of start times for the freight trains, and then using the Bestcase results as a base time for a second run, the analyst can test to determine whether small changes in the schedule can alleviate the congestion. Finally, the

analyst might want to examine the effects of capital improvements (e.g. double tracking the segment between the two segments already double tracked) MICSIM will permit all of these to be analyzed in an environment which is defined by the user.

## CHAPTER 4

### CONCLUSIONS AND RECOMMENDATIONS

#### 4.0 SUMMARY

It has been the central thesis of this paper that when the processes of capacity analysis, train scheduling, and train dispatching are placed in a proper conceptual framework, a "gap" in the current set of tools available to the analyst becomes evident. In particular, the analyst is forced to choose between large scale computer models and sketch planning tools, a severe restriction when the area to be examined is of a small scale but marked by a high degree of uncertainty, such as a complex intersection or a critical track segment within a line. Problems of this sort occur frequently in the railroad operations planning environment. What is needed, then, is a model which is fully probabilistic (to capture the uncertainty), and capable of operating efficiently and inexpensively (to match the small scale of the problem).

In Chapter 1, the processes of capacity analysis, train scheduling, and train dispatching were examined using the Boston and Maine Railroad as an example. These processes were then placed in a conceptual framework known as Sequential Problem Solving (SPS), which showed that while the processes may be performed by different actors within a railroad, the decisions made by any one group are properly viewed as affecting the decisions of the other actors and

the overall operations of the railroad. The SPS framework showed further that the processes of capacity analysis, scheduling, and dispatching are invoked in response to some problem or problems which can potentially be resolved by any or all of the three processes. Chapter 1 showed that decision makers seek to match the level of analysis to the level of importance or permanence of the decision; thus if the problem is of a small scale (such as adding a single train, or altering the priority of a train), it is of great importance that the analyst have available effective models which operate at a low cost.

In Chapter 2 the various analytical tools available were examined in light of a number of features, including computational features, resource requirements, and ability to appropriately represent the uncertainty which characterizes North American railroad operations. While the number of tools available was shown to be great, and the number of potential uses vast, none of the models could be shown to effectively model the potentially critical line segments or complex intersections which sometimes confound the planner or analyst, and do so for a low cost.

Chapter 3 presented the system design for a microcomputer based simulation model which is oriented to the above problems and incorporates a number of state of the art features, including alternative priority allocation schemes, the Peterson and Taylor simple meetability conditions, and thoroughly probabilistic event timing. A

hypothetical scenario, similar to an actual circumstance which confronted the B&M, was used to illustrate how the model might be used to analyze a small scale problem.

#### 4 1 CONCLUSIONS

If there is any single dominant conclusion to be drawn from this research, it is that the processes of capacity analysis, train scheduling, and train dispatching, each of which seemed so distinct at the outset of the project, are intimately related in their effects on the success of railroad operations. The case of recreds was used in Chapter 1 to show that any of the three processes might be invoked to address and solve an operations problem, a number of the models presented in Chapter 2 were claimed to be useful in analyzing 2 or more of the processes. It is perhaps necessary that a railroad separate the management and performance of these three activities, both because the decisions involved range from the very immediate (dispatching) to the very long term (capital investment in new lines), and because the activities have traditionally come under the authority of different departments. The Service Planning approach (14) has shown that a high degree of interdepartmental cooperation and coordination is possible in determining what level of service to offer. A similar level of interdepartmental coordination is possible and desirable among the analysts who examine the issues of this paper. It is hoped that the features of the model presented in Chapter 3, particularly the alternative

dispatching strategies, will facilitate this interdepartmental approach in a manner that parallels the Service Planning approach.

A second conclusion is that the current set of models provides a large and robust set of tools for examining large scale problems. The gap between the sophisticated (and costly) large scale models and the crude and inexpensive sketch planning tools suggests that intermediate models similar to that presented in this paper are a fertile area for academic research. While the model presented incorporates some of the most up to date features available (dynamic priority allocation, probabilistic event timing, fleet meetable dispatching), there are a number of areas which it does not address. The model does not examine sophisticated blocking and signalling systems, and the analysis of train overtakes is severely constrained. If and when the model is actually implemented, the user may wish for a similar model for examining signal systems and block length strategies. The current gap in the models discussed is paralleled in these areas and may prove even more significant at the "critical points".

