DESIGN, IMPLEMENTATION AND APPLICATION OF A RAIL TRANSIT SYSTEM SIMULATION MODEL

by

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SYNOPSIS

This work is concerned with the design and applications of a new rail transit system computer simulation model. Advances in computer hardware technology and software engineering methods have enabled the implementation of a versatile and complex model with a consequent increase in the range of application and accuracy of prediction.

The model is essentially time-oriented with an adjustable update period and expandable event-oriented facilities. Its novel features include a bidirectional hyperdigraph rail network representation. This and the representations of the other system components (i.e. timetables, route lists, trains etc.) are dynamically constructed using linked-list structures during the simulation run. Different traction equipment models can be incorporated into to the model. Movement calculations, when performed, take all train and track parameters into account. Interaction between trains through a traffic regulation system is also considered. New software modules e.g., an energy demand calculator can easily be interfaced. The simulation model is supported by a considerable number of pre and postprocessing programs.

A number of studies have been carried out with the simulation model. Thus, it has been demonstrated that the model is structurally suitable for a large set of applications on both mass rail transit and mainline type systems.

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LIST OF PRINCIPAL SYMBOLS

CHAPTER 2

u : train speed

z : signal block length

n : number of blocks

$d(u_1, u_2)$: distance required to brake from u_1 to u_2

l : train length

p : overlap distance

s : sighting distance

h_d : headway distance

c : line capacity

t : passenger throughput

k : number of train units

b_g : braking rate due to gravity

G : value of track gradient expressed as percentage

CHAPTER 6

T_f : tractive effort

T_{mech} : mechanical braking effort

u_L : base speed

α : chopper mark/period ratio

I_A : armature current

V_L : line voltage

I_L : line current

E : induced voltage

V_b, V_d, V_t : voltage drops in brushes, diodes and choppers

R_L, R_T : line and total resistances

ϕ : flux

k : DC motor constant

n : motor speed

Δx_{n+i-1} : length of track under i th gradient section

g_{n+i-1} : value of gradient under i th gradient section

m_t : total train mass

G_e : effective gradient

F_r : train resistance force

n_x : number of axles per car

F_c : curve drag force

C_e : effective curvature

F_n : nett force of acceleration or deceleration

a : train acceleration or deceleration rate

m_e : total effective mass

Δd_n : train displacement per update period

CHAPTER 8

P_t : electric power input to each locomotive

u_a : average train speed over an update period

ϵ : electrical efficiency of a locomotive

n_x : number of active locomotive

P_a : auxilary load for each locomotive

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CHAPTER 1

INTRODUCTORY CHAPTER

1.1 AIM OF THE STUDY

The movement of trains is central to all rail transit system operations. Consequently, it has been the topic of considerable studies in the recent years. Typical objectives of these studies have been :

1. Planning e.g., to verify cost/benefits of capital improvement or special operational modes.
2. Scheduling e.g., to verify timetables, to develop and test alternative timetables, to experiment with station stop and runtime variations. Queuing, terminal and route capacity, disturbance analyses.
3. Engineering e.g., to design, test and verify signalling schemes, to optimise layout of rail network, to develop and test local/system control strategies, to estimate the energy demand.

The train movements within a rail transit system are hardly amenable to analysis using 'analytic models'. The analytic models developed so far have been either superficial [1] or limited to the solution of a specific rail transit system problem [2]. Alternatively, the behaviour of a rail transit system as it evolves over time can be studied by developing 'simulation models'. The characteristics of a rail transit system meet two of the classical situations in which simulation models are applicable [3]:

1. **The limitation of analytic models :** If available, analytic models generally produce more elegant solutions. The complexities and diversities of rail transit systems, coupled with the nonlinear and random nature of train operations, prevent the comprehensive use of analytical models. In many rail transit system problems, no analytic model is available at all and simulation is the only means of deriving a solution.

2. **The difficulty of experimentation with the real system :** An operating rail transit system can rarely be made the subject of controlled experiments and any partial experiment is seldom representative of the general case. Simulation models can also be used to study systems in the design stage.

System models which are not amenable to analytic solution form a subset usually known as 'simulation models'. Computer simulation models usually takes the form of a set of logical/mathematical assumptions concerning the operation of the system. A 'simulation run' involves the generation of an artificial history of the system by imitating its operations at the required level of detail, and then the observation of that artificial history to draw inferences concerning these operations. Rail transit system operators and designers have recognised the existence of the simulation approach and have made extensive use of 'simulation models' of various types to aid the analysis, design, operation, prediction and control of their systems. The advances in the computer technology indicate that this trend will continue. The other main advantages of the simulation approach are :

1. Whereas analytic models require many simplifying assumptions to make them mathematically tractable, simulation models offer a more adequate

representation of a real-world rail transit system. The use of computer simulation models in the rail transit system area has allowed much more detailed studies to be performed compared to the alternative analytic models.

2. Once a computer model is built, it can be used repeatedly to investigate a wide variety of 'what if' questions about the real system. With analytic models, only a limited number of system performance measures can be computed whereas a large amount of data can be generated with a simulation model which then can be used to estimate many performance measures.

3. Minor structural changes in models may call for an entirely different approach for solution by analytic models, whereas the overall simulation model remains the same.

4. Simulation models can be used to analyse a system even though the input data are sketchy.

After a detailed survey of the existing rail transit system movement simulation models, it has been concluded that the potential capacity of simulation modelling has not been fully explored in the rail transit system area, especially for large scale networks. The main drawbacks of large scale simulation models have been :

1. Oversimplification : Schmidt et al. [5] list some of the disadvantages of large scale simulation. Due to advances in the computer technology and software engineering methods, the argument concerned with the construction, validation costs and the cost and speed of a simulation run is ameliorated and cannot be justified any more. However, these have been the concerns of many movement simulator developers and the justification for some oversimplified models. Naturally, a simulation model is not only a substitute but also an 'adequate' simplification of a real system but if a model is oversimplified as in many large scale simulation models, it will be an inadequate representation of the real system with a consequent decrease in its generality and accuracy of the predictions.

2. **Problem Orientation :** Many simulators also suffered from being problem-oriented. If a model is problem-oriented different models of the same system or new models of different systems will be required as the purpose of the simulation changes. Initially, such problem-oriented models are easier to build but it is more difficult and expensive (if not impossible) to extend their range of applications.

3. **Lack of Software Engineering Approach :** The existing time-based models were implemented in languages that do not support modern software engineering techniques and using outdated simulation methods. The general lack of vital details about the model itself in the literature can be considered as a sign of the absence of a software engineering approach to the design more than a commercial concern.

The project described in this thesis is primarily concerned with the design, implementation and applications of a multipurpose large-scale rail transit system computer simulation model. The advances in the computer technology, software engineering methods and high-level languages have made a versatile, complex and fast model possible with a consequent increase in the application areas and accuracy of predictions. This new model essentially simulates the movements of individual trains on a rail network integrating the equations of motion. The interactions between different trains are also considered. Independence of any particular rail transit system, adjustable level of detail in the representation of a system and movement calculations and adaptability for the analysis of a broad range of problems have been considered to be its prime features. The model has aimed to be structually suitable for large scale complex networks and mixed traffic situations. Small areas of mainline systems (e.g., yards,terminals) and the simpler structures of rapid and light rail transit systems can also be simulated at any level of modelling and calculation detail.

1.2 THESIS STRUCTURE

The project has been broken into three phases and its presentation in this thesis follows the same order. Chapters 2 and 3, describes the essential features of rail transit system control and identifies the system components common to all systems. The simulation model design and implementation phase is described in Chapters 4,5 and,6. The applications of the simulator to four diverse real-world systems with three different objectives are discussed in Chapters 7 and 8.

Chapter 2 : In this chapter, the principles of fixed-block and moving-block signalling are analysed with a unified approach. The chapter also reviews the various fixed-block schemes adopted by different rail transit systems. Determining the similarities and differences between various signalling schemes has provided the necessary basis for their modelling and simulation.

Chapter 3 : This chapter summarizes two most important components of a rail transit system. It describes the main requirements and tasks of train operation control subsystems. In this context, it reviews track circuit principles, route setting and release methods, signal and junction control techniques and automatic train control principles. Some practical installations are also discussed. AC and DC Power supply subsystems are briefly described and compared at the end of this chapter.

Chapter 4 : The use of computer simulation as a technique to model rail transit systems is discussed in this chapter. A classification and comparison of existing simulation models is presented. This discussion leads to the specification of the new simulation model and the justifications of design tool choices i.e. programming language and design methodology.

Chapter 5 : The design of the simulation model has been as much art as science. The main data structures of the model have been identified as rail network, a combined time/route table, trains and precalculated speed profiles. Appropriate representations of these have then been devised. This chapter summarizes the data structure design phase. These data structures and their relationships are also described. Special consideration is given to their implementation in the software.

Chapter 6 : This chapter describes the traction equipment models which have been developed for different simulation applications. The methods, which operate on the data structures described in Chapter 5, that calculate and control the individual train movements and supervise the system operations are discussed in this chapter. The chapter ends with an overall description of the modular software structure.

Chapter 7 : This chapter presents the simulation conditions and the results of the traffic control experiments. It outlines the characteristics of the rail transit systems (i.e. Dockland Light Railway System and Waterloo & City Line) , which are the subjects of traffic control experiments, with reference to their representations in the simulator. The first system has been simulated to investigate its operation with different headway times. In order to demonstrate the independence of the simulation model of any particular system, further simulation runs have been carried out to examine a terminus turnaround situation on the second system.

Chapter 8 : This chapter investigates the maximum energy demand control problem of a large scale mainline system (i.e. Central Division of Queensland Railways). The system is simulated with the objective of estimating its energy demand patterns under different operating conditions. The results of the simulations are analysed and a realtime demand control system, in which the simulator is used to predict future events, is proposed.

Chapter 9 : The thesis is concluded in this chapter with suggestions for further applications of the simulation model and proposals for further work.

CHAPTER 2

A UNIFIED APPROACH TO SIGNALLING SCHEMES

2.1 INTRODUCTION

Whenever more than one vehicle move along a fixed guideway, then vehicle separation has to be carefully controlled. For 'trains' the braking distance usually exceeds the driver's sighting distance, hence signalling has traditionally been employed to maintain a safe distance (i.e. equal to or greater than service braking distance) between two consecutive trains on the same track (i.e. fixed guideway). The other objective of the signalling is to safeguard the movements of trains at conflict areas such as junctions, crossovers, terminals etc. where two or more trains would otherwise occupy the same piece of track at the same time. In modern rail transit systems the train movements can be controlled through these installations with further objectives e.g. increased line capacity, minimised energy consumption or timetable recovery.

The aim of this chapter is to investigate the principles of 'line side', 'cab' and 'coded track circuit' continuous or discrete fixed-block signalling and moving-block signalling schemes with their applications to various types of rail transit systems. The analysis in this chapter assumes ideal single track conditions with no directly opposing routes. The role of signalling in conflict area control will be discussed in Chapter 3.

The basic terminology used in this thesis for signalling problems is described below :

Fixed Block Signalling (FBS) : Conventional signalling schemes employ techniques in which a track is subdivided into a series of fixed sections, called blocks, dependent on the maximum train speed and the worst case service braking rate. Operations are based on the principle that a block occupied by a train causes the following block or blocks to assume restrictive aspects which ensure that any one time minimum train separation is greater than service braking distance. This is the most widely used form of signalling, for both metro and main line operations. In some modern schemes block occupancies are continuously monitored and conveyed to relevant trains.

Moving Block Signalling (MBS) : With the fixed block schemes, the position of a train is determined by the occupancy state of one or more blocks. This represents a very crude form of positional resolution. Alternatively, a fast control system enables the separation between two trains to be regulated according to maximum train speed (MSB - moving space block) or the speed of the following train (PMB - pure moving block) or a constant time separation (MTB - moving time block). Hence , a hypothetical block exists between the two trains.

Indications : Instructions concerning the movement of the train. These instructions are conveyed to the train by visual colour signals or track codes.

Aspects : The subset of indications required for a safe train separation.

Service Braking Distance : The distance required for a train to brake to 'standstill' from a particular speed, usually the maximum line speed.

Sighting Point : The point at which the driver (or an automatic train operation system) would commence a brake application in order to stop at a stop point. For the most of the rail transit systems this distance is assumed to correspond with the entrance of the signal block with the least restrictive signal aspect during the signal layout design.

Overlap : The distance ahead of a 'stop' signal that must be unoccupied before a train may approach that signal from the rear. Overlap is a British practice, in some other applications a full 'forbidden' signal block is required after the 'stop' aspect.

Headway Time : The time between two following trains on the same line passing a given point. The minimum, or design headway times for nonstop trains would require both trains to travel at the speed for which the line is signalled. For stopping trains the design headway time would include a braking period, a station stop and an accelerating period as discussed later.

Headway Distance : The distance which corresponds to headway time.

Line Capacity : In its simplest form it is the maximum number of trains per hour permitted by the signalling scheme, but under mixed traffic conditions definite values of line capacity can be quoted only in relation to the traffic pattern on the line.

Train Length : In this chapter, train length always refers to that length used in the signalling design, but in practice, train length is not necessarily equal to this fixed length.

2.2 ROUTE AND SPEED SIGNALLING PHILOSOPHIES

A common problem for rail transit system operators has been to adopt a multi-aspect signalling scheme which meets all the various conflicting criteria imposed by different train services without being very complicated or containing ambiguities i.e. the same indication means different things in different circumstances. A number of countries in the world have developed their rail transit systems under different circumstances and therefore have adopted different operation practices and principles. This is particularly pertinent in the field of fixed block signalling where there exist fundamental differences on both mathematical and philosophical grounds.

One of the fundamental divisions in signalling philosophies concerns speed and route signalling. The main difference between the two schemes is that whereas route signalling is implicit, speed signalling is explicit. In other words, although both are based on a common foundation of a fixed block separation, the route signalling philosophy simply tells the driver the route information only i.e. where he may be required to stop, whereas the speed signalling instructs the driver how to control the train explicitly. For route signalling, the minimum block length for a 'n aspect n-2 block' signalling scheme is given by:-

$$z = \frac{1}{n-2} d\ (u_m, 0) \qquad (2.1)$$

where d $(u_m,0)$ is service braking distance from maximum line speed to stand still and n-2 is minimum number of signal blocks which separates two consecutive trains in a n aspect fixed block signalling scheme.

The speed signalling philosophy is based on the approach that a train should at all times be told precisely what to do next. Thus, the greater the mix of train types, speed etc., the greater the number of indications required to indicate target speeds (i.e. the speeds which the train should aim for) comprehensively along the routes. In this case block length is:-

$$z = \max (d(u_m, u_1), d(u_1, u_2), \ldots d(u_n, 0)) \qquad (2.2)$$

If the target speeds are optimised for the same train braking curve as that used to space the signals in a route signalled scheme, then Equations 2.1 and 2.2 will yield the same result [6]. Headway distance (minimum train separation) can either be n-1 or n blocks in both schemes.

Speed signalling schemes are logical and successful when applied to homogeneous trains with constant characteristics such as rapid transit systems (i.e. light rail or metro) or purpose-built high-speed railways. However, in speed-signalled mixed traffic systems nominated target speeds, which are not easily changed, must exist and generally there is a conflict between the optimum and the nominated speeds. Consequently, the complexity of the speed signalling scheme increases if line capacity optimisation is the main criterion. It is argued that, particularly in mixed traffic conditions and with manually driven trains, better use of line capacity and better regulation of traffic is achieved by relying on the driver's judgement [7] [8] but, the success of route signalling schemes depends entirely on the route knowledge of the driver. These schemes are also comparatively expensive to automate since complex track-to-train communication systems are required. Therefore, it must be concluded that hybrid route and speed signalling schemes give the best solution for mixed traffic situations [7].

From earlier definitions and from Equations 2.1 and 2.2 one can conclude that an increase in the number of aspects n will increase line capacity by shortening lengths of signal blocks and therefore reducing minimum train separation (i.e. headway distance) which is n or n-1 blocks. But it must be kept in mind that analysis throughout this chapter assumes ideal track conditions. No allowances are made for jerk limiting, or the delays associated with protection equipment and brakes, except sighting distance allowed for manually driven trains. Together with the effects of short block lengths and relatively long station waiting times, an increase in the number of aspects will not necessarily increase capacity [9].

2.3 REVIEW OF MAINLINE SIGNALLING PRACTICE

All of the present mainline signalling schemes employ fixed multi-aspect lineside signals (some with cab signals), and will probably continue in this way for many years to come. Therefore, it is important to ensure that any signalling scheme makes effective use of a multi-aspect scheme. In addition, there is an increasing demand for high speed passenger trains and in most of the cases the problem of high speed signalling cannot be considered in isolation. Unlike a purpose-built line with no other traffic than high speed passenger trains, when a solution is attempted on existing lines, it must be designed as an addition to existing (and already problematic) mixed traffic signalling schemes [6] [10]. The aim of this section is to give an overview of world mainline signalling practice and to highlight the various solutions being adopted to run high speed trains on the existing or the purpose-built lines.

Main line signalling schemes vary quite considerably in complexity, e.g. the number of indications in a sample of 31 mainline rail transit systems varies between 3 and 24. The differences in international practice in connection with the meaning and number of signal aspects and indications is not only a matter of safety or even philosophical standards but also of the choices made which do not appear to depend on current conditions but purely historical precedents.

Today British Railways (BR) with its signalling practice stands almost alone by leaving discretion and integrity to the driver to a significant extent. BR's 4-aspect signalling scheme displaying red, double yellow, yellow, green aspects, concentrates on an 'automatic warning system' (AWS) which supports drivers by audible and visual indications at caution and stop signals, with non-mandatory application of the brakes which makes it less safe than those systems that use automatic brake application. Recent accidents have tragically confirmed this point. The BR signalling scheme started out as an ideal route signalling scheme but has been continually modified in an ad hoc manner in the light of experience, e.g. AWS which was intended as a crude reminder of lineside signals, has now been used for non-signalling speed restrictions.

A 4-aspect speed signalling scheme is used in the U.S.A.. A common restrictive speed value is defined in this scheme whereas it depends on the class of train and the route knowledge of the driver in BR practice [11].

The 3-aspect route signalling schemes displaying red, yellow and green aspects (i.e. stop, warning, clear) are in use on both Italian and French Railways. The two schemes differ in the additional indications they use; for example a yellow-green indication for a speed restriction ahead. Unlike BR practice brake application is mandatory and must commence at warning indication on approach to a stop signal so there is no overlap distance in these schemes. German Federal Railways employs 3-aspect speed signalling. The speed information is conveyed to the driver in the form of additional special indications.

Canadian National Railways adopted a speed signalling scheme for single line mixed traffic situations. The target speeds are slow, medium, limited and maximum, 15, 30, 45 and 60 mph respectively, for freights and up to 95 mph for passenger trains. The main aim of this scheme is to provide uninterrupted movement of freight trains in order to save energy by avoiding stopping and restarting [7].

An interesting example of mixed traffic speed signalling scheme which could loosely be named as the East European type is shown in Figure 2.1.

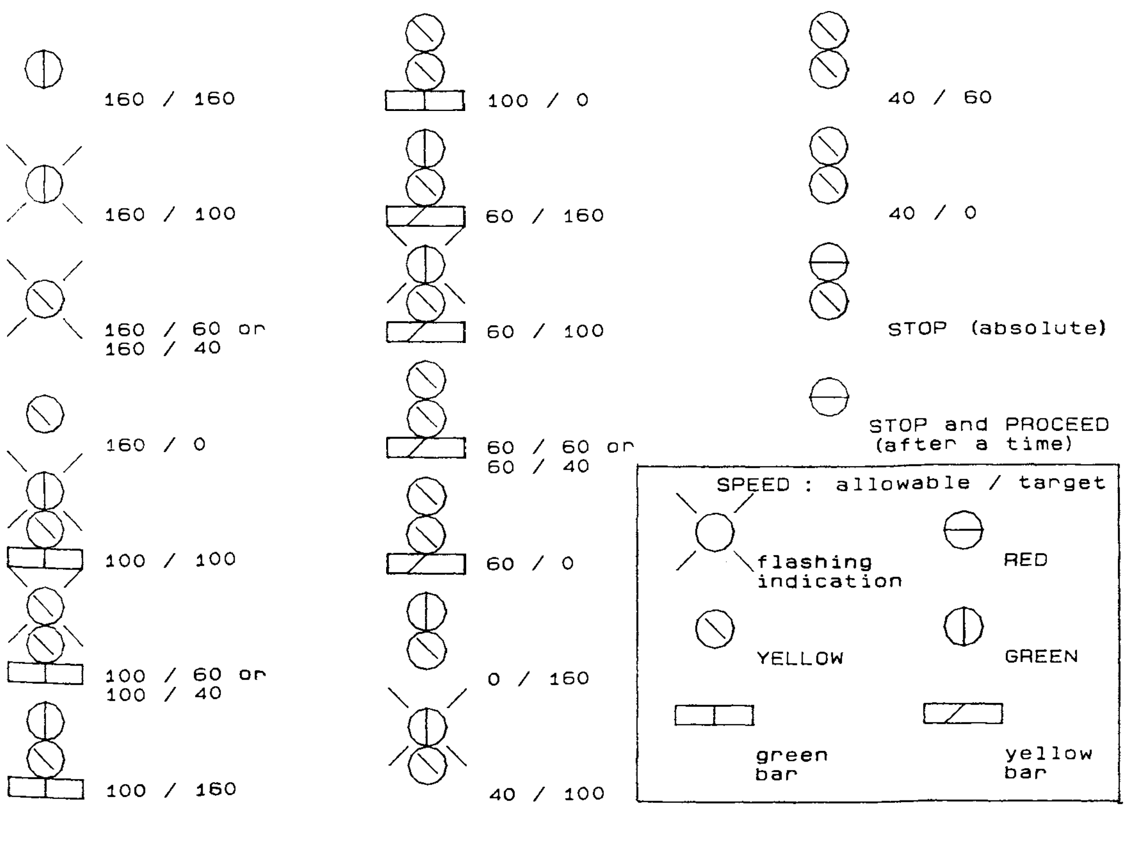


FIGURE 2.1 _ A TYPICAL EAST EUROPEAN TYPE OF ARRANGEMENT.

The maximum speed (160 km/h) is comparable with British or French signalling practices. In this scheme practically everything is indicated and no fewer than 17 indications can be conveyed to the driver e.g., the scheme accommodates direct ways to display instructions to 'decelerate from 160 km/h to 100km/h' and 'continue at 100 km/h' which means exactly the same thing for a train already travelling at 100 km/h. If only target speeds were to be indicated a considerable reduction in the number of indications could be achieved. In this scheme braking distance differs between 1 and 3 blocks (i.e. 2 and 4 aspects) depending on the characteristics of different line sections and trains.

High speed trains running on purpose-built lines like the Tokaido line in Japan [12] and the TGV (high speed train) lines in France naturally use speed signalling schemes with equal-length blocks. Southeast and Atlantic TGV lines utilize 5 and 6 aspect cab signalling schemes respectively [13]. Those trains usually do not have full automation and allow the driver some discretion so the signalling philosophy has to be judged on a somewhat different basis to that used in metro type speed signalling. The aspects are indicated in the cab (cab signalling) for two reasons; at such high speeds (e.g. 300 km/h for TGV) to rely on the observance of lineside signalling by the driver is unsafe and drivers can take advantage of a changing signal aspect immediately. In these applications, the aspects are also used to indicate the speed restrictions at particular points or junctions [12], but being modern purpose-built systems track layout is affected by few constraints and contain few curves and a small number of speed restrictions so the speed can be kept at a maximum.

An obvious compromise between the demand for high speed trains and the large investment needed for purpose-built high speed lines is to run higher speed trains on existing lines. For such applications high speed is defined above the speed the line is presently signalled for, but in a range where the principles of conventional signalling still remain valid with a few additions. It is a common observation of different operators that quite a number of existing lines are adequate (perhaps with limited modifications to the layout) for mixed commercial traffic at higher speeds. To achieve higher speeds on existing lines Italian State Railways choice was to use cab signalling with existing 3-aspect lineside signalling. As shown in Figure 2.2, the cab signal indications are the same as those of lineside signals except for green which is repeated by white or green depending on the free sections ahead. This solution adds one more aspect to the present scheme [14].

SITUATION AHEAD	LINESIDE SIGNAL	CAB SIGNAL
1st block occupied	RED	RED
2nd block occupied	YELLOW	YELLOW
3rd block occupied	GREEN	WHITE
1st, 2nd and 3rd blocks free	GREEN	GREEN
1st, 2nd and 3rd blocks free with speed restrictions	YELLOW-GREEN	"RV"

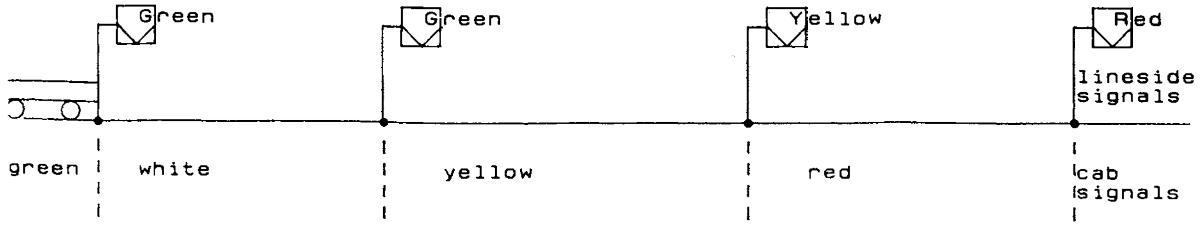


FIGURE 2.2 _ ASPECTS OF ITALIAN RAILWAYS' LINE SIDE AND CAB SIGNALLING.

French mixed traffic high speed trains are also provided with cab signalling superimposed on the existing signalling scheme. The high speed trains mainly running on purpose-built lines necessarily use conventional lines on their terminal routes and frequently take routes alongside conventional lines, for this reason the two signalling schemes are designed to be compatible, with one or two less aspect on the mixed traffic one. Being a pure speed signalling scheme the French scheme is more explicit than the Italian one [6].

When faced with the need to run trains at speeds up to 250 km/h, the German authorities opted for continuous control of train movements, rather than adapt the existing scheme or provide improved braking [15]. It is possible to begin braking trains from 250 km/h before they reach the restrictive aspect which gives the driver visual information of the need to stop at the next signal. The scheme is a cross between fixed-block and moving-block signalling schemes. It improves the overall performance of the rail transit system, since it does not rely on existing signal blocks for braking but, train detection is still done by fixed track circuits [7].

The traffic density expected on the Northern TGV Line of France, which will begin revenue service in 1993, is higher than the existing two high speed lines. On the Atlantic TGV Line headway time has been cut from 5 minutes to 4 minutes and the maximum speed has been increased from 270 km/h to 300 km/h by upgrading the existing Southeast TGV fixed-block cab signalling scheme with an additional aspect. The Northern Line is a 3 minute headway time line for an operating speed of 300 km/h. The number of aspects will not be increased, instead German type continous speed supervision will replace the discrete speed supervision of the fixed-block signalling schemes. This speed supervision scheme will be imposed on a Atlantic Line type 6-aspect fixed-block signalling scheme [13].

British Railways regards the present signal layout with the standard 2-indication AWS adequate for speeds up to 200 km/h but, a new arrangement is considered necessary for their new high speed trains which have a maximum speed of 225 km/h. The initial decision was to retain the 4-aspect signalling scheme and to incorporate the indications in the cab. Braking instructions can be conveyed either at the lineside signal preceding YY (double yellow) or at the exact point where braking should commence. The first option upgrades the existing scheme to 5 aspects while the latter has the advantage of increasing commercial speed and line capacity despite its philosophical incompatibility with the existing scheme [7]. Despite the known fact that the higher the speed the more failure prone the drivers perception of the lineside signals, BR have opted for a cheaper 5-aspect line-side signalling scheme for the East Coast Mainline. Flashing green has been defined as the 5th aspect for high speed trains.

2.4 ANALYSIS OF FIXED BLOCK SIGNALLING SCHEMES

2.4.1 2-aspect Signalling

There are mainly two types of this basic form of signalling in practice, that for rapid transit systems and that for mainline rail transit systems.

2.4.1.1 2-aspect Mainline Signalling

The BR 2-aspect signalling scheme shown in Figure 2.3 would be appropriate to a line with limited service, albeit including trains travelling at high speed (140 km/h or more). The signal spacing might not be governed so much by the service to be run as by certain fixed points on the same line such as stations or siding junctions where signals are required for other reasons. This signalling scheme would also be suitable for single lines [16].

The headway distance from Figure 2.3 is:-

$$h_d = l + p + x + d\,(u_m, 0) + s \qquad (2.3)$$

where l is train length

p is overlap distance

s is sighting distance.

Expressed in terms of time, the headway in time is :

$$h_t = \frac{1}{u_m} h_d \qquad (2.4)$$

The capacity of the line expressed in terms of the number of trains passing a given point per hour is :

$$c = \frac{3600u}{h_d} \qquad (2.5)$$

In order to maximise capacity it is clear that x must be decreased.

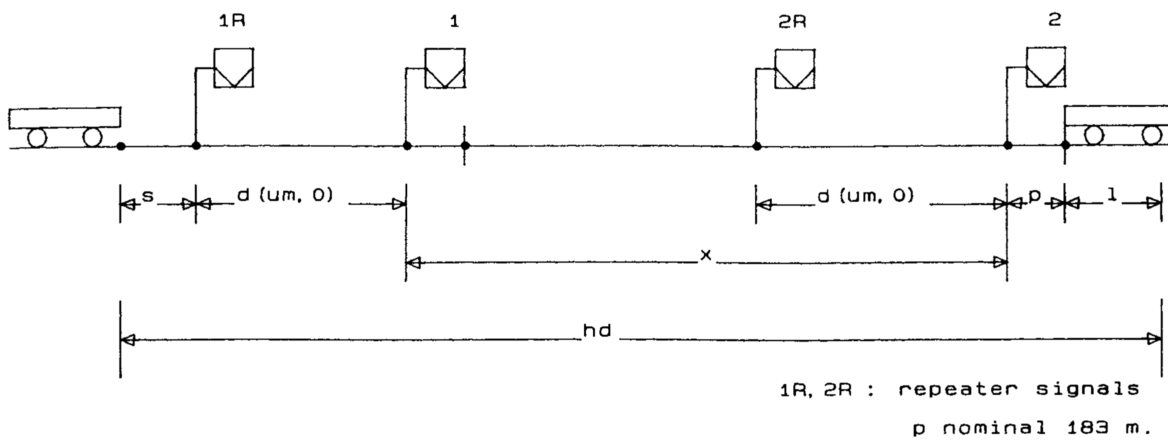


FIGURE 2.3 _ BRITISH RAILWAYS 2 ASPECT SIGNALLING.

2.4.1.2 2-aspect Rapid Transit Signalling

The 2-aspect colour light signalling in Great Britain originated on the lines of London Underground where speeds are relatively slow, braking rates are high and sighting conditions ideal, except where curvature intervenes. If the stop signal cannot be seen at a sighting point a yellow/green repeating signal is provided which is effectively a continuous sight of the stop signal from the sighting point. In some cases more than one repeater signal is needed, the effect of this practice is to take immediate advantage of the stop signal clearing [19]. The arrangement is shown in Figure 2.4.

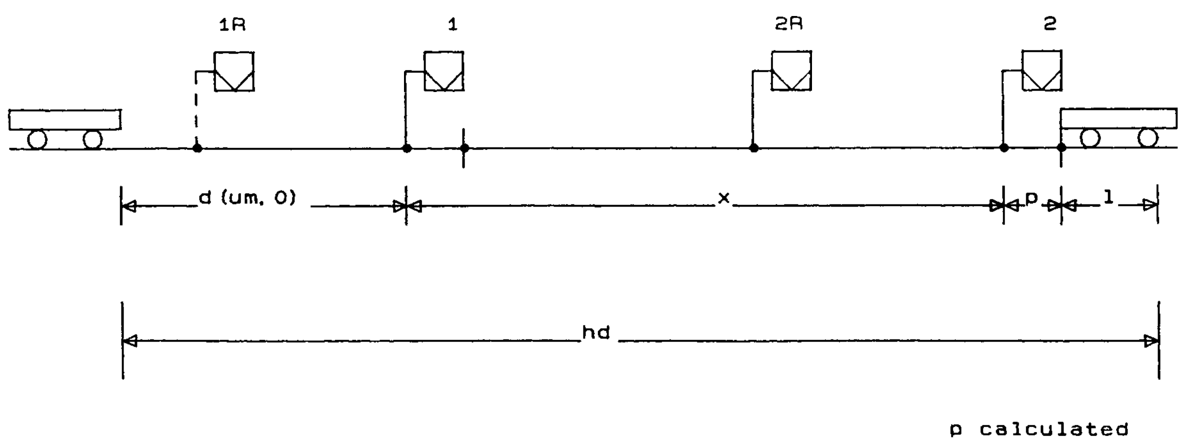


FIGURE 2.4 _ LONDON UNDERGROUND'S 2-ASPECT SIGNALLING.

The Victoria Line, operating under the ATC (Automatic Train Control) system employs this signalling scheme with a special arrangement for platform stops. Associated with each signal are three control points as shown in Figure 2.5.

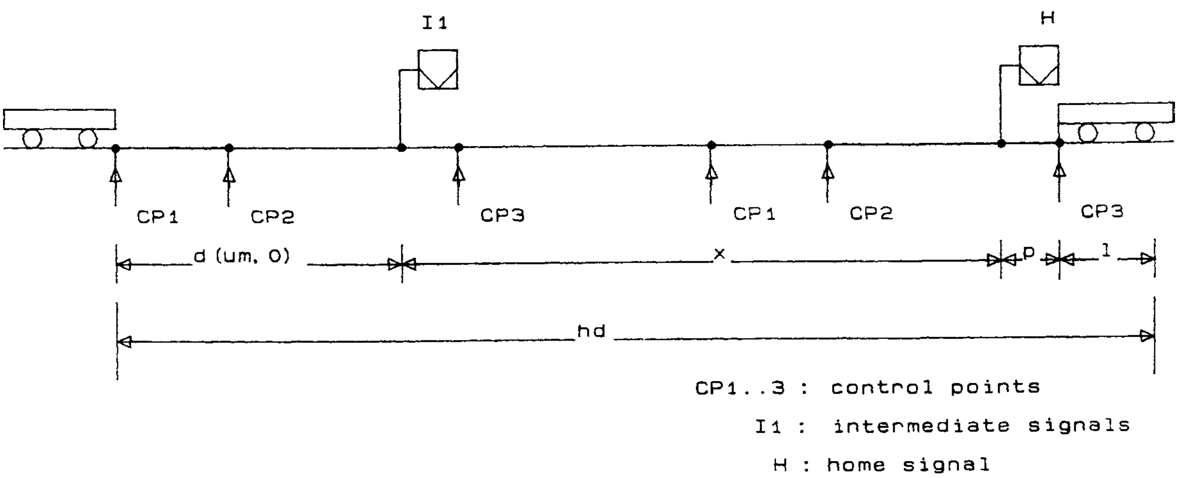


FIGURE 2.5 _ LONDON UNDERGROUND VICTORIA LINE SIGNALLING.

The first control point P_1 refers to sight of the signal ahead. This is placed at a distance in advance of the signal allowing for a maximum speed of 75 km/h. As the train brakes for a stop signal, point P_2 will be reached where its speed has to be reduced to 40 km/h.The braking instruction can be cancelled at P_2. In this application, the headway distance is :

$$h_d = l + p + x + d\,(u_m,0) \tag{2.6}$$

Note that in this application x may be smaller than d to balance headway time for a station to station run.

In this rapid transit application the headway time can significantly increase as a result of relatively long station stops. This problem is particularly important when trains are operating close to design headway [17].

To reduce the effect of station waiting time on headway time a method known as 'controlled speed approach' is used by London Underground. Here, as a train moves away from a station, it successively clears a series of overlaps called 'moving overlaps'. This arrangement allows the next train to enter the platform very closely behind the first train, but at reduced speed [18].

2.4.2 3-aspect signalling

For the conventional applications of colour light signalling a limit will be reached when x becomes equal to d, giving rise to a 3-aspect signalling scheme [16]. The equations applicable to such a scheme are:-

$$h_d = l + p + 2\,d(u_m,0) + s \tag{2.7}$$

$$h_t = \frac{1}{u_m}\;h_d \tag{2.8}$$

$$c_3 = \frac{3600u_m}{h_d} \tag{2.9}$$

If the service braking distance is assumed to be proportional to the square of speed, via. $d(u_m,0) = ku_m^{\,2}$ and taking l, p and s as constant, Equation 2.9 reduces to :-

$$c_3 = \frac{k_1\,u_m}{k_2 + 2ku^2} \tag{2.10}$$

$k_1 = 3600$ and $k_2 = l + p + s.$ (2.11)

Therefore, there is a maximum value of C_3 given by:-

$$u = \frac{k_2}{2k} \tag{2.12}$$

which means that there is an absolute limit to the capacity which a 3-aspect 2-block signalling scheme can yield and this occurs at a definite optimum speed discussed in Section 2.4.6. The service braking distance of the fastest train is not necessarily the most important factor. Strictly, $d(u_m,0)$ is the longest braking distance of all the various types of trains which travel over the line. A typical West European 3-aspect arrangement is shown in Figure 2.6. Note that both s and p are equal to zero.

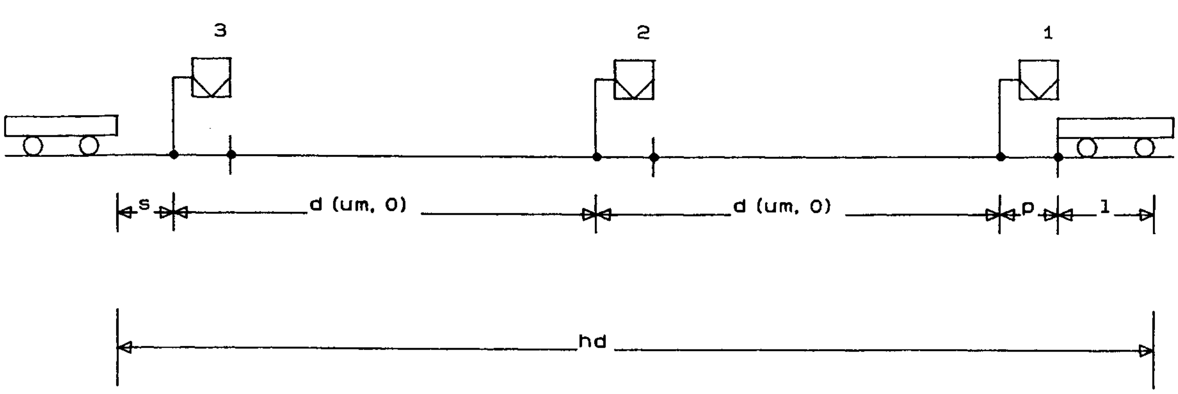


FIGURE 2.6 _ 3 ASPECT 2 BLOCK SIGNALLING.

2.4.3 4-aspect Signalling

To keep trains moving at a higher speed and with closer spacings

4-aspect signalling is used. Referring to Figure 2.7 it is apparent that the headway distance for route signalling is:-

$$h_d = l + p + s + \frac{3}{2} d\ (u_m, o) \qquad (2.13)$$

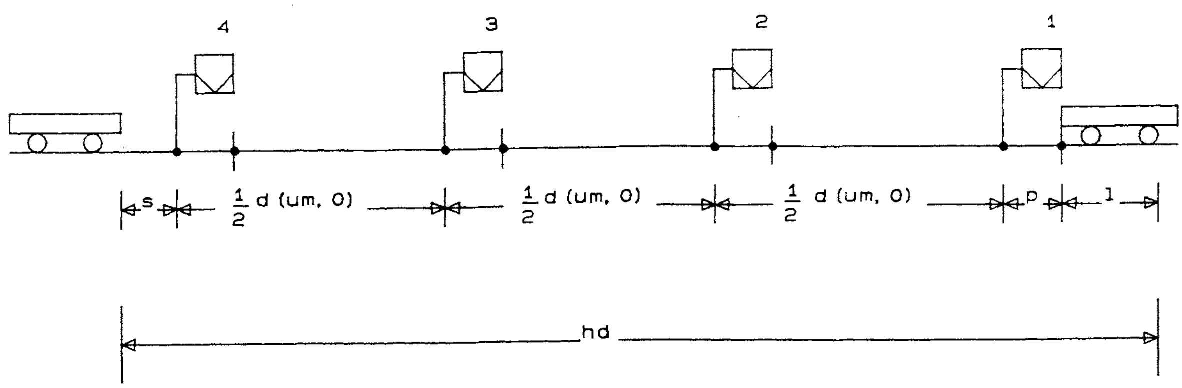


FIGURE 2.7 _ BRITISH RAILWAYS 4 ASPECT 3 BLOCK SIGNALLING.

2.4.3.1 4-aspect Mainline Signalling

Only the 4-aspect signalling scheme has so far found general application on British Railways. As set out by the rule book [16] different aspects of BR's route signalling practice are :

Red	**(R)**	- Stop
Single Yellow	**(Y)**	- Proceed preparing to stop at next signal
Double Yellow	**(YY)**	- Proceed preparing to pass next signal at restricted speed implicit.
Green	**(G)**	- Clear, Proceed

In BR practice headway distance can be adjusted by changing the signal spacing z :-

$$h_d = l + p + s + 3z \tag{2.14}$$

where h_d' is the design headway and $z > \frac{d(u_m,0)}{2}$

The capacity for the trains which the line is signalled for :-

$$C_4' = \frac{3600u_m}{h_d} \tag{2.15}$$

Although the scheme is designed for trains travelling at speed u_m, it can also cater for another class of trains (e.g. suburban trains) travelling at speed u_1 provided that the block length z provides at least adequate braking distance for the trains in question to enable them to treat the double yellow aspect as a proceed indication. The capacity of the 4-aspect scheme for such a service is :

$$c = \frac{3600u_1}{l + p + s + 2z} \tag{2.16}$$

Equation 2.16 is analogous to Equation 2.10 except signal spacing s is independent of u_1 and determined by the service for which the 4-aspect scheme has been designed. [16]

In the U.S.A. practice, the aspects and their indications as set forth by the AAR standard code [11] are:-

RR - Stop

YR - Proceed preparing to stop at next signal

YG - Prepare to pass next signal a restricted
speed - 30 m.p.h. explicit -

GG - clear

In this speed signalling application, signal spacing is :

$$z > \max (d\ (u_m, u_1),\ \ d\ (u_1, 0)) \qquad (2.17)$$

2.4.3.2 4-aspect Rapid Transit Signalling

A number of different signalling strategies have been proposed for mass transit systems with the aim of increasing their capacities by reducing headways. However, a 4-aspect 3-block cab or lineside signalling strategy is preferred by the majority of metro systems throughout the world. These systems differ in their signal block layout constraints. Three target speeds are defined and therefore the aspects are u_m/u_m, u_m/u_1, $u_1/0$ and 0/0 (i.e. forbidden block). In practice these three speeds do not necessarily take the same values for the entire line. The usual constraint on block lengths is same as Equation 2.17. However, for the Montreal metro an unusual overall constraint on block length is defined [20] :

$$z_i > \max (d_i\ (u_1,\ 0)\ ,\ [d_{i-1}(u_m, 0) - z_{i-1}]) \qquad (2.18)$$

In this application u_1 is usually sufficiently large for $d_i\ (u_1, 0)$ to predominate for all i. Derivation of the constraint is given in Appendix 1A.

2.4.4 5-aspect Signalling

The headway distance expression applicable to a route or optimized speed signalling scheme is :

$$h_d = l + p + s + \frac{4}{3} d (u_m, 0) \tag{2.19}$$

In this case trains must be separated by a minimum of 3 blocks. Rail transit systems which use 5-aspect signalling diverge from the minimum requirement given by Equation 2.19.

2.4.5.1 5-Aspect Mainline Signalling

A 5-aspect speed signalling scheme is adopted by the SNCF on the South-east TGV line. In this scheme braking distance is 3 blocks and train separation is 5 blocks including a 'forbidden block' for safety. The block lengths are a constant 2000 m. The aspects ,also called intermediate speed steps, are defined as 270/270, 270/220, 220/160, 160/0, 0/0 [13].

2.4.4.2 5-Aspect Rapid Transit Signalling

Two example metro systems, Hong Kong and Singapore, are both operating under ATC and track codes are used instead of lineside signals [21] [22] [23]. These signalling schemes are named 4-aspect but conceptually, the manufacturer's definition of aspects as being target speed leaves the stop aspect undefined and their operations are analogous to 5 aspect line-side signalling. In these schemes 3 blocks are required for a train to stop from its maximum speed and trains are separated by a minimum of 5 blocks :

$$h_d = 1 + 5z \qquad (2.20)$$

Compared to Equation 2.19 overlap and sighting distances are eliminated but an additional block is added for safety. Associated with each block is a code, which is basically a two figure indication referring to the maximum speed at which the train is allowed to proceed on the particular signal block and to the target speed which the train should attain on leaving the block. Thus, in this arrangement each block would have a length of :

$$z > \max(d(u_m, u_1), d(u_1, u_2), d(u_2, 0)) \qquad (2.21)$$

On a flat track all block lengths would be equal. It may be necessary to change the lengths of blocks according to track geometry to achieve equal headway distance or equal headway time. In practice equal headway distances which are based on worst case braking distances are preferred. If target speeds are optimised, the constraint on block lengths is :

$$z > \frac{1}{3} d (u_m, 0) \qquad (2.22)$$

The rapid transit arrangement of 5-aspect signalling is given in Figure 2.8.