A final conclusion is simply that there is much more to be understood if the processes of capacity, scheduling, and dispatching are to be substantially aided by researchers. Only capacity analysis has anything approaching a theoretical basis, attempts to develop optimal schedules or dispatching strategies from radically simplified assumptions

may well be blind alleys. The author was unable to uncover a single work which examined actual dispatch decisions empirically, nor a single scheduling algorithm in actual use by a North American railroad operations staff. Indeed it is arguable whether strict schedule and dispatching adherence (such as that found on European railways) is preferable to a high level of adaptability in a radically changing environment (the North American railroad approach). It is the author's hope that the increasing awareness of the value of research into basic operations processes will permit the development of theoretical foundations for these vital and substantial areas.

#### 4.2 RECOMMENDATIONS FOR FUTURE RESEARCH

The need to provide reasonable boundaries on this paper forced the author to limit his exploration of a number of interesting and potentially useful topics which this research uncovered. It is perhaps appropriate to close the paper by suggesting some of these areas for further work:

- The actual behavior of dispatchers: Casual observation of dispatchers by the author suggests that the actual decision rules used by the dispatchers may vary widely; whether the effectiveness of the various decision rules varies equally widely is a matter of speculation. Current models seek to mimic the decision rules, but the success which they achieve is measurable only by inspection of the output of the models by dispatchers, not by empirical or theoretical work which precedes the generation of

dispatching algorithms. Conversations with Peterson lead to the conclusion that a detailed study of dispatching could provide useful information to both railroad managers and to model developers

- Development of heuristic tools to aid in schedule development. Current research is focussed on either development of optimal scheduling routines or the testing of wholly man made schedules. Clearly tools which aid in generating and quickly testing feasible schedules could prove useful to schedulers in the early stages of the schedule development process. There is strong anecdotal evidence to suggest that a large number of feasible schedules are not even generated or examined in the schedule development process.

- Relation of train dispatching, train scheduling, and locomotive utilization: The SF Operations Planning Model, which iterates between schedule adherence and "optimization" of locomotives highlights the fact that the relationships between power utilization and train dispatching is a matter of concern to railroad managers. Work by C.K.Mao (12) has begun to frame the organizational and decision making processes which govern this relationship. Clearly the rising capital costs for locomotives will motivate further work into these relationships.

If pursued, these lines of research would begin to develop an understanding of the capacity, scheduling, and dispatching problems that this thesis has sought to explore.

## GLOSSARY

Automatic Block Signalling- A system by which the trains themselves control the signalling system such that the entrance or exit from a segment of track sets the signals to inform other trains whether the segment is occupied.

Block- A group of cars with a common destination station.

Crew Change Point- The location on a train's run at which the crew operating the train is replaced by another train crew.

Crew Turn- The amount of time a train crew must wait between completing a run and operating a return train to their home terminal. In the U.S. the time must be at least 8 hours.

Dispatching Algorithm- A set of logical rules used by simulation models to determine which trains may occupy which segments of track.

Federal Hours of Service Law- The rule that a train crew may not work more than 12 hours before being given an eight hour rest. Upon reaching the 12 hour limit, the train must be stopped and a replacement crew used to complete the train's run.

Home Terminal- The station from which a train crew is assigned. After completing the train's movement, the crew must be returned to the home terminal, subject to the laws governing crew rest. (See Crew Turn, above.)

Intermediate Stop- Stations or locations between a train's origin and destination stations at which it picks up cars, sets off cars, or changes crews.

Line Capacity- The number of cars per unit time that can traverse a rail line; this is frequently measured subject to a level of service constraint such as acceptable delay (See Section 1.2.)

Meet- The circumstance in which the continued forward movement of each of two trains travelling in opposing direction would lead them to occupy the same segment of single at the same time.

Overtake- The circumstance in which the continued forward movement of a higher speed train requires it to pass a lower speed train travelling in the same direction. This is also known as a pass, or run-by

Pickup- The process by which blocks of cars are added to a train at an intermediate station.

Power Turn- The time needed between the termination of a train's run and the next scheduled use of its locomotives on another train. The time must be great enough to allow for fueling and servicing and for variations from schedule, but small enough to insure adequate utilization of this expensive resource.

Recrow- The term applied when a train's crew reaches the limits imposed by the Federal Hours of Service Law before reaching the train's destination station or a crew change point. When a recrow occurs both the expired crew and the replacement crew are paid the full labor expense of the entire scheduled service.

Revenue Traffic- Loaded cars for which the railroad is paid by a shipper. (the railroad is not paid for the movement of empty cars.)

Run Through Train- A train which has its origin station on one railroad and its destination station on another railroad, and carries cars classified for the second railroad.

Schedule Bunching- The grouping of the scheduled departures from an origin station to the same destination station at or near the same time with few or no trains at other times.

Setoff- The process by which blocks of cars are removed from a train for delivery at an intermediate station.

Stringline Diagram- A chart which displays the movement of trains over a rail line. The axes of the diagram are time and space. (An example is shown in Figure 6.)

Structured Programming Language- Any computer language in which programs are composed of independent segments organized in a hierarchical way. The advantages are primarily in ease of understanding and modifying large programs. Examples include PASCAL and PL/1.

Timetable- A listing of all the scheduled times, routes, pickups, setoffs, and crew change points of the freight trains operated by a railroad.

Tower Operator- A railroad employee who provides the intermediate link between train dispatchers and the crews of trains moving over a line. Frequently they are positioned at towers which overlook entrances to yards, where the operators can visually inspect the track segments affected by the dispatching decision. This function is gradually

being taken over by electronic monitoring and communications systems.

**Train Dispatching-** The process by which decisions are made about which trains may enter, exit, and move across track segments at which times. (See Section 1.4.)

**Train Scheduling-** The process by which train times, routes, and work assignments are developed. (See Section 1.3.)

**Train Sheet-** The record of all dispatching decisions made within a particular territory or line. In the U.S., train sheets are maintained by the dispatchers and must be preserved for several years.

## NOTES

### Chapter 1

1. Developed in conversation with C.D. Martland, based on Martland (13).
2. Conversations with officials on 3 other railroads and the author's observation of scheduling on the Maine Central RR. suggest the scheduling processes on the B&M are common in the industry, subject to limited variations.
3. Based on discussions with schedule planners on 3 railroads.
4. The author worked on the development of data and plans for the Joint Control Application over the Boston and Maine and Maine Central Railroads by Guilford Transportation Industries. A Key issue was insuring that both railroads maintained service levels and key connections under a run-through train service.
5. Based on an interview with Stan Maxwell, the Director of Planning, Boston and Maine RR., Oct. 12, 1981.

### Chapter 2

1. Based on conversations with Joe Dratch, Transportation Data Systems, Nov. 4, 1981; Dennis Wierdak, ICC Rail Service Planning Office, Nov. 3, 1981; and E.R. Peterson, CIGGT, Nov. 20, 1981.
2. Conversation with Steven Rothberg, Southern Pacific Railroad, Nov. 3, 1981.
3. Conversation with Dratch, Nov. 4, 1981; with Wierdak, Nov. 3, 1981; with Peterson, Nov. 20, 1981.
4. Conversation with Peterson, Nov. 20, 1981.
5. Conversation with Dratch, Nov. 4, 1981.
6. Conversations with Dratch, Wierdak, and Peterson (op cit.), conversation with V. Mukhodar, Boston and Maine RR., Nov. 2, 1981.
7. Conversation with B. Ryan, Mgr. of Operations Research Development, Burlington Northern RR., March 31, 1982.
8. Conversation with Peterson and A. J. Taylor, Nov. 10, 1981.

9 Conversation with Taylor, Nov 20, 1981, and Bierdak  
(op cit )

### Chapter 3

1 It has been brought to the author's attention that network models specify "direction" to links. It is believed that the combination of single and double track specification along with the Flagfile structures of Section 3.2 1 make the specification of "direction" unnecessary.