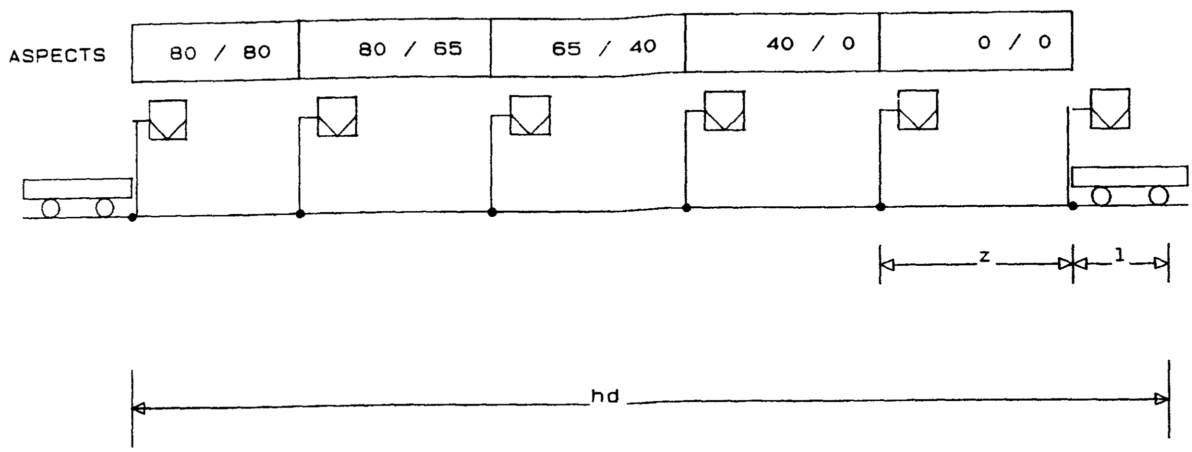


FIGURE 2.8 _ HONG KONG MRT 5 ASPECT 5 BLOCK SIGNALLING.

It should be noted that the analysis above, like the others in this chapter, assumes ideal conditions and no allowances are made for the factors like jerk limiting, delays associated with protection equipment and brakes etc. which have a significant cumulative effect on calculations [9].

2.4.5 6-aspect Signalling

Because the signalling scheme in operation since 1981 on the Southeast TGV has been highly satisfactory, the new Atlantic TGV has used the same signalling principles with some minor technological changes. In this application the signalling scheme has been upgraded to 6 aspects in order to introduce a new maximum speed of 300 km/h. The new aspect is 300/270, braking distance is 4 blocks, train separation is 6 blocks and block lengths are equal throughout the line [13].

2.4.6 Generalised Expressions for Multi-Aspect Signalling

In the generalised case of n aspect n-1 block signalling, headway distance is written as :

$$h_d = l + p + s + \frac{n-1}{n-2} d\ (u_m, 0) \qquad (2.23)$$

In the limiting case of Equation 2.23 the speed optimized headway distance becomes :

$$\lim_{n \to \infty} \frac{n-1}{n-2} d\ (u_m, 0) = d\ (u_m, 0) \qquad (2.24)$$

$$\lim_{n \to \infty} (h_d) = l + p + s + d\ (u_m, 0) \qquad (2.25)$$

Figure 2.9 shows that for a given number of aspects n and for a train of given characteristics, there is an optimum speed for which the line capacity is maximised and therefore headway time is minimized. The figure also highlights that an increase in the number of aspects would increase capacity in diminishing proportions and capacity tends to a finite value. A practical limit therefore exists of 5 or 6 aspects which explains why French Railways opted for a continuous signalling scheme for their Northern TGV line.

In Equation 2.23, shorter trains seem to provide higher line capacities. However, to maximize passenger 'throughput' it may be necessary to use longer trains under the assumption that number of passengers is directly proportional to the train length :

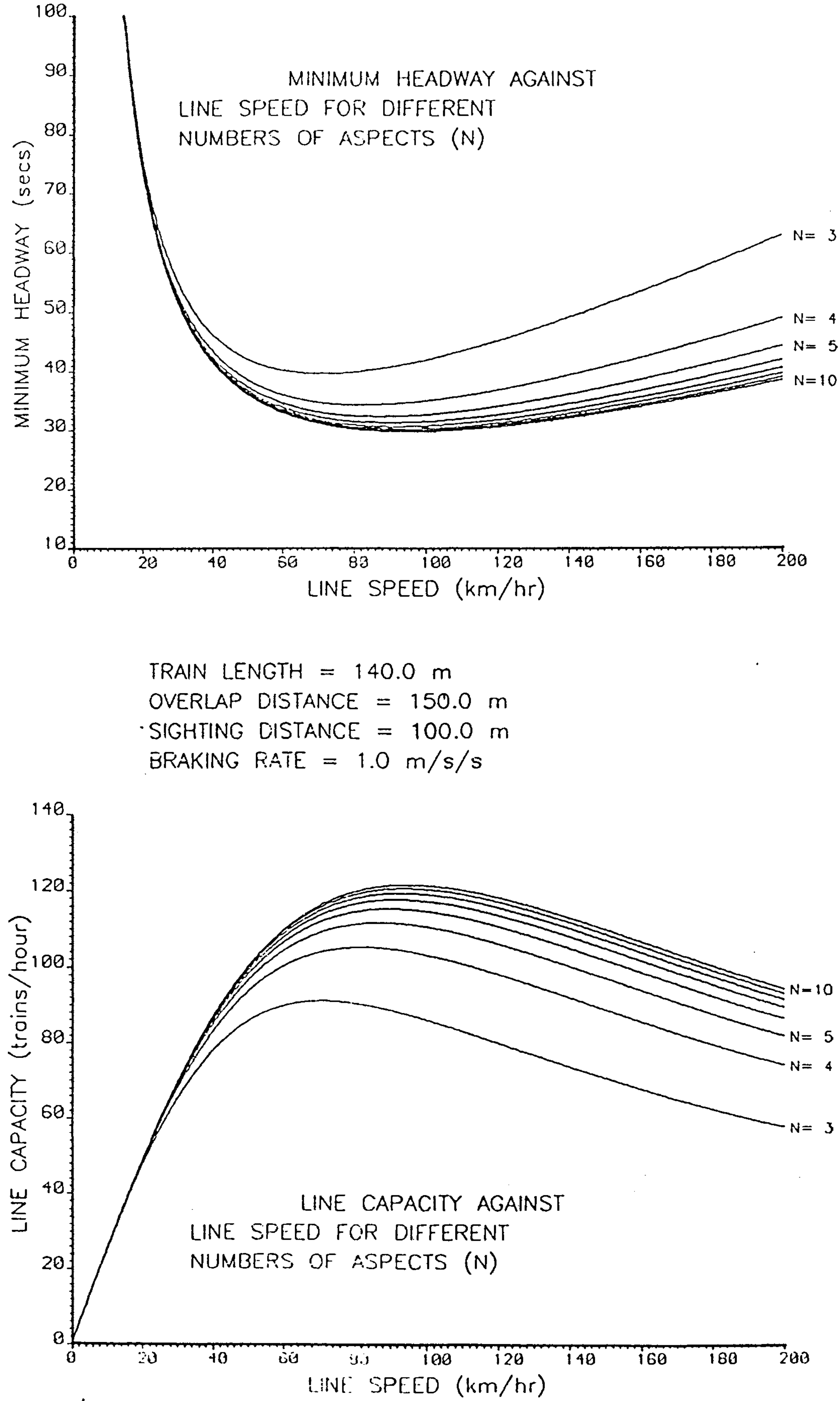


FIGURE 2.9 _ FIXED BLOCK CHARACTERISTICS
A _ MINIMUM HEADWAY TIME VERSUS LINE SPEED
B _ LINE CAPACITY VERSUS LINE SPEED

$$T = \frac{3600\, u_m}{kl_1 + p + s + \frac{n-1}{n-2}\, d\,(u_m, 0)} \quad kp_1 \qquad (2.26)$$

where T is passenger throughput

k number of train units

l_1 and p_1 length and passenger capacity of a unit respectively.

2.5 ANALYSIS OF MOVING BLOCK SIGNALLING SCHEMES

Another type of control which is in limited use in practice exerts direct control over the train spacing as they move along the line [9] [24] [25]. By comparison with fixed block schemes these schemes are known generically as moving block. Three types of moving block schemes will be discussed.

Moving Space Block (MSB) : The constraint imposed by MSB is that a constant distance must be maintained between successive trains. This separation does not depend on their speed but maximum permissible speed of the line, and given by :

$$h_d = l + d\,(u_m, o) \qquad (2.27)$$

Moving Time Block (MTB) : MTB demands that each train be separated by a constant time t_s, which is independent of their running speed. Assuming that the following train is travelling at a speed u, the train separation is given by:-

$$h_d = l + t_s u$$
$$= l + d(u_m, o)\frac{u}{u_m} \qquad (2.28)$$

where u_m is the maximum line speed.

Pure Moving Block (PMB) : The PMB scheme represents the absolute minimum train separation which is the basic requirement of any signalling scheme. The only constraint imposed by PMB is that trains should be separated by the current stopping distance of the following train. The separation is given by :

$$h_d = l + d(u,0) \qquad (2.29)$$

The capacities achieved with the three types of moving block signalling can also be calculated by Equation 2.5. Figure 2.10 shows how the minimum train separation and steady state line capacity of each type varies with train speed. From these curves it may be seen that PMB scheme gives the maximum capacity and that the capacity of MTB is greater than the capacity of the MSB over almost all over the operating range. Although lower than the PMB capacity, the MTB capacity is less sensitive to speed variations. Ward [24] argues that both MSB and MTB cannot be operated at all without violating headway distance restrictions and it is more natural to adopt a PMB control with an explicit safety factor rather than MTB or MSB where the safety factor, except at maximum speed, is hidden within the spacing dictated by headway distance.

In principle, all moving block schemes require a continuous knowledge of the spacing between the trains but in practice the spacing determined by the scheme is likely to suffer from errors due to quantisation. Quantisation occurs when the trackside transducers or transposed conductors laid along the centre of the track are discrete. They merely detect the presence of train on a piece of track rather than measuring its distance from a reference point. Thus, the scheme behaves as a fixed block scheme whose block length is the distance between detectors. Train-borne or track-based methods (e.g. radar, wheel revolution counters etc.) to estimate the absolute positions of trains are feasible and are being used, but they are not considered sufficiently safe for signalling installations and are therefore usually superimposed upon fixed detectors to get non-vital additional information.

2.6 COMPARISON OF MAXIMUM STEADY STATE CAPACITIES

Capacities of both fixed and moving block schemes depend on minimum train spacing which itself depends on the information provided by the signal. If the braking rate is constant, for a n-aspect capacity optimised fixed block scheme under ideal conditions this spacing is:-

$$h_d\ (u_n) = \frac{u_n^2}{2a} = (n-1)\ z \qquad (2.30)$$

where u_n is the line speed for which the signal layout is optimum

a is the constant braking rate.

At some speed $u_{n-1} < u_n$ the spacing may be decreased by one block. At this new speed the spacing is at a minimum :

$$h_d\ (u_{n-1}) = \frac{u_{n-1}^2}{2a} = (n-2)\ z \qquad (2.31)$$

A recurrence relationship may be set up between the speeds at which the capacity function is discontinuous :

$$u_{n-1} = u_n \frac{n-2}{n-1}$$

Therefore :

$$u_{n-j} = u_n \frac{(n-2)}{(n-1)} \frac{(n-3)}{(n-2)} \cdots \frac{(n-j-1)}{n-j}$$

$$= u_n \frac{n-j-1}{n-1} \qquad (2.32)$$

Although the fixed block capacities do approach PMB capacity as n increases, the approach is extremely slow and restricted by other practical factors discussed in Section 2.4.6. Figure 2.11 shows the capacity curve of 4 aspect fixed block signalling with the corresponding PMB capacities. A non-optimized fixed block signalling scheme will have a similar discontinuous but lower capacity characteristic under the envelope defined by PMB curve. It should also be noted that the capacity characteristics of a PMB scheme with quantisation effect is identical to an n-aspect fixed block signalling scheme in practice.

The MTB characteristic is similar in structure, but the discontinuity points will be linearly spaced along the speed axis as the MTB spacing criterion is linear rather than quadratic. The recurrence relationship in this case is :

$$u_{n-j} = u_n \frac{n-j+1}{n-1} \qquad (2.33)$$

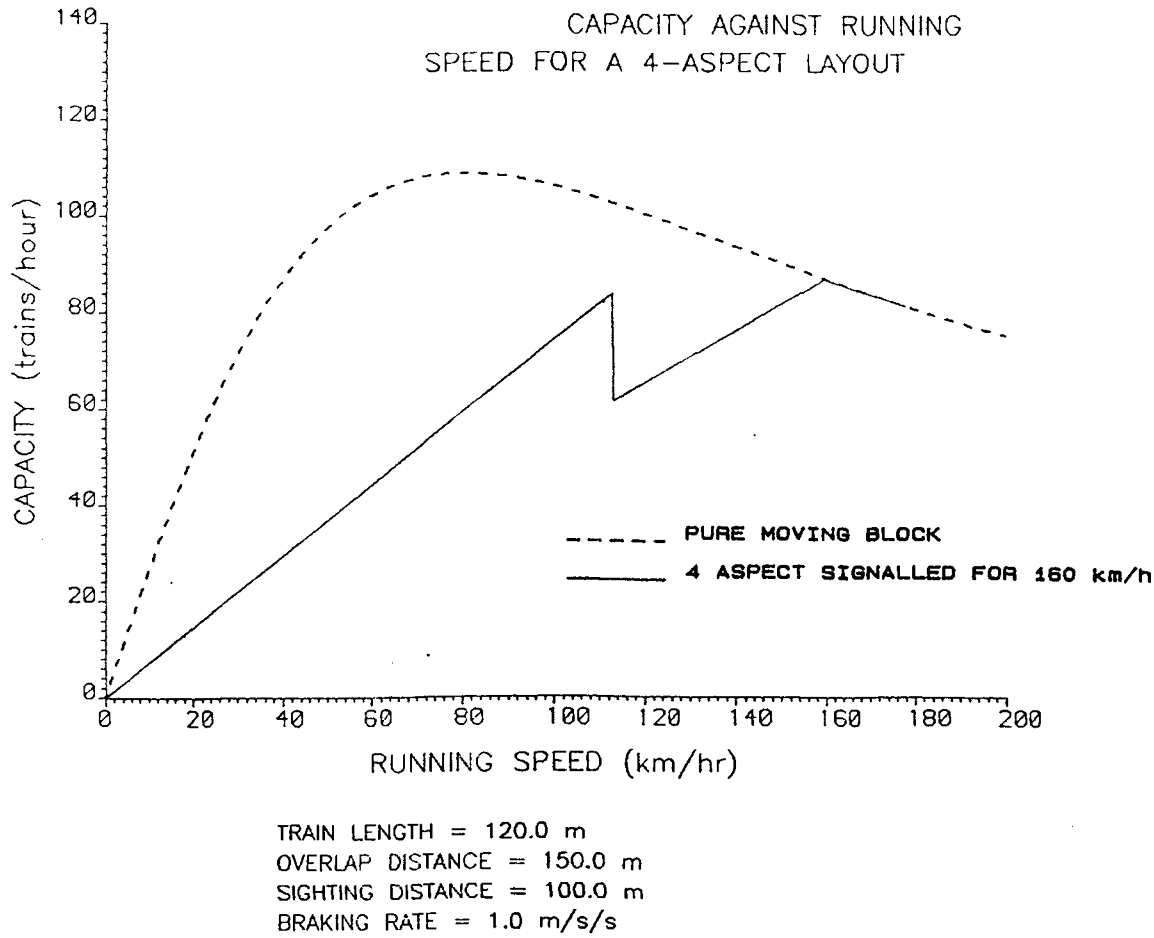


FIGURE 2.11 _ CAPACITY CHARACTERISTIC OF A 4 ASPECT SCHEME

2.7 FACTORS AFFECTING SIGNAL LAYOUT

2.7.1 Design Criteria

Under ideal conditions, to get the minimum headway time the signal block lengths should be regular and equal to:-

$$z = \frac{n-1}{n-2} \quad d\ (u_m,\ o) \qquad (2.34)$$

In practice the track is not ideal and the braking rate of the train is not constant; furthermore the signal block lengths are affected by the following considerations or constraints :

a. In general, signalling schemes are designed using 'the design headway time' which is usually above 'the minimum headway time' attainable by optimum signal layout which maximizes the system's passenger/freight capacity by minimizing the train separation for a given signalling scheme.

b. For local reasons it is necessary for signals to be located at certain fixed points at junctions, platforms etc. which may well conflict with the spacing required to yield a minimum headway time.

c. In the systems which have a complicated track geometry or a limited traffic flow, regularity of signal layout may be considered more important than attaining a minimum headway time.

d. In mixed traffic situations, characteristics of other traffic are taken into account. For example, the problem of obtaining adequate headway for a stopping service through a station is often a limiting factor in devising a signalling scheme mainly for an intercity service.

2.7.2 Effects of Track Geometry and Braking Force

The analysis put forward so far in this chapter has assumed level track and a constant braking force. In practice however, gradients and curves of the track vary and the braking force of the train may not be constant. For a track gradient G the effect on the braking rate can be given by :

$$b_g = G \cdot g \tag{2.35}$$

where g is the acceleration due to gravity

G is the track gradient expressed as percentage.

If braking rate is not constant due to track gradient or braking characteristics then for a intermediate signal block i Equation 2.1 must be rewritten as :

$$z_i = \frac{1}{n-2} \max \left(d_{i-n}(u_m,0)\ ,\ d_{i-1}(u_m,0),\ d_i(u_m,0)\right) \tag{2.36}$$

By increasing braking distance, the effect of descending gradients is to increase the minimum headway time while calculating the braking distance $d_i\ (u_m,0)$.

2.8 CONCLUSIONS

This chapter has described and compared the inherent capacities of seemingly diverse signalling schemes from a steady state headway time consideration. It has also given an insight into the trade-offs possible between various factors governing capacity, and the effects these trade-offs have on the line capacity. However, steady state studies are open to a number of objections on the grounds of realism. The calculations are difficult to relate to the capacities achieved by practical rail transit systems, especially with mixed traffic, where line capacity can be quoted only in relation to the traffic pattern on the line at the particular time of day and where the signal layout is not regular.

If it is desired to investigate the traffic flow in a rail transit system under various signalling schemes, combined with their transient performances under various methods of train speed and acceleration control, interlocking, junction optimisation, scheduling etc., simulation models appears to be an essential adjunct to analytical models and a better alternative to small area, full scale experiments. Problems having this degree of complexity can be studied realistically with a general purpose rail transit system computer simulation model like the one described later in this thesis. This model is capable of simulating the various fixed block signalling schemes as well as all significant components of a rail transit system for deterministic or statistical analysis.

The material of this chapter will later be used to develop the line section (i.e. the sections of tracks with no directly opposing train routes) representation within the simulation model which is described in Chapter 5. The generalized automatic route setting/release methods of the model described in Chapter 6 are also based on the unified approach developed in this Chapter. The installation details of different signalling schemes have been left out of this chapter. One of the aims of the following chapters will be to broaden the understanding of realisation and operational details of signalling installations by describing them as the elements of practical traffic regulation systems.

CHAPTER 3

GENERAL SYSTEM REVIEW

3.1 INTRODUCTION

Rail transit systems are characterized by the operation of the vehicles on fixed guideways. Although no universally accepted classification exists for the various systems in operation, four broad categories can be identified :

a. **Mainline :** This refers to the systems that operate long distance mixed heavy passenger and freight trains which stop only in major stations.

b. **Suburban line (suburban system) :** This usually refers to the suburban sections of mainline systems that serve the outer areas of cities or towns. Station stops are more frequent and passenger flow rate is higher than mainline systems.

c. **Rapid rail transit (metro, mass rail transit, subway, underground, U-Bahn) :** This refers to purpose-built urban rail transit systems where passenger flow rates are from 20,000 per hour upwards and average speeds ranges between 25 and 50 km/h. Such systems consist of segregated rights-of-way formed from deep and shallow tunnels and elevated sections and single type trains.

d. **Light rail transit (light metro) :** This concept is an extension of the traditional tramway, with the benefit of modern technology. Each train typically consists of two vehicles on rights-of-way and/or on streets used by road traffic. The average speeds and the passenger flow rates, ranging from 10,000 to 15,000 per hour, are low compared to rapid rail transit systems. Lower civil engineering costs make these systems a very attractive urban transport alternative.

For modelling purposes any modern rail transit system can be viewed as a combination of two subsystems : traffic regulation and power supply. Since more than one train is moving on the tracks which usually form a rail network, traffic flow must be carefully regulated by a 'traffic regulation system'. Although practical installations differ significantly in their technical details and in their additional control objectives, in broad terms 'traffic regulation' can be defined as a process by which the movement of trains is regulated for the purpose of safety and efficiency [26]. Power feeding systems are integrated parts of the modern electrified rail transit systems which are to be simulated. The electrical energy required by the trains are supplied either from a DC or an AC power feeding system, through overhead conductors or conductor rails. The aim of this chapter is to review these subsystems.

3.2 REVIEW OF TRAFFIC REGULATION SYSTEMS

The aim of this section is to review the elements of rail transit system traffic regulation installations. A knowledge of these 'traffic regulation' subsystems is needed in order to be able to model and simulate their operations. This section also aims to broaden the understanding of signalling schemes, already analysed in Chapter 2, by describing them in a 'traffic regulation system' context.

Practical installations differ significantly in their level of automation, chosen technology and operation details. However, both partly (e.g. main line system control) and fully (e.g. metro or light rail transit system control) automated traffic regulation systems would perform the following functions [23] :

a. **Determine the presence and location of the trains** : In modern multi-aspect signalled rail transit systems this function is performed by 'track circuits'. The first purpose of a track circuit is to prove that a section of track is clear. That being done, 'points' may be operated and 'signals' then cleared for trains to proceed with the assurance that it is safe to do so. It should be noted that the term 'signal' also refers to other methods of track to train communication for signalling purposes. The second purpose of a track circuit is to detect the presence of a train so the track section ahead of it can be locked to ensure its safe transit. It also provides the information on train locations and movements. Typical track circuits are described in Subsection 3.2.1.

b. **Ensure safe separation between trains** : The 'route section' of a train is a track section between a main 'entrance signal' and a main 'exit signal' next ahead. A train runs through several route sections between its 'origin' and 'destination'. This sequence of route sections defines the route of a train. Each route section must be 'clear' and 'reserved' for the train before it is allowed to proceed. The route section is 'set' before a train is permitted to occupy it and then 'released' completely or by sections as the train runs through it. If a route section is a simple track section (i.e. with no directly opposing routes), it can be set and released and signal indications can be changed automatically by creating interdependencies between the track circuit and the preceding signals at a local level. This process is known as 'automatic signal setting'. If the route section is a conflict area (i.e. with incompatible routes) its control may require strategic decisions and a set of track circuit and point checks at a centralized level as described in Subsection 3.2.2.

The route set and release process is usually known as 'interlocking'. If a part of the route section is occupied by or reserved for another train the interlocking fails. The system elements (i.e. signals, track circuits, point machines) and the equipment that handles the process will be referred as a 'signalling interlocking subsystem'. The decision (i.e. whether the train is allowed to proceed on its route) is communicated back to the train by either an 'entrance signal' or through a 'track-to-train communication system'. Some practical installations are described in Subsection 3.2.3. Besides ensuring the safe separation of trains a 'signalling interlocking subsystem' must fulfil the following requirements :

1. Fail only to the safe side : This is also known as fail-safe principle. Any failure of a signalling interlocking subsystem should not affect safety e.g. it is not acceptable that any failure might lead to a signal showing a 'proceed' indication. Therefore, during the design stage all possible hardware and software failures have to be considered and checked for their consequences. For this reason many rail transit system operators have been reluctant to introduce solid state electronics in their interlocking and signalling installations until recently [27].

2. Be reliable : Reliability is an important safety feature. In the

case of a safe-side failure, the running of the trains is first stopped and then normally controlled by manually overruling the equipment. As a consequence the safety is lowered considerably. Therefore, an equipment failure to the safe side not only disturbs the scheduled operations but also does reduce the overall safety considerably.

3. **Improve the efficiency :** Modern traffic regulation approaches also aim for improved system efficiency by optimising train operations. No matter how carefully the traffic is planned, trains deviate from the service schedule. These deviations lead to train conflicts and causes a deterioration in overall system performance. Traffic regulation systems seek to recover trains deviated from the planned schedule, in the shortest time possible.

3.2.1 Track Circuit Principles

3.2.1.1 DC Track Circuit

Without full technical details, the functioning of DC track circuits can be described as follows. The running rails are used as conductors connecting a source of electrical energy at one end of the track section to a relay at the other, the section of track being electrically isolated by insulated rail joints. Figure 3.1 illustrates the principle of operation [19]. In conflict areas usually one rail is isolated at strategic places, e.g. between points, in order to sectionalise the track. In this way 'single-rail' track circuits are created. For long track circuits like open lines, both rails have to be isolated for reasons of the electrical characteristics of the whole circuit.

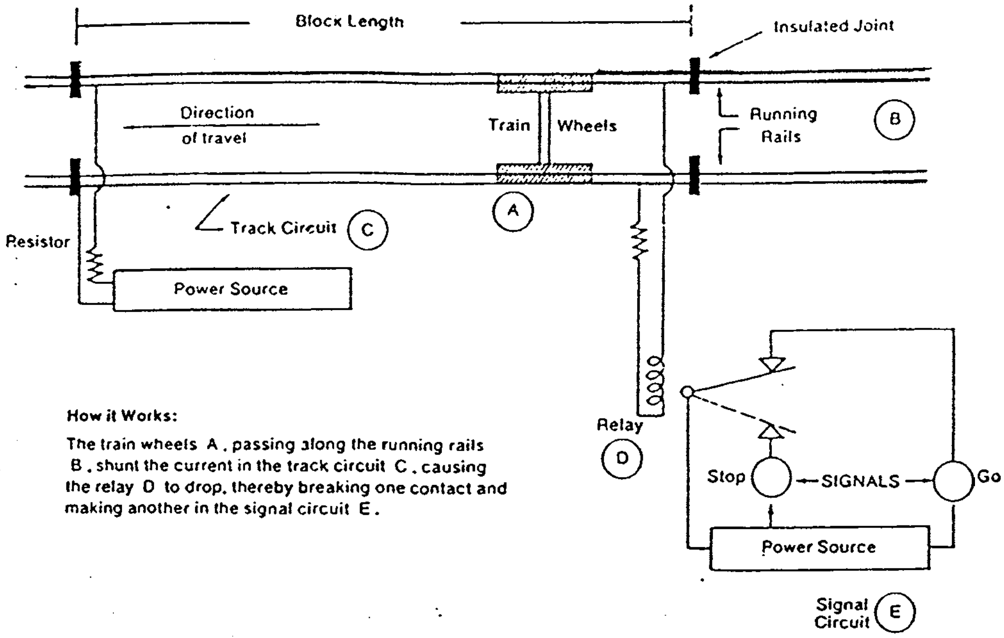


FIGURE 3.1 _ A TYPICAL DC TRACK CIRCUIT CONFIGURATION

In a conventional signalling interlocking subsystem, the track relay is energised as long as the current loop is closed. This relay drops if a train causes a decrease of the electrical resistance. The relay also drops if a rail or a wiring connection breaks, or if the power supply fails etc. According to the fail-safe principle, these failures lead to a de-energised relay and therefore become manifest as if a train were present.

However, there are some other phenomena with which a signalling interlocking subsystem should be able to cope. For example, if a short circuit of the joints happens, both track-relays drop. If the failure vanishes spontaneously, the train seems to have passed by. When the mechanical load on the rails caused by the weight of a train is considered, this type of short circuit is more likely to happen than one might expect. Another phenomenon is the possibility that a track-relay is energised for a short moment, while the track section is occupied by a train. This is caused by e.g. rust or leaves on the rails which increase the resistance between wheels and rails.

3.2.1.2 AC Track Circuit

The principal limitation of the DC track circuit is its incompatibility with the DC electrification systems, which use the running rails for traction return currents. Another disadvantage is the need for numerous insulated joints where shorter blocks are essential to achieve short headway times i.e. rapid transit systems. The AC track circuit overcomes some of the problems encountered with DC track circuits. There are two types of AC track circuits in practice ; power frequency and high frequency :

a. **Power frequency circuit :** A typical power frequency circuit is shown in Figure 3.2.

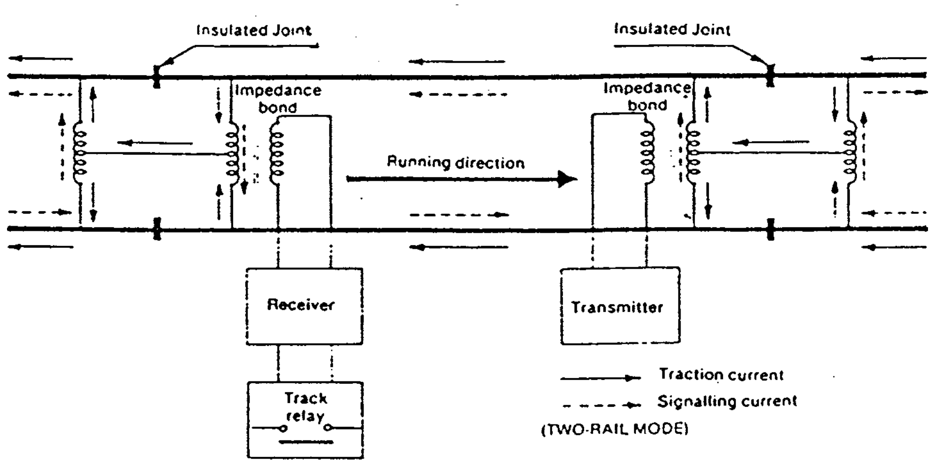


FIGURE 3.2 _ A TYPICAL POWER FREQUENCY AC TRACK CIRCUIT

Frequencies used fall in the range of 25 to 150 Hertz and impedance bonds are used to discriminate the AC current from the DC traction return currents. These provide continuity for the traction current but present a high impedance to the AC track circuit currents. An advantage of this arrangement is a better distribution of the traction current in the rails, thereby reducing interference effects. The principle of operation to detect a train's presence is the same as in a DC circuit, and insulation joints are still required.

b. **High frequency circuit :** High frequency AC track circuits, operating at frequencies of several kilohertz, can eliminate the need for running rails with insulated joints. Sometimes called an audio-frequency track circuit, it is constructed by special transformers connected across the rails. A typical arrangement is shown in Figure 3.3.

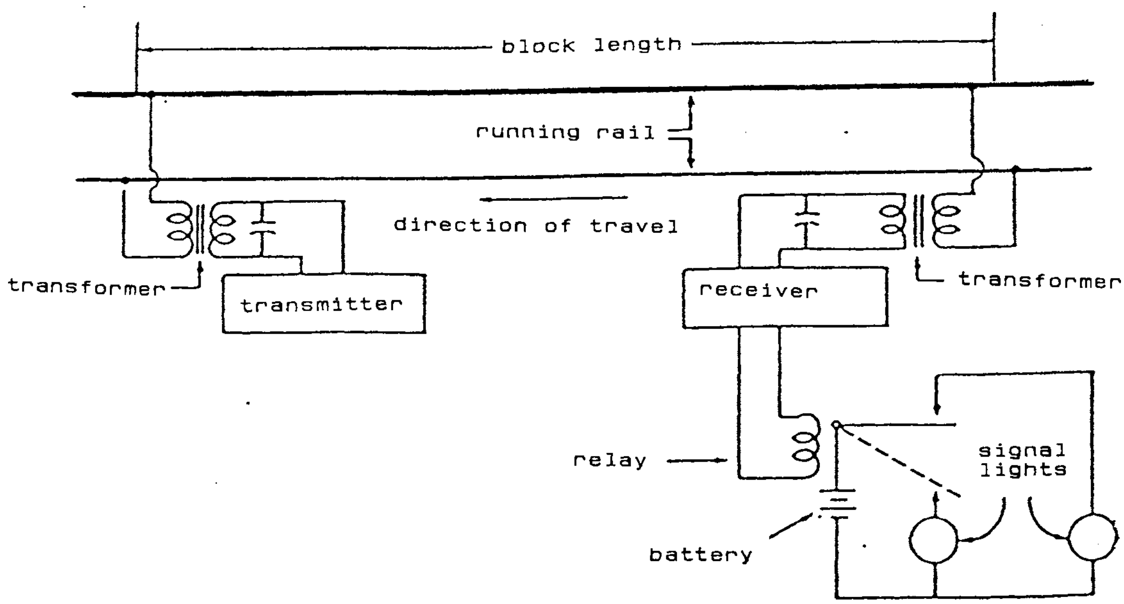


FIGURE 3.3 _ A TYPICAL HIGH FREQUENCY AC TRACK CIRCUIT

One of the transformer windings at the transmitting end forms part of a resonant circuit, tuned to the circuit operating frequency. In a conventional installation,adjacent track circuits are designed to operate at different frequencies, and the resonant circuit at the receiving end is designed to respond to the specific frequency. The high frequency track circuit allows the running rail to be continuous for the return of traction currents and also for track-to-train communication. In the case of electrified rail transit systems, the frequency spectra which occur in the traction current of modern traction vehicles with chopper or three phase drives can not be totally suppressed. A critical situation arises when the traction current has AC elements which fall within the frequency range of the track circuits and, therefore the signal-to-noise ratio is insufficient. Therefore, the vehicle manufacturers must adhere to specific limits with respect to harmonic content but, when there are several vehicles on the track, the overlay of harmonics can only be roughly quantified. In order to end this dependency on adherence to set limits, in modern track circuit equipments transmission between the transmitter and receiver is safeguarded by sophisticated signal coding, modulation and error correction techniques.

3.2.2 Control of Conflicting Train Movements

3.2.2.1 Basic Control Strategies

Trains passing through conflict areas use different route sections according to their entrances and exits. Route sections not compatible with each other must not be used simultaneously. In cases where two or more trains would otherwise occupy incompatible route sections, a 'supervisory subsystem' or a signalperson usually equipped with operational aids is expected to make appropriate decisions in order to resolve (and/or to prevent) the conflicts. The best known methods for decision making are given below [28] [29] :

a. **Scheduled sequence :** Trains are authorised to pass through the conflict area in the order provided by the timetable, without regard for their actual delays.

b. **First come, first served :** Trains may pass through the conflict area in their actual order of arrival at the sighting point.

c. **Priority index :** Trains are authorised to pass according to their priority indexes representing their train classes.

d. **Maximum capacity :** The train whose route is incompatible with the greatest number of other wanted route sections is authorised through the conflict area first. This rule is supposed to give the maximum capacity over the conflict area by reducing the number of conflicts faster than any other strategy.

e. **Search for a new route :** The choice is based upon the instantaneous analysis of the conflict and searches for alternative routes which eliminate the conflict.

In practice, a combination of these methods can be used simultaneously for the decision making process. If the choice is to be made by the signalperson, it is hard to define and evaluate all the factors which are used whilst performing this action. If a supervisory subsystem is used, each conflict must be evaluated according to a merit function depending on timetable, actual delays, new delays due to decision, priority indexes etc.. Examples of such subsystems can be found on many suburban and mainline systems in Europe and Japan.

However, these subsystems do not perform well in the event of serious perturbations to the timetables. In this case, a different choice of the merit function would obviously be necessary and a complete examination of the decision, which is consequential upon the entire rail transit system, is required rather than a local solution. Such global optimisation methods are difficult to formalize and implement, particularly in complex rail networks. With such an increase in problem complexity, the use of 'knowledge-based' supervisory subsystems become a more feasible choice. These subsystems work by exploiting the heuristic rules of the best solutions rather than optimizing merit functions.

In the operation of a rail transit system optimal solution of conflicts before or when they occur is not the only criterion. The realtime control can involve other objectives e.g. recovery from perturbations caused by unexpected events or random variations in the operation, optimization in terms of system capacity, total energy consumption or energy demand patterns etc.. These should also be considered by a 'supervisory subsystem'. This kind of control cannot be discussed in general terms since the main requirements of each rail transit system should be evaluated individually. Therefore, the discussions in the following subsections are limited to the interlocking process which aims to avoid incompatible train movements. Feasibility of implementing a supervisory subsystem (in this case a realtime energy demand controller) with the main objective of smoothing daily energy demand patterns of a mainline rail system is discussed in Chapter 8.

3.2.2.2 Route Setting Process

The elements on the route section (i.e. signals,track circuits, points) must be checked and the following conditions must be met before a train is permitted to 'proceed'. Although the rules adopted by BR for the control of the route setting are set out here, it will be found that these are similar to the rules of any other rail transit system operators. The differences will be found to lie mainly in the methods of achievement. It must also be noted that these conditions do not cover all details of a route setting operation :

1. All track circuits must be clear between the main 'entrance signal' and the main 'exit signal' next ahead.

2. Track circuits in the overlap immediately ahead of the 'exit signal' must be clear. In the case of automatic signals a separate overlap track circuit may not be provided but the signal block track circuit can be extented to cover the overlap as well.

3. Track circuits which are not in the route section but in the other route sections diverging from or converging to it must be clear to form 'flank' protection against overruns.

4. Track circuits on which trains could stand foul of the route must be clear.

5. All points in the route section between the main 'entrance signal' and the main 'exit signal' next ahead must be set, locked and detected in the correct position.

6. Points which trap conflicting movements or overruns or otherwise give 'flank' protection to the route section must be set, locked and

detected in the correct position.

7. Points in the overlap at the exit signal must be set, locked and detected in the correct position.

8. The 'exit signal' must be proved to be alight.

9. The entrance signals of directly opposing routes must be proved to be at 'stop' indication.

10. Approach release track circuits, where applicable, must be proved occupied or the associated timing-out feature to have operated.

11. The approach locking, where applicable, must be proved to be in operation.

In practice, a multiple-aspect signal may be operated automatically at all times by the passage of trains provided that:-

1. There are no points in the route section to the next signal

2. There are no points in the overlap.

3. There is a unique overlap (i.e. not shared by other signal blocks).

4. There are no directly opposing routes.

There are two reasons why the automatic operation of signals is favoured wherever it is practicable to do so :

a. It is less costly than centralised control.

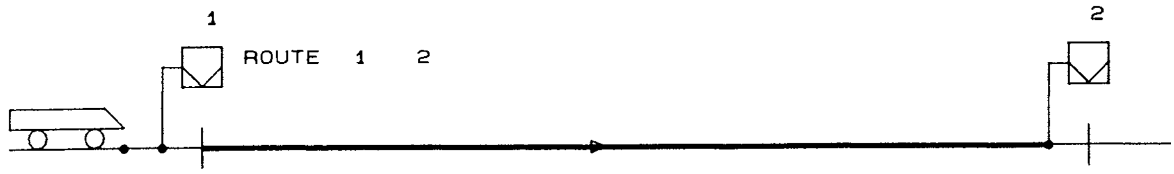
b. It is not subject to human error and it lessens the central control centre's work load.

In some modern transit systems all the route sections in a conflict area can be set and released automatically by a supervisory subsystem. This process is known as 'automatic route setting'. However, even in the manual operation of the route setting, the signalperson is usually equipped with an operational aid called the 'entrance-exit equipment' (NX). He or she only has to indicate the entrance and exit of the route section; the route section is then checked and set automatically by this equipment.

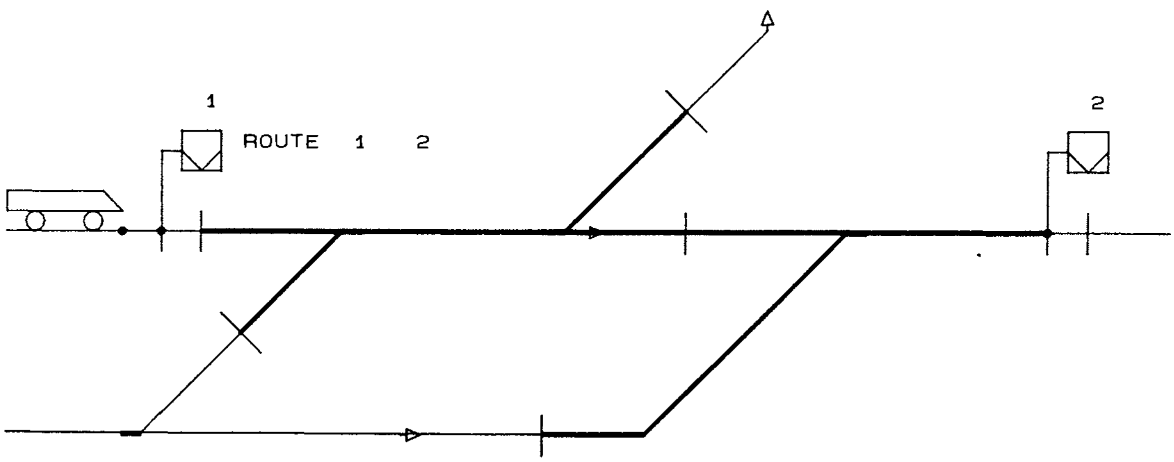
3.2.2.3 Route Release Process

The route section, which is set up, fulfils its purpose completely as soon as the train runs through it. In cases where there are no opposing routes and no points in the route section it is released immediately, once the train passes the entrance signal (e.g. the situation in Figure 3.4a). Points may only be released after the train has passed them by (e.g. the situations in Figure 3.4b and 3.4c). Where there are more than one opposing signals, the route section is released once the train has completely passed the last opposing signal and all points.

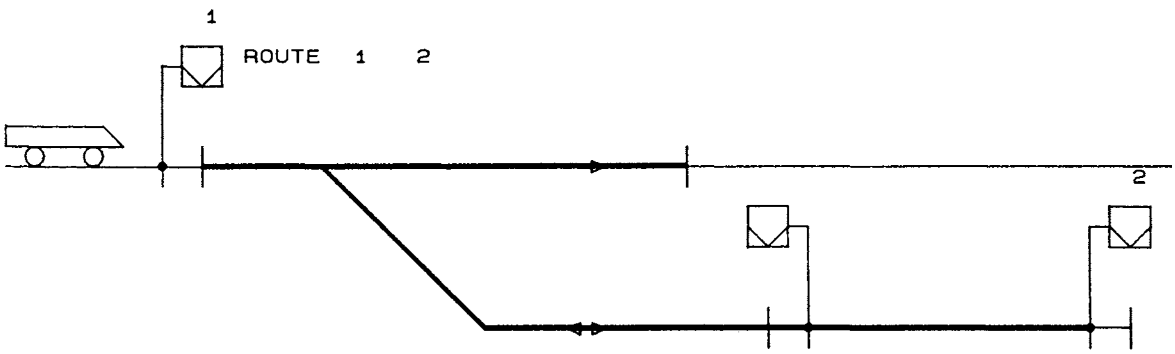
In general, each track section is released as soon as the train leaves it. In some conflict areas, it might take a relatively long time between the moment the train leaves some track sections required by another train and the moment the train completely clears the area. By the above given definition of route release, it is impossible to set up a new route although the required track sections are already left by the old train. Therefore, the automatic partial release of route sections is necessary instead of releasing as a whole [19]. The released track sections become available for the next train and the capacity of the conflict areas is increased considerably. In practice, a route section is released in parts if the passing of the train is detected by successive track sections becoming occupied and indicating unoccupied some moments later in the correct order.



_ A _



_ B _



_ C _

FIGURE 3.4 _ THREE TYPICAL ROUTE SECTIONS
A _ NO OPPOSING SIGNAL, NO POINTS IN THE ROUTE
B _ NO OPPOSING SIGNAL, POINTS IN THE ROUTE
C _ OPPOSING SIGNAL, POINT IN THE ROUTE

3.2.3 Different Design Approaches

3.2.3.1 Requirements of an Signalling Interlocking Subsystem

As stated earlier, except automatic signal setting on simple track sections, route set and release (i.e. interlocking) is a centrally controlled process. In the automated mass rail transit systems it is one of the main functions of the Automatic Train Control (ATC) systems. The function is performed by Automatic Train Protection (ATP) subsystem and checked by Automatic Train Supervision (ATS) subsystem as will be described in Subsection 3.2.4. In conventional mainline or suburban system 'interlocking' is a Centralized Train Control (CTC) System function. The route set and release decisions are made either by a signalperson usually equipped with an 'entrance-exit equipment' or a 'supervisory subsystem', in both cases in interaction with the 'signalling interlocking subsystem'.

A reliable installation of a signalling interlocking subsystem can be realised only by :

1. a choice of technology with known failure modes.

2. a correct design, based on the characteristics of the chosen technology.

3. a correct realisation, i.e. construction, assembly, installation.