## BIBLIOGRAPHY

- 1 Akyilmaz, Mehmet O , "Level of Service and Volume Relationships for Single Track Railroads", in Proceedings-Transportation Research Forum, Vol. XXII, No. 1, 1981, pp 473-480.
- 2 English, G.W., "An Analytic Model for the Analysis of Congested Rail Lines", in Lake, R.W , et.al. (Ed.), The Eighties: A New Rail Era, pp.203-218, Canadian Institute of Guided Ground Transport, 1978.
3. Ernst and Ernst, A Survey of Software Systems and Computer Programs, report to U.S.R.A , 1979.
4. Frank, Ove, "Two-Way Traffic in a Single Line of Railway", Operations Research, Vol 14, 1966, pp.801-811.
5. Harris, R.G., Restructuring the Railroads: Cost Savings for Branchline Abandonments, FRA Report #FRA-OPFD-80-6, Dec 1977.
- 6 Hay, William W., An Introduction to Transportation Engineering, (Wiley: New York), 1977.
7. Interstate Commerce Commission, A Train Dispatching Model for Line Capacity Analysis: Executive Summary, Rail Services Planning Office, 1976.
- 8 Kant, K., "Dynamic Railway Traffic Control: A New Approach", Rail International, June, 1981, pp.257-263
- 9 Kehr, C.L., Kloer, C.D., and Pai, A.N., "Estimating Railroad Line Capacity", in Proceedings of the 1978 Summer Computer Simulation Conference, pp.427-434, (Afips Press: Montvale), 1978.
- 10 Manheim, Marvin L., Fundamentals of Transportation Systems Analysis, Volume 1: Basic Concepts, (MIT Press. Cambridge), 1979.
11. Manheim, Marvin L., Heirarchical Structure; A Model of Design and Planning Processes, (MIT Press. Cambridge), 1966
- 12 Mao, C.K , and Martland, C.D., "Utilization of Railroad Motive Power: Train Delay Impacts and Organizational Considerations", The Logistics and Transportation Review, Vol 17, No.3, 1981, pp.291-312.
- 13 Martland. Carl D., Lectures in Transportation Systems Performance, Class Notes for MIT Course 1 211, 1981

14. Martland, C.D., Messner, M.G., and Nowicki, Victor, Implementing an Operating/Service Plan. A Case Study of the Boston and Maine, Studies in Railroad Operations and Economics, Vol. 29, Nov. 1980, MIT Report No. CTS 30-3.
15. Morlok, Edward K., Introduction to Transportation Engineering and Planning, (McGraw Hill: New York), 1978
16. Peat, Marwick, Mitchell, and Co., Parametric Analysis of Mainline Capacity, Portion of Section 901 Study of the Railroad Revitalization and Regulatory Reform Act of 1976, Draft Final Report for U.S.D.O.T., Contract No. DOT-FR-65153, Sept. 1977.
17. Peterson, E.R. and Merchant, R., "Scheduling of Trains in a Linear Railway System", submitted to INFOR, February 1978, revised June 1980.
18. Peterson, E.R. and Taylor, A.J., "Line Block Prevention in Rail Line Dispatch and Simulation Models", Queen's University Working Paper 81-4, July 1981.
19. Peterson, E.R. and Taylor, A.J., "A Structured Model for Rail Line Simulation and Optimization", Paper supplied by authors, July, 1981.
- 19A. Philip, Craig E., Improving Freight Car Distribution Organization Support Systems: A Planned Change Approach, Studies in Railroad Operations and Economics, Vol. 34, MIT Report No. CTS 80-17, 1980.
20. Prokopy, J.C. and Rubin, R.B., Parametric Analysis of Railway Line Capacity, DOT Report FRA-OPPD-75-1, 1975.
21. Railroad Research Information Service, Railroad Research Bulletin, prepared for U.S.D.O.T., FRA Report No. FRA/ORD-76-281, Vol. 3, No 2, Autumn 1976.
22. Rudd, D.A. and Storry, A.J., "Single Track Railway Simulation- New Models and Old", Rail International, June 1976, pp.335-342.
23. Transportation Data Systems, Train Simulation/Capacity Model, Brochure from firm, 1981.
24. Van Dyke, Carl D., Microcomputers and the Service Planning Model: Designing A More Useful Tool for the Rail Industry, M.S. Thesis, MIT, 1981.