A traditional signalling interlocking subsystem is relay-based, the interlocking being provided by 'safety relays' whose contacts are connected in such a way that interdependences are created between track circuits, signals and points. But different rail transit operators have developed software-based subsystems to replace their relay-based installations in recent years. This is both for economic reasons and for the new operation control possibilities that this development offers.

The following subsection reviews two main approaches to the design of interlocking and signalling installations

3.2.3.2 Elementary Unit Approach

Rail transit system operators have developed much experience with the elementary-unit relay-based installations. In these installations the geographical layout can be mapped onto the wiring connections between the relay-units. These relay-units represent the elements like a signal, a pair of points or a track section. In fact this type of subsystem constitutes an electrical analogue of the conflict area layout.

In the installation described by Schmitz [30] each relay-unit is connected to relay-units of its adjacent elements in the actual layout. It is also connected to :

a. the equipment, e.g. signals, point-machines or track circuits.

b. the control panel

c. the display panel

d. the auxiliary equipment, e.g. train-describer or automatic route setting equipment.

This subsystem functions as follows: A command e.g. route-set command, comes from the control panel into the relay-units of the 'entrance' and the 'exit' signals. The further processing i.e. acceptability test, reservation, lock-check etc. is done completely by the relay-units, by exchanging information with their neighbours via their connections. In this way a route section reservation is stored in a distributed manner. The route-release procedure is handled in the same manner: the relay-units exchange information of changes in track occupation and unlock if all checks are positive.

The same approach is chosen by the Swedish State Railways (SJ) in their software-based signalling interlocking subsystem [31] [32]. For each element in the actual layout there is a set of static data in which the addresses of neighbour elements can be found. A piece of program code particularly reflects such logical relationships of this element. This structure is comparable with the interconnections in relay-based installations which reflects the geographic layout. The variable data of the elements, which define the actual states, are also stored in this structure. These data define the actual state of the element and, therefore, are comparable with the position of relays. The installation of Japanese National Railway (JNR) as described by Okumura [33] adopts the same approach in their software-based subsystem : an actual layout is described in a data file called a 'spur file', consisting of several 'spur units'.

The elementary-unit approach is often called the 'geographical approach' or 'geographical circuitry' [19] but, as the geographical layout can also be recognised in some of the free-wired approaches [27], the term 'geographical approach' is not appropriate to pinpoint the differences between the two approaches.

3.2.3.3 Free Wired Approach

The advantage of the elementary-unit approach is standardisation. Standardisation leads not only to savings in design and manufacturing costs, but also the possibility of using standard methods for testing the units, interconnecting cables and the complete interlocking and signalling installation.

The disadvantages are that units are prepared for all possible interconnections and therefore contain redundant relays and wiring in many less complex situations. Further, flexibility may be lost by not being able to adapt the interlocking rules to specific operational requirements or the specific characteristics of an actual layout.

These are the reasons for adopting the free-wired approach. In such designs certain standard pieces of circuitry are used but the design is particular to a certain conflict area. For instance, in BR practice there is a lot of free wiring even when elementary units are used [19]. This is partly due to the differences in operating suburban lines with dense traffic and secondary lines.

This approach is also reflected in the design of BR's software-based subsystem called 'the solid state interlocking' [25]. Some basic characteristics for a signalling interlocking subsystem are also implemented but, the interlocking rules have to be described in the data. The flexibility reached in this way has to be paid for by extra effort being put into checking the correctness of the data.

3.2.3.4 Software-Based Installations

The interlocking is a distributed process so the information 'a route section is clear' is also distributed. A software-based subsystem can either hold it distributed (i.e. by the route elements itself) like in a relay-based system or transform it into individual route decisions for each train (i.e. the routes are explicitly described as data-entities and the 'route setting and release' is defined as individual processes).

All known signalling interlocking subsystems which are based on programmable electronics e.g., the ones developed by JNR [34] [35]. SJ/Ericsson [31] [32], DSB/Dansk Signal Industri A/S [36], BR [25] [37] and GRS [38] are in essence extrapolations of either the elementary-unit approach or the free-wired approach with or without adaptations. In most of these software-based installations the relay position (up or down) is simply replaced by the bit (1 or true for up, 0 or false for down) therefore the structures which are originally developed for relay-based subsystems can be recognised in the software. Only SJ/Ericsson differs in its use of a set of reduced Boolean functions with 2^n different input combinations mapped to Boolean variables 0 (route section not available) and 1 (route section is available). Route decisions for individual trains with conflicting route section demands are reached as a result of evaluating these functions.

In designing a software-based signalling interlocking subsystem, an important difference between relays and programmable electronics has to be taken into account. Programmable electronics constitute a sequential machine which can perform only one action at any time unlike relay-based subsystems where many actions can take place in parallel. Describing these actions sequentially is possible, but the order of evaluating them must be considered carefully.

Although these new systems are inherently reliable, there is no basis for the presumption of a 'right side' failure (i.e. a failure which cannot lead to a 'proceed' signal indication) when they fail. To minimize the risk of 'wrong side' failures, a degree of redundancy is built in these subsystems. Software and/or hardware is doubled or triplicated to improve the reliability. The structures of some installations can be summarised as follows :

JNR : triplicated subsystem, hardware voting of outputs, identical software, a geographical layout description.

SJ : one computer with diverse programs, hardware comparison of outputs, geographical layout description.

DSB : one computer with diverse programs, hardware comparison of outputs, tabular layout description

BR : microprocessor based triplicated subsystem, software voting, identical software, data describing both interlocking rules and layout.

Siemens : duplicated subsystem, hardware comparison, identical software, geographical layout description.

GRS : one computer, partly diverse software, controlling hardware, data describing both interlocking rules and layout.

3.2.4 Automatic Train Control Principles

In view of increasingly complex control demands, substantial automation of rail transit systems is inevitable. Many subsystems in rail transit systems have already been automated. Consequently, total automation of the system is becoming a common practice especially for rapid and light rail transit systems where the traffic patterns are regular. A typical Automatic Train Control (ATC) system which is shown in Figure 3.5 can be viewed as Automatic Train Operation (ATO), Automatic Train Protection (ATP) and

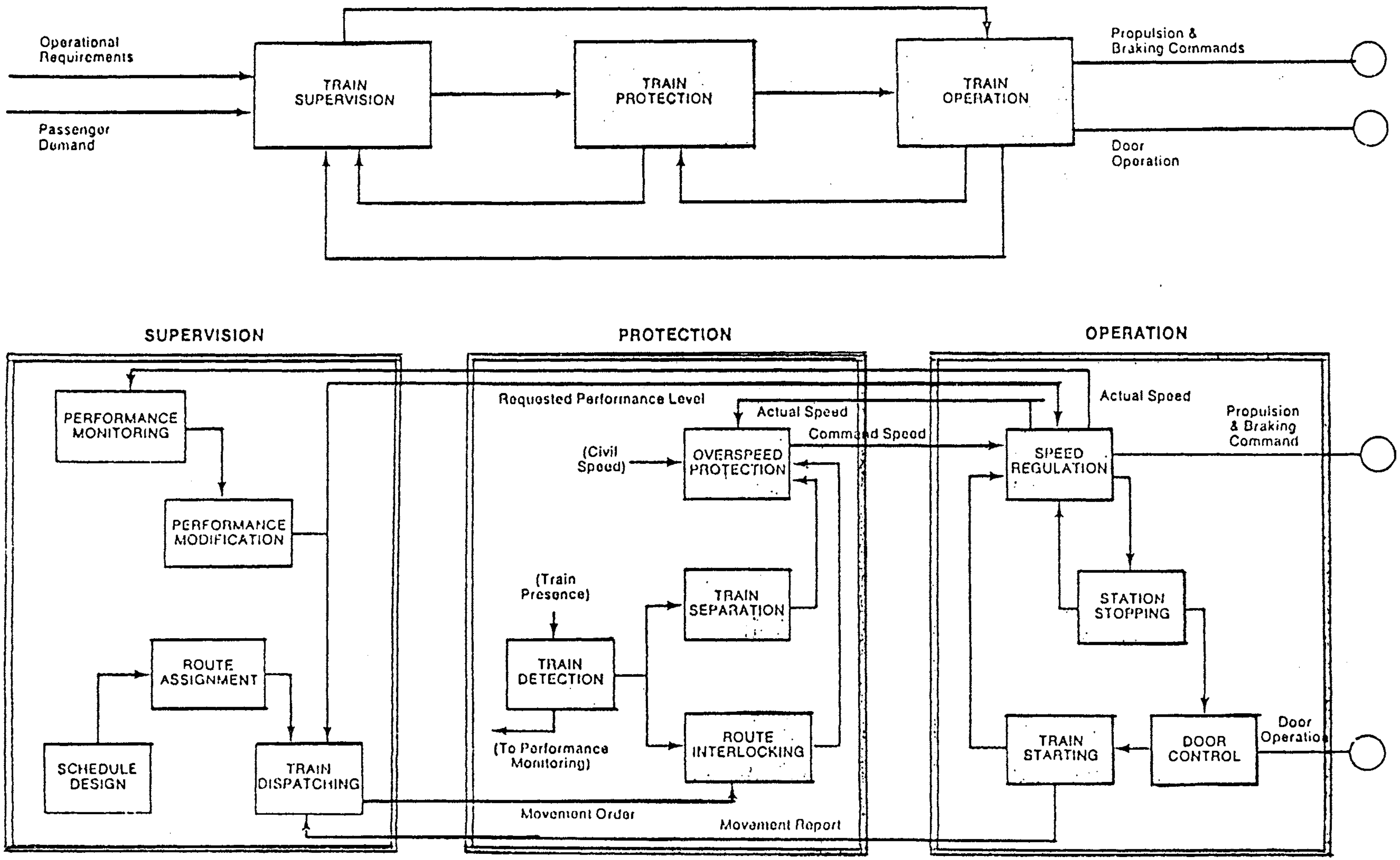


FIGURE 3.5 — AUTOMATIC TRAIN CONTROL FUNCTIONS

Automatic Train Supervision (ATS) subsystems working in interaction.

Automatic Train Operation : Automatic Train Operation can be defined as the automatic control of individual trains, specifically the regulation of speed and stopping at stations [39]. Automation of the typical train crew tasks overcomes the wide variations in driver performances, thus improving the quality of service.

Typical control of a station to station run involves acceleration, maintaining target speeds, coasting if required and braking into the next station. These represent the speed profile of a train. The ATO is a nonvital subsystem and is normally used with an ATP subsystem.

Automatic Train Protection : An Automatic Train Protection subsystem should perform the functions of a conventional signalling and interlocking subsystem. It also ensures that train speed is not excessive.

ATP has priority over both ATO and ATS since safety cannot be compromised. For the majority of ATC designs, the ATO and ATP subsystems are functionally and physically separate and interaction is kept to a minimum.

Automatic Train Supervision : The Automatic Train Supervision subsystem is mainly responsible for monitoring and coordination of individual train movement in relation to timetable and route assignments. The ATS subsystem controls the interlocking and signalling at conflict areas, enabling trains to be routed correctly and takes decisions when unexpected operating conditions arise. It is also expected to perform any other operation optimization tasks. Besides these, the subsystem performs data-logging and recording functions etc. which may not be directly concerned with train safety and movements

3.3 REVIEW OF POWER SUPPLY SYSTEMS

The electrical energy required by the trains are supplied from a DC or an AC power supply system, through overhead conductors or conductor rails. These systems are integrated parts of the modern electrified rail transit systems which are to be simulated. Although its design and interfacing was out of the scope this study, it is possible to interface to the simulation model a detailed power supply network model like the one described by Chan [40]. A simplified AC power supply system model will be described later in Chapter 8.

The DC system is preferred for mass and light rail transit systems and for suburban services. The DC voltage is obtained from an AC power transmission network, through transformers and rectifiers located at substations.

AC systems are generally used for mainline transit systems, covering distances exceeding 30 kilometres. The line voltages are much higher, typically 25 kV, sometimes 11 or 50 kV, and the traction currents are smaller than those in DC systems. The cost of the total power supply system in a typical AC system is likely to be 20 to 30 percent less than an equivalent DC system due to the high voltage used [41].

3.3.1 AC Traction Power Supply Systems

3.3.1.1 Development of AC Power Supply Systems

The application of 3 phase overhead supply system for electrified rail transit systems was introduced around the 1880's [42]. This early installation was not widely developed mainly due to complexity and cost involved in constructing a three wire supply system. While it is easy to transmit AC power at fixed frequency, this is not the most suitable form of power for traction drive systems which have a wide variation of speed [43]. It is necessary to convert the fixed frequency AC supply to DC or variable frequency AC in order to make use of efficient traction motors. Suitable equipment was not available for either option in the early days of electrification. Single phase AC commutator machine which is required to operate at a low frequency, typically 16.66 or 25 Hz , were used as a compromise. Consequently, a high power supply network at a special frequency is required for feeding the power system. The construction of such special systems was clearly not desirable, and thus other schemes were sought.

In the 1950's robust and reliable static converters were developed for the needs of high power traction applications. This encouraged the development of DC drives which possess control characteristics inherently suitable for traction. With the advent of high power semiconductor technology, single phase industrial frequency power supplies and semiconductor control equipment on trains have been widely adopted for most of the mainline electrified systems [44].

Power from national power distribution systems (i.e. grid systems) is much cheaper than the power specially generated at low frequencies for the low frequency systems. Therefore, the systems that uses the power directly at the commercial frequency from the grid has been developed. In these systems the extra high voltage (EHV) from the grid, generally at 66 kV, 132 kV or 275 kV, is stepped down in a substation and fed to the 'catenary'. The substations are usually constructed along the line at regular intervals. The length of feeding sections between the substations depends on the line voltage and the intensity of the service. While most rail transit systems have multiple feeding points, only one substation may be needed for some short length systems. The catenary voltage is further stepped down on-board the train. Usually, solid state converters are used to power the DC traction motors. Recently there appears to be a renewed interest in the use of 3 phase induction motors. This is mainly due to the development of sophisticated 'inverter' circuits and control methods.

A working voltage of 6.6 kV was considered to be adequate for most of the traction installations of 1930's. As the power demand increased, the supply voltage was also raised. In 1950's 25 kV was adopted as a world standard. The booster-transformer scheme commonly adopted in these systems is described in Subsection 3.3.1.2.50 kV has been subsequently selected for highly loaded long distance rail transit system in the 1970's. Increasing the line voltage results in an increase of feeding distance. This increase leads to fewer substations and subsequently less capital investment and maintenance costs. The conductors for transmission are also smaller and hence lighter supporting structures are required for overhead. This is especially beneficial in long distance routes and has led to adoption of the 50 kV scheme with regular 2:1 ratio autotransformers feeding the catenary at 25 kV. Further expansion of 50 kV single phase AC power supplies is foreseen owing to the numerous advantages of this type of systems [45] [46].

3.3.1.2 25 kV Booster Transformer Scheme

In a booster transformer supply system line current is supplied through the overhead catenary wire. A booster transformer is essentially a 1:1 ratio current transformer, the primary winding of which is connected in series with the catenary and the secondary winding is either linked in series with the insulated return rail or is connected to the return conductor at regular intervals along the line. A typical arrangement with return conductor is shown in Figure 3.6.

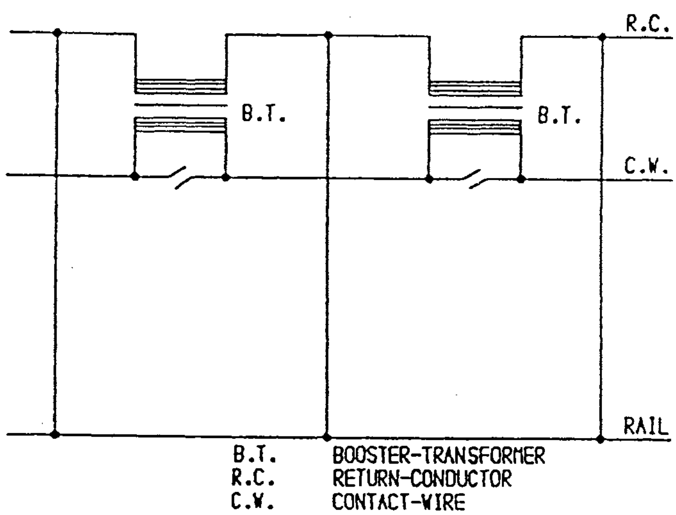


FIGURE 3.6 _ 25 kV BOOSTER TRANSFORMER SCHEME

The function of the transformer is to force the main traction return current to flow through the return conductor instead of running rails. Since the return conductor is arranged close to and in parallel with the contact wire, external inductive coupling effects are greatly reduced. However, the impedance of the booster transformer with a return conductor system is increased by about 50% compared with the simple supply system without booster transformer [47]. This implies that more substations are needed for the same distance due to extra voltage drop along the contact wire. In addition, the isolation section at each transformer causes arcing problem if large power is taken by a locomotive while passing across the isolation gap [48].

3.3.1.3 50 kV Autotransformer Scheme

The first autotransformer (AT) feeding scheme was implemented in the early 1920's with a system voltage of 12 kV [49]. The difficulties of the implementation compared to booster transformer schemes delayed the wider acceptance of the scheme for about fifty years. A simplified AT feeding system is shown in Figure 3.7.

In the early 1970's Japanese National Railways (JNR) adopted a 50 kV autotransformer feeding scheme because of the drawbacks experienced with their standard 25 kV booster transformer scheme. The main advantage of this scheme is while the transformation voltage is raised to 50 kV, all standard 25 kV equipments can still be used since the voltage to earth is the same as before. The power system losses are generally less for the AT system. The voltage drop along the contact wire caused by series connected booster transformer is eliminated because of the parallel connections of autotransformers along the line. Consequently, the system gives a better supply voltage regulation and the interference with lineside communication cables is further reduced [50]. As an inherent feature of this system, the current flowing through the feeder wire and catenary is almost balanced for most load conditions. This provides a similar function to the booster transformer scheme. It is also claimed that the overall cost of the system is less than that of the 25 kV booster scheme [51] [52].

Due to these advantages , the scheme has recently been adopted by the Queensland Railways of Australia for the electrification of their central network [53].

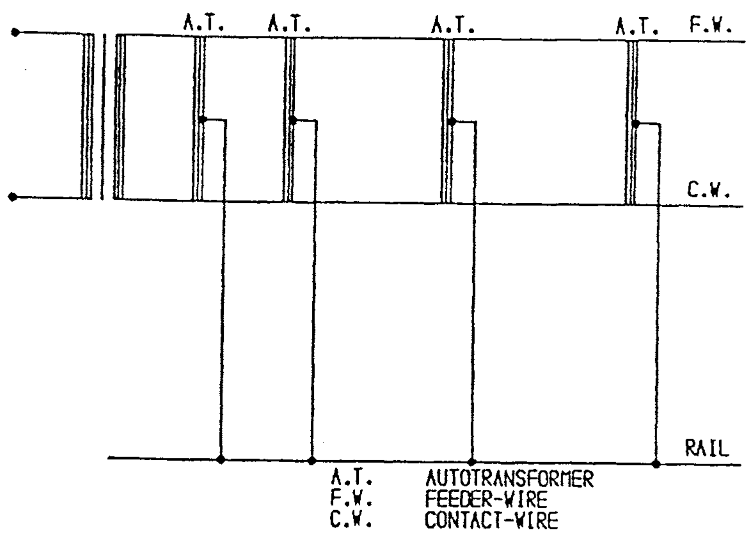


FIGURE 3.7 _ 50 kV AUTOTRANSFORMER SCHEME

The scheme consists of the contact wire and its supporting catenary, a feeder wire and a protection wire connecting the mid points of all autotransformers. The centre tap of each transformer is linked to the running rail through a neutral wire (or return conductor).

3.3.2 DC Traction Power Supply Systems

3.3.2.1 Development of DC Power Supply Systems

In the early history of rail transit system electrification, equipment that could be carried on-board trains for converting AC to DC was not available and a DC supply is generally used. The advent of reliable on-board equipment made possible the use of high voltage AC as described above. The obvious penalty is the extra load the trains has to carry. In suburban,rapid transit and light rail transit systems the high traffic density characteristics of such systems make AC uneconomical, both in capital and running costs [54]. The higher system losses are tolerable because of the high density of traffic on much shorter routes.

3.3.2.2 DC Power Supply Schemes

DC rail transit systems are supplied at nominal voltages which typically range between 500 V and 3000 V, but are usually one of three standard voltages :

750 V nominal : Usually chosen for urban rapid transit or light rail transit systems and using a third rail e.g. Dockland Light Transit System or a trolley wire as the traction supply e.g. Istanbul Light Rail Transit System.

1500 V nominal : Usually chosen for high capacity urban rapid transit systems and using an overhead traction supply e.g. MTRC Hong Kong.

3000 V nominal : Predominantly used in mainline and suburban systems.

From the substations the current is fed to the trains by either a third rail or an overhead cable. Usually the running rails are used as the return conductor. However, in a few cases a pair of separate rails are used as the supply positive and negative [55]. Elements of a typical DC traction supply are shown in Figure 3.8 [56].

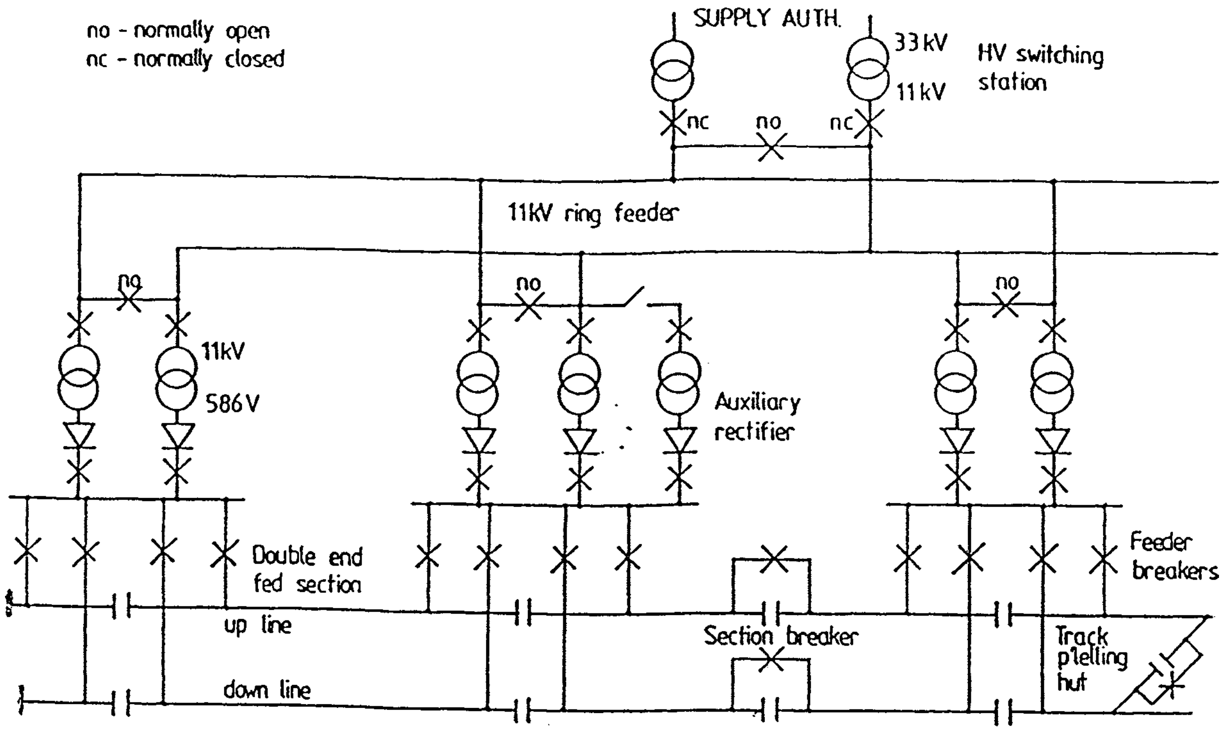


FIGURE 3.8 _ A TYPICAL DC TRACTION SUPPLY NETWORK

3.4. CONCLUSIONS

This chapter has reviewed the two main subsystems of rail transit systems. Like Chapter 2, this chapter has also aimed to emphasize common principles of rail transit system operation and largely avoided the irrelevant technical details of these installations.

Train detection, control of conflicting movements and signalling interlocking system design topics and automatic train control principles have been reviewed in the initial sections. These discussions lay the foundations of the representations described in Chapter 5 and the processing methods described in Chapter 6. They also complement the descriptions of the rail transit systems which are to be simulated. The level of detail for the simulation model specified in Chapter 4 has also been deduced from the background research summarized in this review.

Power supply systems (networks) have become an integral part of modern rail transit systems. Therefore, a brief review of different schemes has been included to this chapter. It is possible to interface the simulation model to one of the existing power supply models for detailed system performance studies provided that a synchronized time-oriented configuration of the simulation model is used. The traction motor models described in Chapter 6 are voltage sensitive, as well as being speed and load dependent, and this allows the train performance calculations to be linked to the results of the power supply network solution.

CHAPTER 4

COMPUTER SIMULATION APPROACH

4.1 INTRODUCTION

The main aim of this chapter is to compare the philosophies and structures of existing computer-based rail transit system simulation models. Based on this review a new computer model will be specified and the required design methodology and tools to implement this model will be identified.

Beginning with tedious and difficult graphical techniques used early in the century for calculation of speed profiles of trains, various types of simulation models have been developed to solve transit problems [57]. These include :

Analogue : Analogue computation has been applied only to simplified models; an example is described by Lehman [58]. In this example he solves the equations of motions for a single train. Typical applications have been the calculations of speed profiles, energy consumption or run times. Analogue simulation has also been used for calculation of energy optimal driving strategies, prediction of braking distances, research into the influence of track geometry on energy use, run times and route capacity etc.

Hybrid : The obvious drawback in using analogue simulation is the difficulty of entering changing track geometry and speed restrictions e.g. to simulate gradients a chain of distance comparators would have to be used to switch gradient potentiometers in and out [57]. This can be overcome by using hybrid simulation. In this case the computer can store all the track geometry and speed restrictions. An example of minor hybridization is given by Lehmann [58] as used for calculation of minimum headway. The movement of two trains following each other is simulated on an analogue computer. Safe distance is calculated and the following train is maintained at this distance by braking. At the end of the run, the cumulative interaction (i.e. number of times the brakes were applied) between the trains is used to calculate the headway time for the next run on a digital computer.

Digital : Most of the modern simulation models fall into this category. It is unimaginable to think that simulation models could have reached any success without the digital computer. A review of digital computer simulation techniques is presented in Section 4.2.

4.2 CLASSIFICATION OF DIGITAL COMPUTER SIMULATION MODELS

A complete taxonomy of such models is beyond the scope of this review, but a rough and ready classification may be achieved by focusing on two closely related aspects; the representation of the passage of time and the level of detail. It must be noted that the simulation of rail transit systems reported in the literature usually lacks vital details about the internal organisation of the software which makes their comparison difficult. Some of the existing simulation models, which are not mentioned in this chapter, are listed in Appendix 1.

4.2.1 Representation of Time

Simulation models are developed to analyse the behaviour of systems as a function of time. From that standpoint, two possible methods of representing the passage of time suggest two simulation approaches, namely 'time-oriented' and 'event-oriented'.

1. **Time-oriented (continuous) simulation :** A time-oriented simulation proceeds in regular time increments. Time is considered constant while the behaviour of every 'activity' in progress at that time is updated. At the end, the time is incremented and the simulation cycle is repeated.

2. **Event-oriented (discrete) simulation :** In an event-oriented simulation the passage of time is not regular but rather, as its name suggests, the simulation proceeds from event to event. In the context of rail transit system simulation, suitable activities or events would be a train's entry to or exit from the network, the clearing of a signal, approach to a junction etc. Event-oriented simulations of an entire rail transit system usually include stochastic variables for passenger demand and travel times. A typical application is given by Levene et al. [59], for the assessment of the application of realtime control at junctions in order to increase the throughput of traffic on sections of London Underground. Other analyses described in the literature cover such problems as timetable studies, supervision strategy studies, passenger queuing problems and dispatch policies.

At first sight, an event-oriented simulation promises to give a faster computer run time. This is because time is not wasted by repetitive calculations and just waiting for an 'event' to happen. However, this argument takes no account of the difficulties involved in synchronizing the train movements. The movements are not calculated simultaneously for all trains or as is the case in many existing models are not calculated at all. Therefore, it is possible in a perturbed system that future events will not be completely determined at the time the prediction is performed (e.g. how long must a train stop before the signal clears at a junction). To deal with such cases some existing simulation models move forward and backward in time, scheduling and rescheduling events to determine the effect of the present situation on other trains [59]. But the success of such methods are limited to particular applications and they usually make the software very complex and inflexible.

This drawback of event-oriented simulation approach makes it unsuitable for the applications which require knowledge of the network state at any given time (e.g. a power network solution, moving block,cab or continuous signalling, automatic traffic regulation and junction optimization methods). In time-oriented continuous simulations, the above difficulties do not exist; the trains move simultaneously, interactions through signalling system or power network are detected as they occur and immediately influence the simulated system. However, handling discrete events is inefficient; this entails checking at each simulation cycle whether a new event has occurred. The checking requires the comparison of all outstanding events with current time and positions of trains including the trains that are idle.

The decision whether or not to add facilities for handling discrete events to the continuous simulation depends on the number of events and range of different applications planned for the simulation model. After comparing these two simulation approaches Eichler and Turnheim [61] conclude that a rail transit system has a sufficient number of such events to justify the addition of event-oriented features to time-oriented simulation models (i.e. combined simulation). The combined simulation approach is also supported by McDowell [60] specifically recommends the inclusion of special event handling facilities in time-oriented models.

4.2.2 Level of Detail

In practice, the main application purpose of the simulation determines the level of detail. In this context, existing simulation models can be classified into four main groups.

1. **Macro-economic models :** The 'macro-economic models' are characterised by a very high level of abstraction; each simulation run covering months or years of real time. In the simulation study reported by Chiesel and Newell [62] the infrastructure of the network is not represented at all. The smallest unit of time considered in the program developed by Oisen [63] is one day (compare with an extreme example by Guieyess [64] where the time increment is 0.001 s). Further examples of this type of model are reported by Dunbar et al [65] and by Miyata and Ozeki [66].

Comment : Models such as these may only loosely be termed rail transit system models, being much more concerned with collecting pertinent statistics e.g. on the effects such a system might have on the economics of the region than with analysis of the system itself.

2. **Rail network models :** At a lower level of abstraction and with a corresponding shorter time scale of weeks or months per simulation run come

the 'rail network models', perhaps the best known examples of which are the Association of American Railroads (AAR) Network Model [67] and San Francisco Railway Frisco Simulation Model. In these and most other models in this group the topology of network is approximated , with individual conflict areas being considered single vertices of the rail network. Both AAR and San Francisco Railway Frisco Simulation Model consider their terminals and decision points as vertices, and these vertices are connected by lines representing tracks. Similar models are reported by Alward [69] and by Prokopy et al. [70]. The network model described by Tashker and Wang [71] differs slightly from this pattern by treating both line sections (tracks) and vertices as edges of an abstract network, each edge associated with length, transit time characteristics and both constant and time dependent delays. The emphasis in the U.S.A. is on the freight handling capabilities of the system; a 'what-if' question frequently answered by this type of simulation models concerns the performance of particular sections of network in terms of the delays suffered by trains due to the single track structure of the American freight network.

A rapid transit system simulation model whose organisation is quite similar to the above network models is described by Nielsen et al [72]. The purpose of this model is to evaluate the efficiency of the proposed central management system network control algorithms. This simulation is notable for an interesting approximation technique used for movement simulation. The headway time between vehicles is approximated from the length of line section and number of vehicles on it. The vehicle speed is derived from a standard speed vs. headway time curve. By contrast, in a similar study on network control, Levene et al [59] used a normal distribution function fitted to observed data to assign speeds to trains.

Comment : Naturally, this group of simulation models is event-oriented. Train movement is not explicitly calculated using equations of motion but is dealt with by inter-node transit times derived from operational data or a lower level train performance calculator. The network representations of these models are not sufficiently accurate to represent the conflict areas satisfactorily.

3. Train movement simulators : British Railways' general area time-oriented train simulator (GATTS) reported by Brocklehurst et al [73] is more detailed than American models in that the rail network topology is modelled more accurately. GATTS is primarily intended for simulation of areas with multi-aspect signalling, provision being made for signals with 3 or 4 aspects and for 2-aspect distant signals [74]. Movement simulation is derived from a lower level train performance calculator. Signalling is explicitly handled within the simulation model. In terms of its time scales of several hours up to a week, and its level of detail, GATTS can be placed at the lower end of movement simulators.

Eichler and Turnheim [61] report a very basic rapid transit system movement simulation model. The main thrust of their work has more to do with the methodology of train simulation and a comparison of benefits of event-oriented, time-oriented and combined simulation as defined by them, than investigating a specific problem.

Conrad and D'Esopo [75] provide an interesting example of a rapid transit system movement simulation model where the same model functions at a variable degree of fidelity depending upon how it is configured. In this simulator, it is possible to use a family of related modules with broad application to a variety of analysis tasks. Some modules can then be common to all users while others can be tailored to have a level of detail required for a particular user.

However, not all the movement simulation models are flexible in structure. Some, e.g. the one reported by Mellitt and Goodman [76], are limited in their applications by their problem-oriented designs. This model does not have a proper rail network representation and only operations of trains on a single line can be modelled. An essential feature of the model is the interlinking between train movement calculations and power supply network modelling. Trains and substations are modelled in such a way that they form a linear electrical network. This model has also been used to test some signalling schemes or system control strategies on a single line with regular working patterns and identical traction equipment [9] [23]. Another example of problem-oriented movement simulator is described by Caprio et al [28]. The main aim of this simulation is to develop and test on-line control strategies to be used when solving problems caused by traffic conflicts.

Comment : The level of structural detail provided by a train movement simulator is greater than a network model. A typical simulation run usually represents hours of real time rather than days or weeks. Track gradients and speed restrictions are explicitly dealt with and the rail network topology is represented accurately. Details like the length of train are usually taken into account because they have significant effects on the runtimes. All the existing models are written in unsuitable programming languages without any modern software engineering approach and most of them do not have proper network representations which restricts their range of applications.

4. Train movement calculators : The last group of programs considered is concerned only with train movement calculations. In these programs accuracy of movement is a prime consideration and many factors e.g., jerk limiting, equipment reaction times etc. which are ignored or approximated in the previous groups are dealt with much more accurately. Train movement calculators may either stand alone [77] [78] [79] [80] or may be used with higher level of programs in a suite [73] [81]. In either case the facilities provided by them are very much the same. In a suite, they are most commonly used to provide a data base of runtimes from which a higher level network model derives its simulation of movement.

4.3 DESIGN CONSIDERATIONS

4.3.1 Software Design Concepts

Some of the basic concepts used in the simulation model design related sections of this thesis are defined in this subsection :

Data type : This term refers to the kinds of data that variables of a programming language can hold. Modern languages like Pascal can support both built-in and user defined data types. User defined data types are extensively used within the simulation model.

Data structure : This is a representation of the logical relationships among individual elements of data. Data structure dictates the organisation, methods of access, degree of associativity, and processing alternatives for information. Entire texts e.g., [82] [83] have been dedicated on these topics. There are, however, a limited number of simple data structures that form the building blocks of the representations described in Chapter 5. These simple data structures are arrays (i.e. vectors and n-dimensional spaces) and linked lists.

Linked list : A linked list is a data structure that organizes noncontiguous scalar data items, vectors, or matrices of various data types in a manner called nodes that enables them to be processed as a list. Each node contains appropriate data organization and an address field that links it to the next node. The more complex data structures e.g., multi-linked lists, hierarchical trees, sparse matrices etc. that are utilized in the simulation model are constructed using this fundamental linked list data structure concept.

4.3.2 Kernel Features of the Simulation Model

The scope and objectives of the rail transit system simulation model design are summarized in this subsection.

1. Combined simulation : The model will be time-oriented with some significant event-oriented features. In choosing to implement an essentially time-oriented model, a different balance regarding the benefits of each method has been reached than by Eichler and Turnheim [61]. Two main reasons can be advanced for this decision.

a. The difficulties of simulating the modern continuous train traffic regulation methods which require a knowledge of the system at any given time.

b. The difficulties of interfacing a power supply network solution module which require to know the positions and power demands of the trains at any given time.

A rail transit system is itself partly continuous in nature (e.g. equations of motion) and partly discrete (e.g. dispatch of trains and interlocking). In a pure time-oriented simulation the disadvantages discussed in Section 4.2 exist. Therefore, inclusion of explicit event handling facilities to a time-oriented simulation model can potentially use the best features of both approaches. For the applications in which interactions occur only at the entrances of the signal blocks (i.e. multi-aspect fixed-block signalling), event-oriented simulation features will be extensively used to reduce the amount of repetitive computer work. These features will be easily extendable so that the model can cope with the repetitive simulation runs e.g., Monte-Carlo type simulation or optimization applications, without reducing the level of detail of modelling or calculations.

2. Data-structure oriented design : The simulation model will be a data-structure oriented design and makes use of modern programming concepts (e.g. data abstraction, modularity etc.). New modules (e.g. motor models, energy calculations methods) can easily be linked into the main structure. The program should also be easily transportable. The reasons for this choice will be explained in Subsection 4.3.3. It will also be demonstrated in Chapter 5 that this design approach is well suited to the nature of the system.

3. New application areas : In addition to the wide range of conventional 'what-if' applications, the software techniques that will be applied in this design, along with the development of fast computers, allow the possibility of developing realtime control systems with predictive simulation. To date no implementation of this kind has been reported although such realtime applications have been suggested in the literature [57] [59]. The feasibility of this approach for maximum energy demand control will be discussed in Chapter 8. The model should also be suitable for interactive design, optimization applications and statistical analysis of the system.

4. Adaptability : The development cost of a comprehensive simulation model is very high, therefore, the simulation model should be completely independent of any particular rail transit system. This model aims to simulate all types of rail transit systems without major modifications to software. The maximum size of the area which can be simulated will depend entirely on the capacity and speed of the computer available. This feature of the simulation model has been confirmed by applying it to four diverse rail transit systems as will be described in Chapters 7 and 8.

5. Level of Detail : The simulation model should take into account the following features :

a. The track layout, including speed restrictions, gradients, signal positions, structural details of conflict areas etc.

b. The mechanical (i.e. mass, length, braking rate, the curves of tractive effort and train resistance curves) and electrical (i.e. line current and line voltage) characteristics of the trains.

c. The timetable and train routes. Interactions between the train movements and the signalling system.

The level of detail of the rail network or traction equipment models or the movement calculations should be adjustable and application dependent. This feature of the model has been demonstrated by the applications presented in Chapter 7 and Chapter 8.

6. Time scale of simulation : The simulation model will calculate the movement of individual trains using the equations of motion. It should be capable of simulating the movement of trains over a period of several hours and up to several days.

7. Traffic regulation features: The simulation model will model multi-aspect fixed-block signalling schemes. Interfaces will be defined to incorporate other signalling schemes.

8. Selectivity of output : Rail transit systems are characterised by a large number of variables. Therefore, the user will be able to select and arrange the required variables for output.

4.3.3 Design Methodology Choice

Computer programs usually operate on an information domain. In most cases the information is not simply amorphous masses of numerical values; it involves important structural relationships between its elements. The computer simulation model of a rail transit system is bound to contain a great number of such relations.

The structure of the information is a major influence on the design method. Data flow-oriented design methods use information flow characteristics to derive program structure. These methods are mostly used in engineering applications e.g. complex numerical analysis where the structure of information is a side issue. Data structure-oriented design methods, like data flow-oriented methods, focuses on the information domain. However, rather than concentrating on data flow, the information structure is used as the basis for the design [85].

The design of the simulation model adopts a data structure-oriented approach. Simple structures like vectors and n-dimensional spaces proved to be unsuitable when the design problem called for several arrays of varying sizes and types. By storing each type of information in different arrays of maximum size computer memory is wasted. More important than this, it is also clearly sensible for the simulation model itself to reflect the structure of a rail transit system it represents. For some time, many authors such as Jackson [86] and Cameron [87] have advocated modelling of the systems in a natural manner. Array structures are inadequate to represent structural relationships and interconnections in the real system in a natural manner.

The representation problems of the simulation model have been solved by using complex data structures based on 'linked lists' whose definition is given in Subsection 4.3.1. In this type of representation, the information domain is classified into 'nodes' which have address and data fields [88]. The appropriate organizations of these nodes to represent rail transit system components (e.g. signal blocks, trains, timetable) proved to be a suitable abstraction. These data structures, which will be further described in Chapter 5, are capable of representing the structural relationships of a rail transit system naturally. Consequently, design to source code translation is easier which is an important factor in software readability and maintainability.

This application of the data structure-oriented design can be viewed as an object-oriented design in the sense that it creates a model of rail transit systems that can be realized in the software. The methods to manipulate the data structures are kept separate from the related data structures because of programming language restrictions.

4.3.4 Programming Language Choice

In the literature, the programming language chosen to implement a rail transit system simulation model varies from assembler to a conventional high-level language e.g. FORTRAN or a specialized simulation language e.g. SIMSCRIPT, SIMULA. Shannon [89] provides a detailed discussion of choosing a simulation language and the criteria for making that choice. If a time-oriented model is contemplated, the choice of languages is restricted since the major simulation languages like GPSS, GASP IV, SIMULA, SIMSCRIPT lead naturally to event-oriented implementations.

After the data structure has been designed, the choice of implementation language is based upon the following criteria:-

1. The language must support structured programming.

2. The language must provide for data definition constructs. These constructs make the program text as a whole clearer.

3. The language must provide linked-list processing facilities so the program structure can be designed in a natural manner.

4. The language must provide carefully chosen control structures and powerful data structuring capabilities.

5. The language has to be fixed, precise and concise without ambiguity.

Where the choice of language is mentioned in the time-oriented rail transit simulation literature, local availability and existing expertise seem to be just as important considerations as the applicability of the language to the simulation design. Coates and Clarke [81] cite precisely these reasons for choosing FORTRAN to implement GATTS. FORTRAN has been to used implement many other time-oriented simulation models. In fact, it has been 'force-fitted' into a non-numerical programming area for which it was never designed. The major drawbacks of FORTRAN are :

1. It does not satisfy any criterion of a modern language and lacks almost all of the data abstraction features present in the third generation languages.

2. It provides only a very coarse control over the visibility of data which makes it harder to debug.

3. It is not strongly typed and leaves the detection of common errors to runtime rather than compile time e.g. implicit declarations make mis-spelling hard to detect and potentially disastrous.

4. Unlike third generation languages it is problem oriented, rather than language oriented, which limits its range of applications.

The above defined criteria satisfied by the most of the modern general purpose high level languages e.g. Pascal [90], C [91], Modula-2 [92], and Ada[93]. Pascal and C compilers were locally available at the time of design. Pascal has been chosen to implement the simulation model described later in this thesis. The over-flexibility of C and the unreadable code it produces have been found unsuitable for this application. Since portability is a critical requirement, local extensions have been avoided and source code has been restricted to International Standards Organization (ISO) standard. The main reason for the choice of ISO Pascal is the integrity of this language. Since its introduction in the early 1970's, Pascal has found great support from the software developers. It is a powerful language which has been the most successful at reconciling conflicting design criteria

[85]. Unlike C, it forces block structuring, data type consistency and, consequently, much more readable source code.

Structured languages with object-oriented extensions (e.g., object Pascal, C++, Smalltalk) can combine data structures with a set of methods (i.e. procedures and functions) that operate on them [94]. This facility will make the design more natural and the code much cleaner e.g. one can define a train object that holds not only all the data but also the methods necessary to run it on a rail network. This approach to software design suits better the nature of the simulation model design problem. If a standard object-oriented version of Pascal had been available during the design phase it would have been favoured.

4.4 CONCLUSIONS

This chapter has reviewed the existing computer-based rail transit system simulation models. These simulation models have broadly been classified as rail network models, movement simulators and movement calculators according to their level of modelling details and as time-oriented (continuous) or event-oriented (discrete) according to the manner the calculations are performed and sequenced. Thus, an event-oriented model only evaluates the system variables when certain events take place. It is therefore difficult to model the continuous interaction between the trains through a continuous traffic regulation system or power supply system since the train movements are asynchronous within the simulation.

After discussing the existing models, a time-oriented model with expandable event-oriented features has been specified. In this model, train movements can be synchronized or asynchroned in time with respect to each other according to the type of application. This new model aims to be able to model any type of rail transit system at any required level of detail and to support a wide range of studies. To realize this level of flexibility in the model modern software engineering techniques must be employed. The design methodology (i.e. data structure-oriented design) and the programming language (ISO Pascal) chosen to design and implement the model have been introduced and the choices have been justified. Further details of the design and implementation will be discussed in the following chapters.

CHAPTER 5

DATA STRUCTURES

5.1 INTRODUCTION

In this chapter data structures for representing rail networks, time-tables, train route information and trains will be described together with the arrangement of output structures. The predefined set of simple data structures provided within even modern programming languages e.g., scalar items, sequential vectors and matrices, are not adequate for rail transit system modelling. Therefore, new sets of data structures, based on these predefined data structures should be defined and implemented to represent the essential components of a rail transit system. An implementation of a data structure can be defined as below :

Implementation of a data structure : An implementation of a new data structure D is a mapping from D to a set of predefined data structures E. This mapping specifies how every object of D is to be represented by the objects of E.

These complex structures also represent the logical relationships among individual elements of data. Because these structures determine the organization and degree of associativity of data and the access and processing methods, they have had to be carefully specified.

5.2 RAIL NETWORK REPRESENTATION

5.2.1 Network Representation Concepts

In this section some important concepts of graph theory are presented in the context of rail network representation. However, for a more rigorous treatise of the theory the reader is referred to Seshu and Red [95] or Swamy and Thulasiraman [96]. For a general treatment of graph theory for programming applications Horowitz and Sahni [97], Welsh and Harary [98] and Knuth [99] will be found most useful.

Four basic definitions from graph theory are given below :-

Graph : A graph $G = [V,E]$ is defined as a set V whose elements are called vertices and a set E whose elements $e \in E$ are ordered pairs of vertices called edges.

Line Section : An edge without its distinct endpoints is called a line section.

Network : A graph with weighted edges is called a network.

Hyperdigraph : A graph structure in which vertices of the graph may themselves be expanded as hyperdigraph structures.

In the rail network model of the simulator structures like terminals, stations, junctions are represented by a set of vertices. These vertices are connected by weighted line sections representing the tracks.

The structural properties of a rail network and programming requirements have led to some relaxations in these definitions. Notable exceptions are:-

1. The maximum degree of a vertex (i.e. the number of line sections incident to that vertex) is limited to 4. If the actual degree of vertex is greater than 4 (e.g. complex junction areas) or if physically two or more vertices appear together (e.g. attached junction, station structures), these are represented by a number of adjacent vertices.

2. Since G [X,U] is a set, a network may not have multiple occurrences of the same edge. But in a rail network more than one line section may lie between two vertices (i.e. multiple parallel tracks running between two stations). In such cases the chosen route can be indicated in the route table or a the physical vertex can be represented by a set of vertices connected with zero-weight line sections using the hyperdigraph concept.

3. Two separate networks can be simulated simultaneously as if they are parts (i.e. subnetworks) of the same network. These two networks must be connected by a zero-weight line section. Similarly, a network can be viewed as composed of several subnetworks.

4. If a line section is not on the route of any train, it is defined as a zero-weight line section. This concept is used to skip irrelevant parts of a network while keeping its structure.

5.2.2 Representation Techniques Available

While several representations of networks are possible the three most commonly used ones are considered ; adjacency matrices, adjacency lists and adjacency multi-lists. The choice of the representation technique depends upon the type of the application and the functions to be performed on the network model.

5.2.2.1 Adjacency Matrix Representation

Definition - Adjacency Matrix : Let G = [V,E] be a graph with n vertices, n > 1. The adjacency matrix of G is a 2 dimensional n x n array A, with the property that A [i,j] = 1 if the edge (V_i,V_j) exists and A [i,j] = 0 if there is no such edge in G.

Comment : This basic method has traditionally been used in representation of electrical networks. Unlike an electrical network, in a rail network both the vertices and the line sections are structured and therefore, contain several data fields. Additionally, a practical rail network is very sparse i.e. most of the terms in the adjacency matrix will be zero. A better representation of such a network can be achieved through the use of linked lists in which only the edges that are in A are represented.

5.2.2.2 Adjacency List Representation

Definition - Adjacency Lists : In this representation the n rows of the adjacency matrix are represented as n linked lists. There is one list for each vertex in G. The nodes (i.e. the structured elements of the lists) represent the vertices that are adjacent to a vertex. An example of this representation is given in Figure 5.1. Each node of a list has at least two fields: vertex and link. The vertex field of node i contains the index of the next vertex adjacent to vertex i. Each list has a head node and the head nodes are arranged sequentially providing easy access to the adjacency list of any particular vertex.

Comment : The main advantages of this representation are spatial economy and easy random access to any vertex.

5.2.2.3 Adjacency Multi-list Representation

Definition - Adjacency Multi-lists : If the same vertex structure is shared among several adjacency lists, a multi-list representation of a network is preferred. In this representation there exists exactly one node for each vertex. This node can be linked to different lists through its address fields.

Comment : This is the representation used in the simulation model because of its close structural similarity to a real rail network structure. In the network representation of the simulation model, a large amount of data (e.g. identification numbers, route and interlocking data, address fields etc.) is kept in each vertex structure. The operation of interlocking logic, for example, depends on checking all connections of a vertex. The data structures created by using only one node for each vertex gives further spatial economy combined with easy sequential access. A headnode array keeps the addresses of the vertices to provide easy random access.

As shown in Figures 5.2 and 5.4 the vertices of the network are linked by three sets of doubly linked lists which represent line sections. The development of this representation is discussed in detail in the following

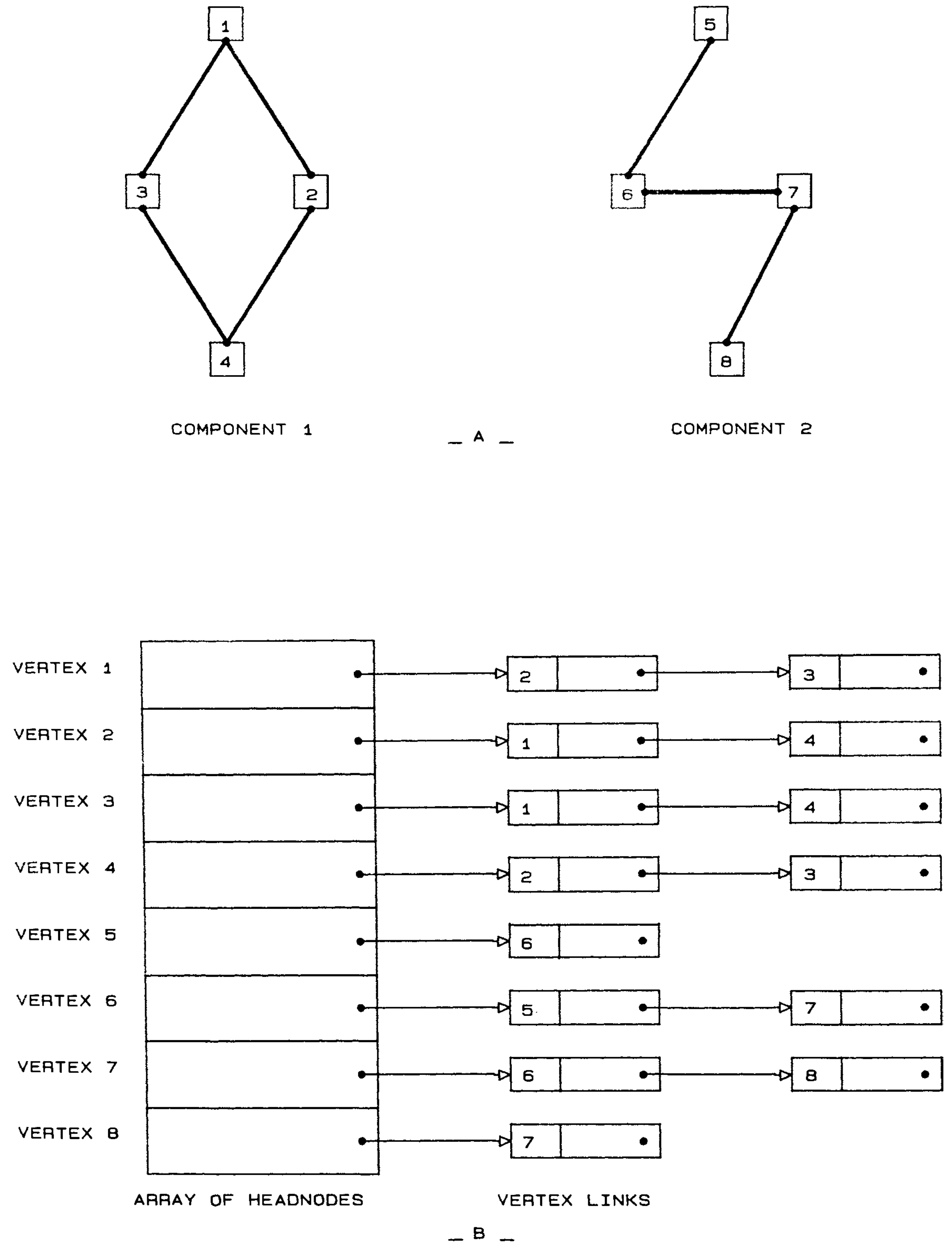


FIGURE 5.1 _ ADJACENCY LIST REPRESENTATION OF A GRAPH.
A _ AN UNDIRECTED GRAPH G WITH TWO UNCONNECTED COMPONENTS.
B _ REPRESENTATION.

subsections.

5.2.3 Line Section Structure

In a conventional rail network, a line section is nothing more complicated than any number of signal block sections and track circuits joined together. Line sections have three types of information associated with them: signalling, track geometry (i.e. gradients and curves) and speed restrictions. It was decided that in order to ease the task of experimenting with different signal layouts or track speed restrictions (i.e. usually permanent civil engineering restrictions) on the same network, the three types of information should be kept independent from each other. So, the line section representation problem calls for several ordered lists of varying sizes through which the train moves accessing this information sequentially.

Since the amount of information related to a line section (i.e. the number of signal blocks, track circuits, overlaps, speed restrictions, track geometry information etc.) varies, storing each type of information in a different array of declared maximum size would waste storage. In addition to this, some means of looking forward and backward on the line section is necessary during the train operations.

An elegant solution to this problem of data structuring in sequential representations is achieved by using doubly linked lists with both backward and forward links. It was found convenient to treat the tracks as a series of discrete blocks within which the equivalent gradient, curvature or track speed restriction is constant. This approach requires piecewise continuous representation of track geometry. Consequently, all information lists can use the same structure whose Pascal declaration is given in Appendix 2. This structure consists of the data and address fields described below :-

i.d_numbers : an array of block identification numbers

same_circuit : a track circuit identification number for indicating if the same track circuit is shared between different signal blocks.

train_existence : a boolean variable to indicate the existence of a train structure accessing the structure.

block_location : an array to hold the positions of the block with reference to the vertices

block_length : length of the block

block _value : value of gradient or curvature or speed restriction or position of an overlap if signal block.

more_circuits : Some signal blocks have several track circuits. This optional array holds the positions of these track circuits if they are not represented independently.

section_link : array of pointers for connections to the other blocks

Prior to a simulation run the given gradient and curvature values are transformed to the effective track geometry. The transformation, described in Section 6.3, enables the train to be treated as a point mass and the track as a continuous curve. The representation of a line section before this transformation is shown in Figure 5.2. Some modifications to this structure are introduced after track geometry data is transformed.

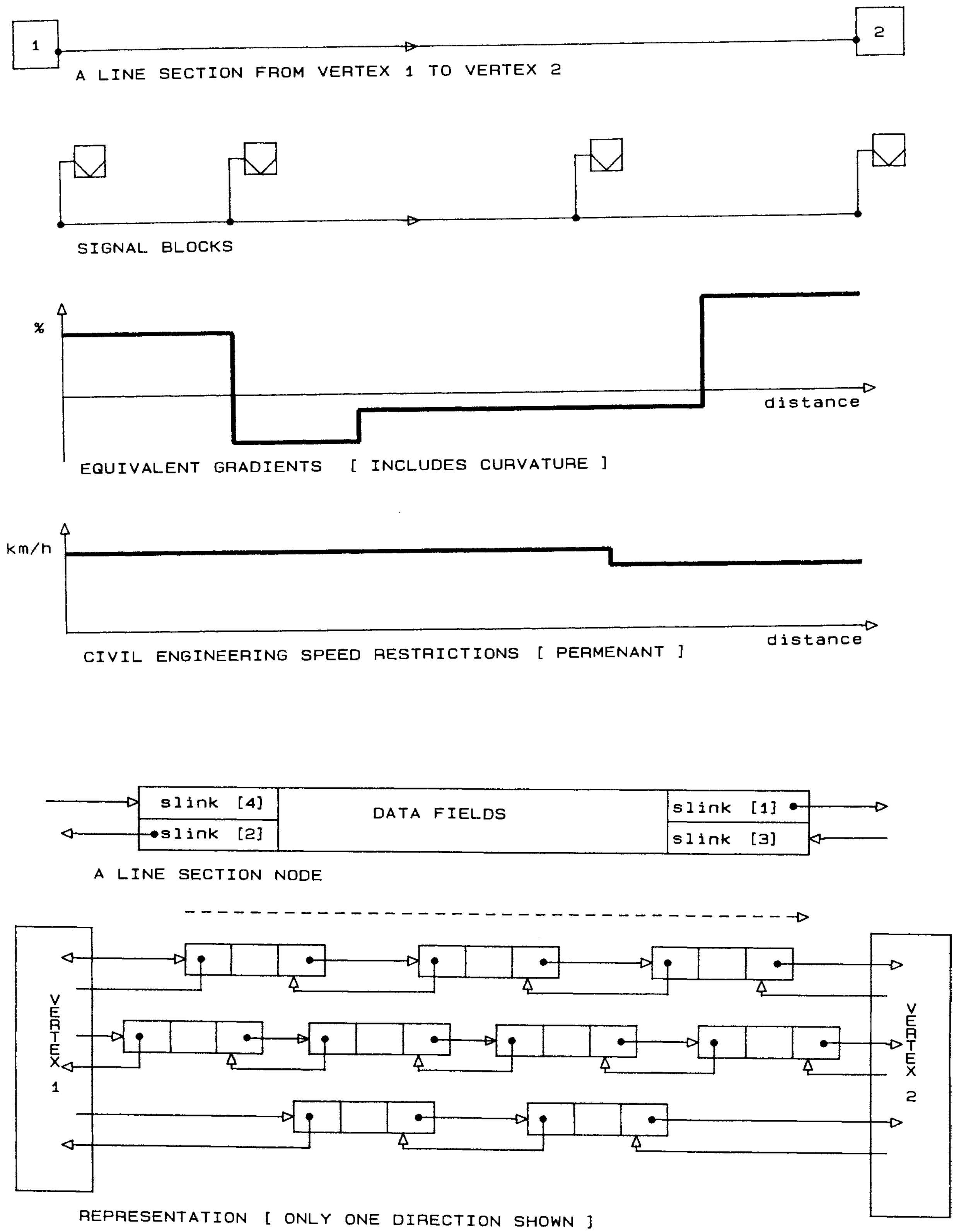


FIGURE 5.2 _ REPRESENTATION OF A LINE SECTION IN THE SIMULATION MODEL.

5.2.4 Vertex Structure

Each conflict area is represented by a main vertex. Each main vertex can consist of one or more vertices and line sections (i.e. a subnetwork) which forms the 'functional unit' model of a conflict area. A functional unit is not necessarily an explicit representation of a physical structure but a operational equivalent of it at a required level of detail. Its level of detail is naturally determined by the type of the application considered. Together with the traffic control methods, described in Section 6.5, these functional units model the specific structures of a rail network. In this way a hyperdigraphical representation of the rail network data and relationships is formed.

Basic network structures (i.e. simple stations, diverging and converging junctions or basic terminals) can usually be modelled using a single main vertex structure. For some types of applications, it may still be possible to model more complex conflict areas by a main vertex. For example, if 'pass through' times are known, modelling of some internal signal blocks, points and track circuit interdependencies may not be necessary. But if the layout of a conflict area can be divided into more basic structures also connected with line sections (i.e. hyperdigraph structure), a higher level of structural detail can be obtained. This concept is illustrated with an example in Figure 5.3. The Pascal Declaration of a vertex structure is given in Appendix 2. This structure consists of the data fields described below :

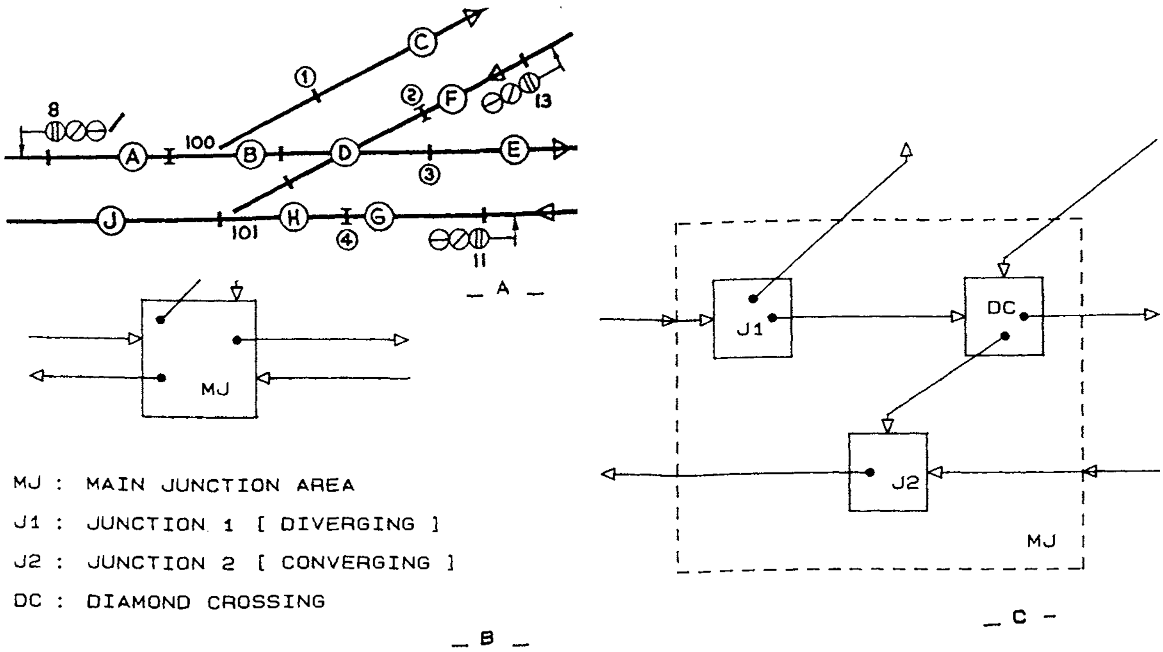


FIGURE 5.3 _ A TYPICAL BR LEFT HAND JUNCTION AND ITS REPRESENTATIONS.
A _ LAYOUT OF THE JUNCTION
B _ ONE VERTEX REPRESENTATION
C _ THREE VERTEX REPRESENTATION

i.d_number : identification number of the node.

vertex_name : name or description of the node.

vertex_logic : The track circuits and their interdependencies are not always modelled in detail. Instead, this Boolean matrix is used to set or release a route in a conflict area. This matrix is used if parallel movements are allowed through the node. The elements of this matrix are set or released by vertex control algorithms according to a given strategy e.g. first come first served,timetable order, overall or weighted delay, etc.

train_order : This matrix keeps the order which the trains will pass through a conflict area. The order is dictated by a given control strategy.

thru_time : Although all conflict areas can be modelled with sufficient track geometry detail, there exist some applications where such levels of detail and accuracy are not required. In such cases through times for different routes can be calculated prior to the simulation run and stored in this matrix. Normally the elements of this matrix are zero.

thru_route : This matrix keeps the identification number of the vertices to which the vertex under consideration is connected. The simulation program matches the route information of the train with an element of this matrix and connects the train to a new line section.

length_shift : This variable holds the length difference between signal blocks and gradient, speed restriction blocks.

vertex_link : Each vertex has 28 address fields. This limits the number of outbound or inbound line sections to 4. Dis tribution of address fields is, 4 for signal block subsection pointers (see Subsection 5.3.5.1), 16 for incoming and outgoing track geometry blocks, 8 for track speed restriction blocks.

5.2.5 Rail Network Structure

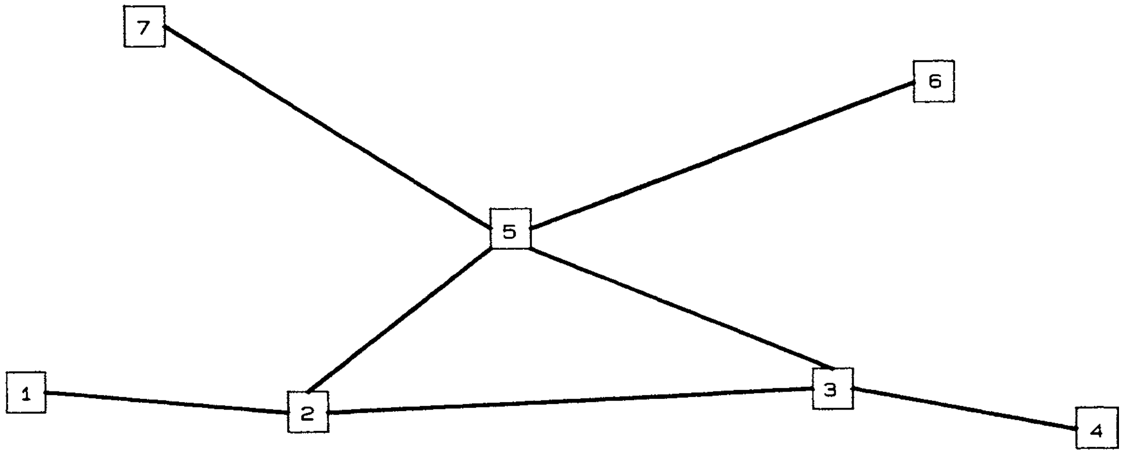
5.2.5.1 Initial Network Structure

At the very first construction of the network in the memory at the beginning of the simulation, signal blocks are not defined. Signal blocks are placed independently of the track geometry and speed restrictions. Signal block address fields are used to keep to the addresses of adjacent vertices at this stage. This direct access to adjacent vertices makes network construction and checking a lot more efficient. An example network and its adjacency multi-list representation are shown in Figure 5.4. It should be noted that only one of the three links between two vertices are shown.

5.2.5.2 Final Network Structure

By applying the effective track geometry technique, as described in Section 6.3, the gradient and curvature breakpoints are transformed according to the length of each class of train running on this line section. The transformed track geometry is held in newly created doubly linked lists.

In the existing network model, additional structures named 'subvertices' are created and linked to vertices through subvertex address fields. These new structures hold addresses of the signal blocks and effective track geometry lists. Usually, certain classes of trains run on certain line sections, so train routes are checked to avoid creating redundant



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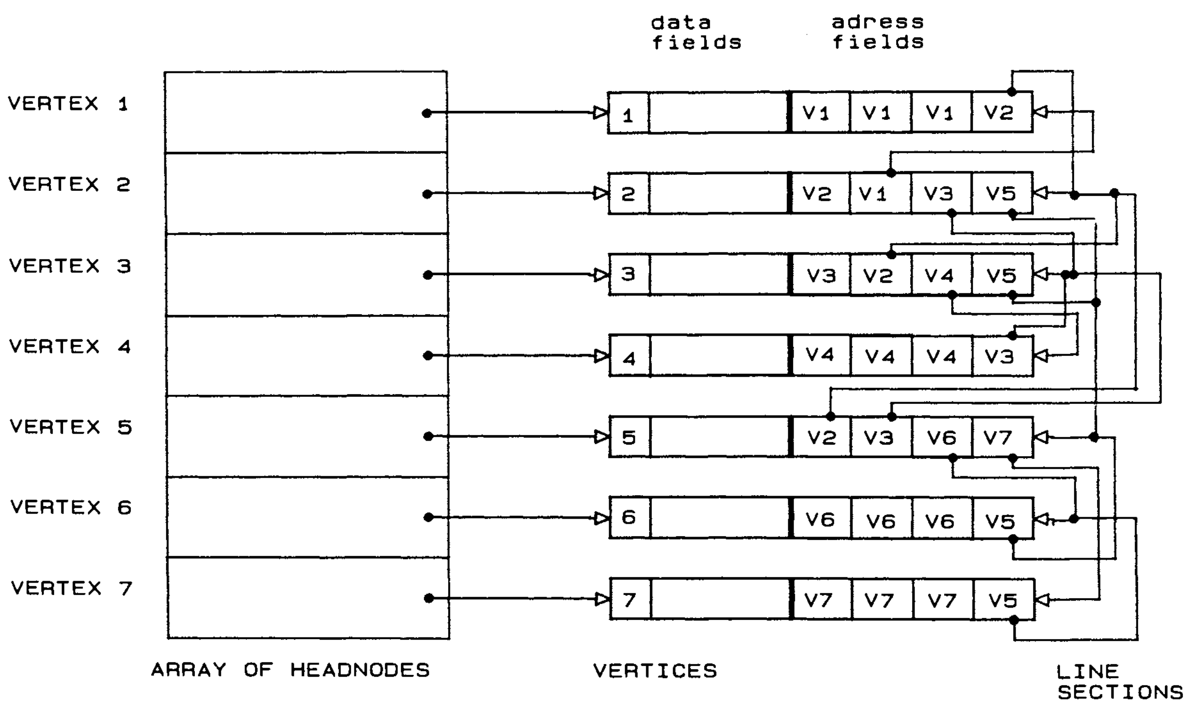

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FIGURE 5.4 — ADJACENCY MULTILIST REPRESENTATION OF A RAIL NETWORK.
A — RAIL NETWORK
B — REPRESENTATION

structures. After all new track geometry lists are created and connected, the original track geometry lists are returned to 'available space list'. A fragment of the new network structure is shown in Figure 5.5.

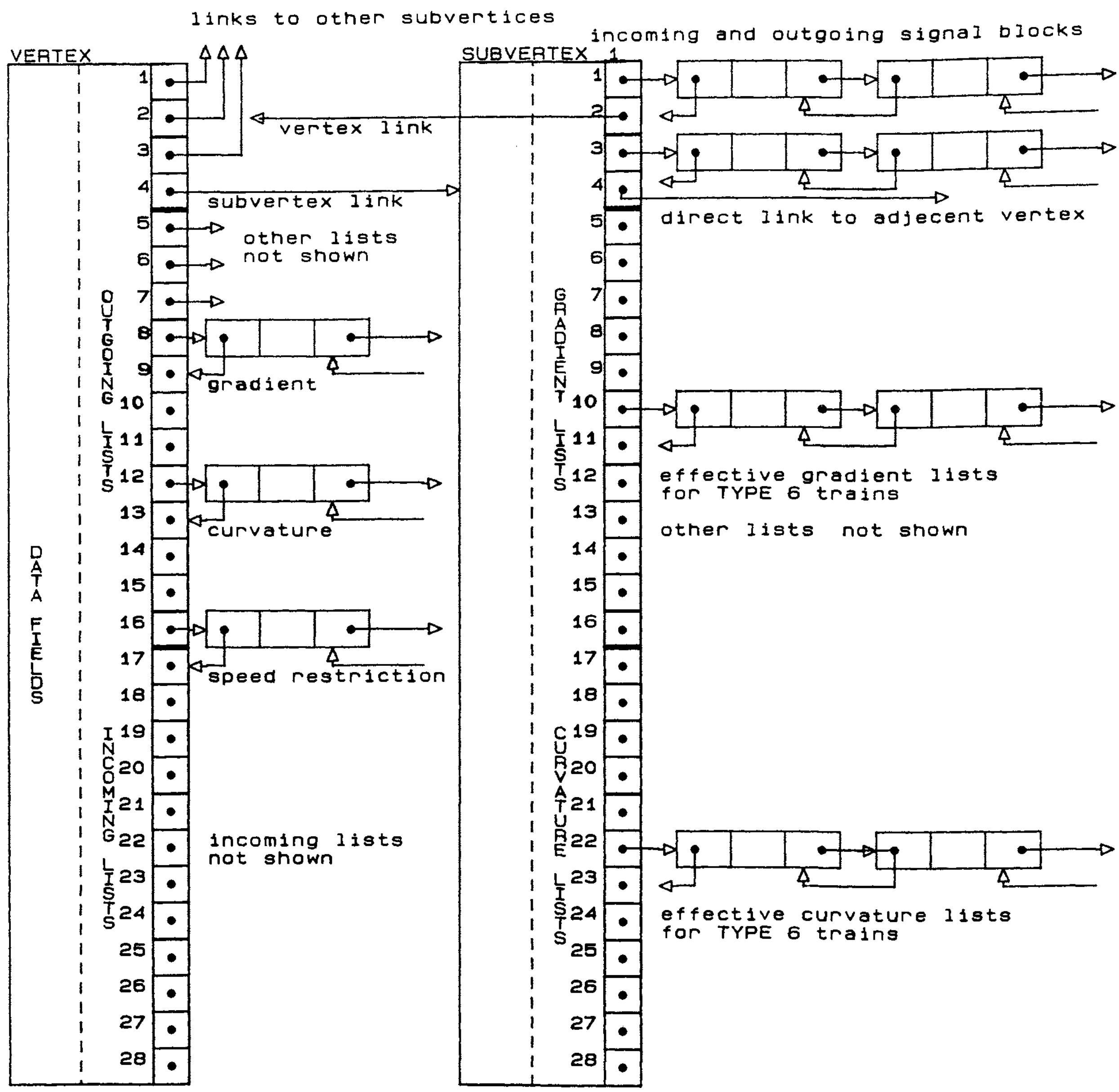


FIGURE 5.5 _ MODIFIED VERTEX STRUCTURE AFTER EFFECTIVE TRACK GEOMETRY LISTS CREATED.

5.3 TIMETABLE AND TRAIN ROUTE REPRESENTATION

5.3.1 Sparse Matrix Representation

A combined time/route table is one of the basic structures of the movement control in the simulator. It is a plan of what ought to happen during a simulation run, in terms of what train should be where and when. If a time/route table is represented by a basic matrix structure (i.e. trains as rows and vertices as columns) it will generally be sparse since each train runs only at a certain part of the rail network. The matrix will also vary in size in different applications or different runs on the same network. More important than these, the time/route structure is not be a 'perfect' matrix since trains can pass through the same vertex several times during their run. Therefore, some relaxations will be required.

When matrices are sparse (i.e. many of the entries are zero or do not exist), then much space and computing time can be saved if only the non-zero terms are retained explicitly. Linked structures, which facilitate efficient representation of varying size structures, can overcome these shortcomings of the basic matrix representation. A sequential storage scheme based on these structures will be used in which each non-zero term (i.e. a vertex on a train's route) is represented by a node with at least three data fields: row, column and value and address fields to link it to adjacent nodes [97]. In this representation each column is represented by a circularly linked list and a head node. Each row is also circularly linked in the same way.

Each node is linked into the lists for row i and column j, hence it is simultaneously in two different lists. This structure complies with the criteria defined by Gray [100]; it is flexible, memory efficient, capable of modification and dynamic growth and also any node in the structure is accessible sequentially from any other node.

The characteristics of train routes and rail networks will lead to some relaxations in order to include them in the data structure. The chosen representation can readily handle these relaxations. The main differences of the time/route table structure from a usual matrix representation are:

1. The field pointing to the next node (i.e. next vertex on a train's route) does not necessarily link a node with a greater column (vertex) number but merely to the next vertex on the train route.

2. Since a train can pass through a certain vertex more than once during its journey, there may exist more than one node with the same row and column number.

5.3.2 Combined Time / Route Table Structure

Three ways of using this table immediately suggest themselves :

1. Given a train, it is necessary to know its route and at what times it will be at the various places (e.g. stations, junctions etc.) and how long it will stop.

2. Conversely, given a vertex a list of trains that are supposed to be passing through this vertex with their times of arrival is also very useful.

3. A list of train-vertex events ordered in time suggests itself in an overall performance evaluation.

This structure is best represented by a matrix where each row or column is a doubly linked circular list, with a head node. Each node has a field called 'head'. This field is used to distinguish between head nodes and nodes representing existing matrix elements.

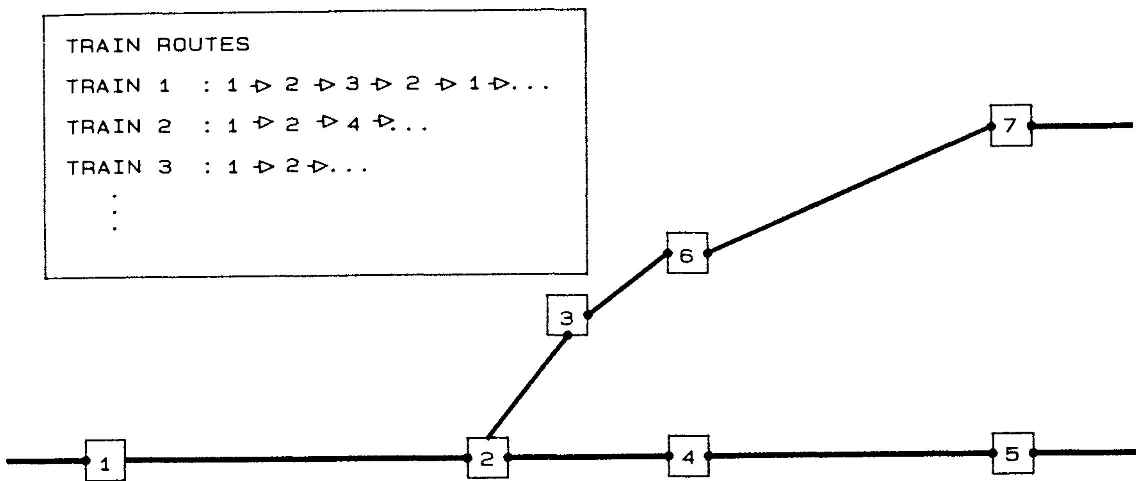
Each node has five address fields: down, up, right,left and next. The total number of head nodes is the greater of the number of trains, and the number of vertices. The head node for train i is also the head node for column j.

Every head node has five address fields: down, up, right, left and next. The 'down' and 'up' fields are used to link the neighbouring nodes in the same column, and 'right' and 'left' fields link to the neighbouring nodes. The 'next' field links the head nodes together.

Thus, if a_{ij} exists then there is a node with head = false, row = i and col = j. This node is linked into lists for row (i.e. train) i and column (i.e. vertex) j. Hence, it appears simultaneously in two different lists.

Each head node is in three lists : a row list, a column list and a list of head nodes. The list of head nodes itself has a head node which is identical to the one used to represent existing elements. The 'row' and 'col' fields of this node are used to store the matrix dimensions. Also another address array is used to keep the addresses of the head nodes for direct access.

Having arrived at this representation for the time/route table, the



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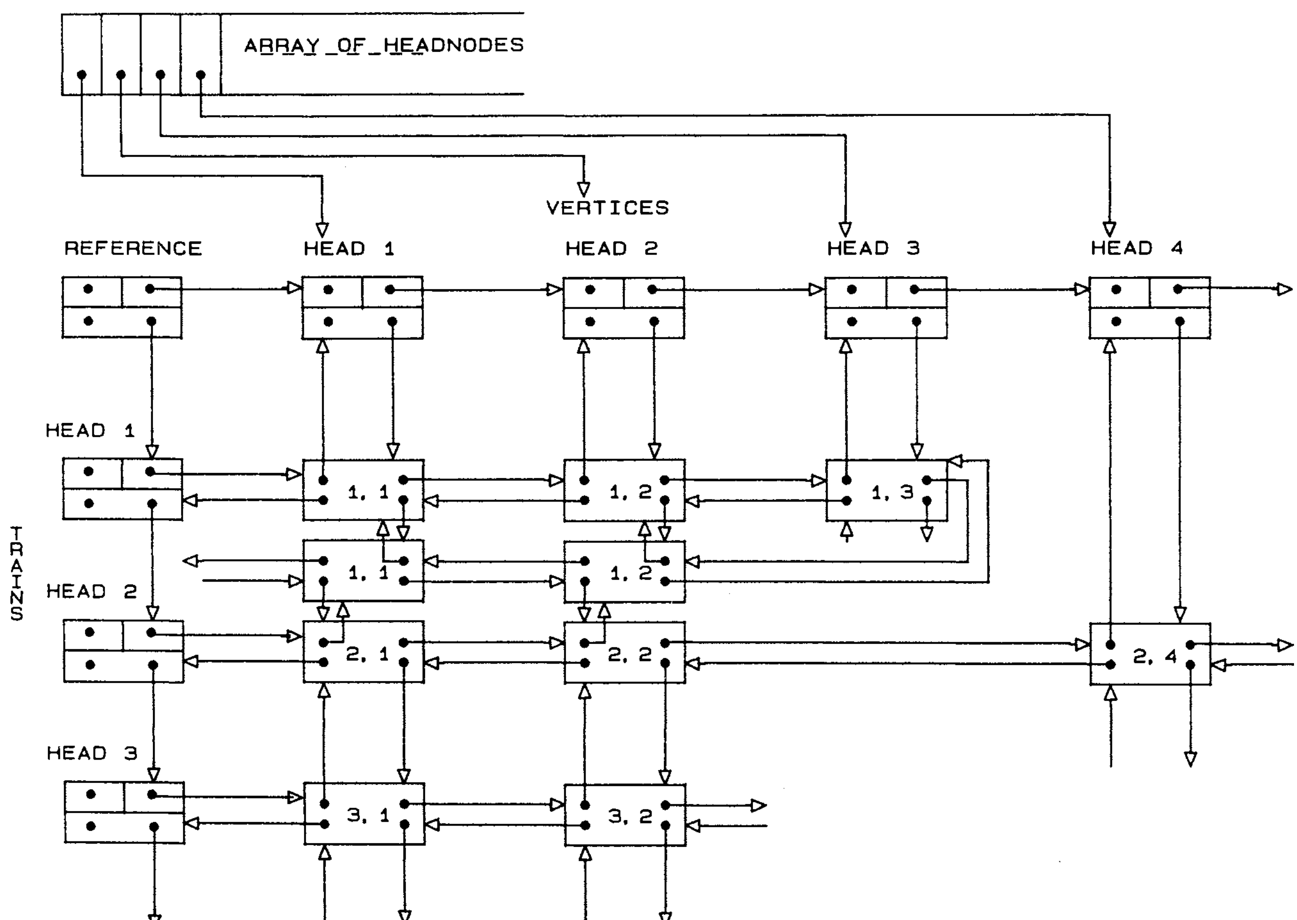


_ B _

FIGURE 5.6 _ TIME/ROUTE TABLE REPRESENTATION
A _ FRAGMENT OF A LARGER RAIL NETWORK
B _ MODIFIED SPARSE MATRIX REPRESENTATION.

Pascal definition of a node is given in Appendix 2. The data fields are defined as below :

scheduled_time : An array to keep scheduled arrival and waiting times.

simulated_time : Actual arrival time of a train at a vertex.

type_number : Train type number. In the simulator identical trains are grouped together.

row : Number of the train which corresponds with row number of the representation.

col : Column or vertex number.

The linked representation of a fragment of a larger time/route table is shown in Figure 5.6. In this diagram head nodes are duplicated for clarity.

5.4 TRAIN REPRESENTATION

Train data can be separated into two groups; general data common to all trains of a certain type, and specific data such as train mode, acceleration rate etc. which change continuously during the run.

Trains are manipulated in sequential order and repetitively during the simulation run. The solution to this kind of data movement problem is achieved by using circular lists (i.e. the last node points to the first) to keep specific data and an array of records which keep general data and arrays of pointers to other structures i.e. the rail network and time/route table. General and specific data structure declarations in Pascal are given in Appendix 2. The fields in a 'general' data structure are defined as below :-

- **train_exist** : a Boolean variable, false if this class of trains is not in the rail network.
- **class_size** : number of trains in this class
- **class_ident** : an array of train class identifiers
- **train_model** : number of the relevant traction equipment model.
- **network_links** : an address matrix for the network connections of all members of this train class.
- **table_links** : a similar address matrix for time and route table connections.
- **train_char** : an array of train characteristics e.g. tare and passenger weights, speed controller parameters, acceleration and deceleration values etc.
- **signal_speed** : an array of maximum allowable speeds at different signal aspects for this class of trains.
- **train_resist** : coefficients for train resistance equation.
- **train_link** : address field to the circular list of specific train structures.

The 'train_char', 'signal_speed' and 'train_resist' arrays can be overwritten by traction equipment model input files. Management of data movement is less complicated when an array of the above structure is used instead of arrays of different data types.

A circular list is used to store specific data for each train and the dynamic variables that change during the simulation run. This representation of trains is best illustrated by the diagram given in Figure 5.7.

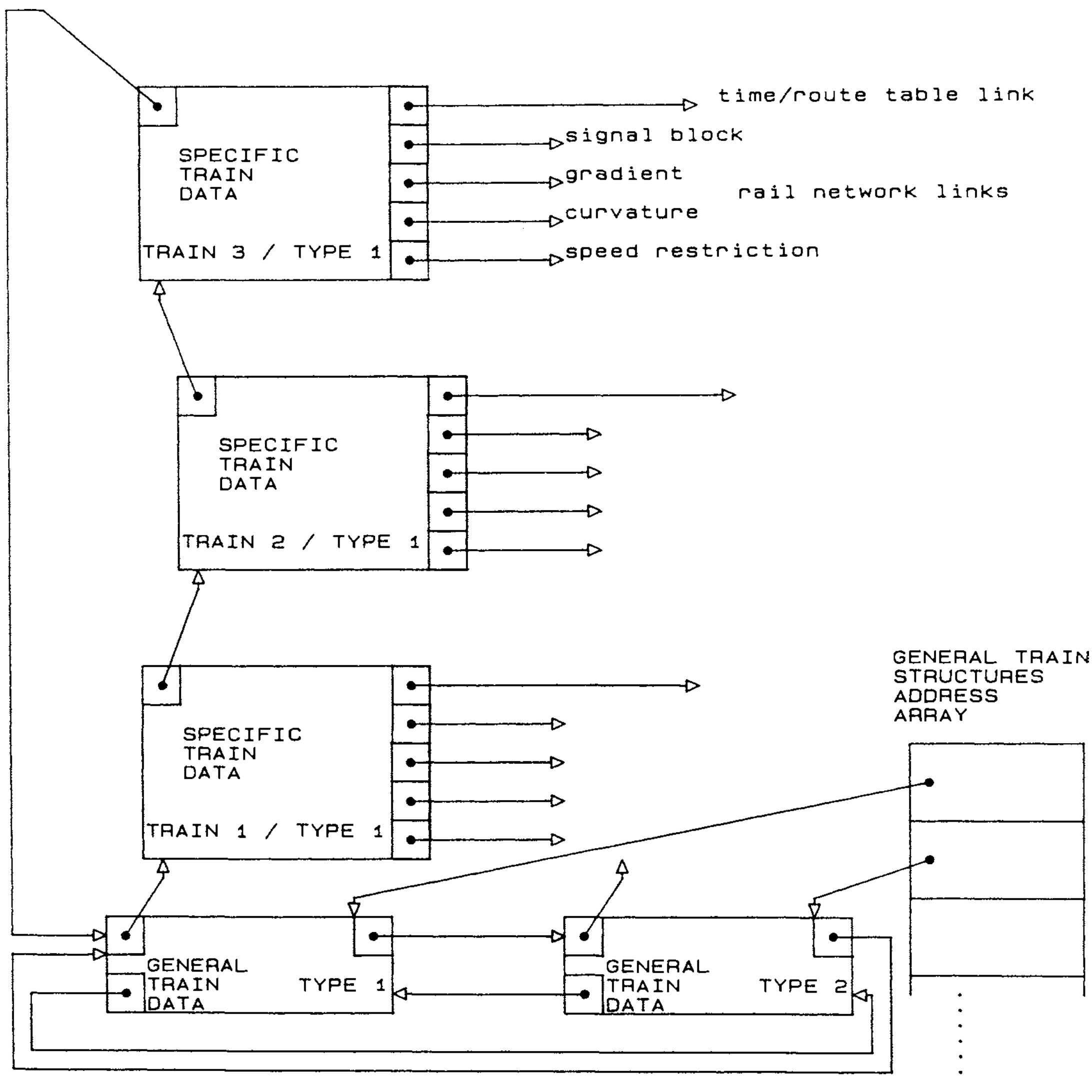


FIGURE 5.7 _ TRAIN STRUCTURES.

The node declaration given in Appendix 2 consists of the fields described below :

- **current_time** : a dynamic variable to hold the specific time of a train.
- **signal_time** : a dynamic array to hold the signal set and release times (i.e. when a train enters a new signal block, clears a signal block, clears an overlap)
- **train_number** : train identification number
- **train_string** : a string for the verbal definition of the train in output files.
- **dynamic_info** : an array to store dynamic variables e.g. last known speed, acceleration rate, tractive mode etc.
- **restricted_spd** : a boolean variable ,true if there is a speed restriction in the section ahead.
- **run_done** : a boolean variable , true if the run is completed so that the train can be removed from the circular list .
- **train_link** : address field to form a circular list of specific train structures.

5.5 RUN PROFILE STRUCTURES

Doubly link lists are used to store pre-calculated braking profiles as well as the run profiles generated during simulation run. This structure was found most suitable since the amount of data needed to be stored varies greatly with the scale of simulation and the structure of the rail network.

This structure supports additional facilities such as moving backward and forward in time and easier management of the traffic control methods, which are also found very useful. The declaration of the node is given in Appendix 2. A node consists of:

rnlinkl, rnlink2 : forward and backward pointers,

run_time : simulation cycle.

run_dist : distance of the train from the vertex ahead.

run_speed : speed of the train.

Pre-calculated braking profiles for scheduled stops and speed restrictions, which are described in Section 6.3, are kept in two different sets of list structures. Each profile is separated from the proceeding one by a head node. Head nodes are also used to share curves so only one set of curves is kept for all the trains of the same class passing through a particular line section. The data and address fields in a head node are defined as :

run_time : total number of time increments in the list.

run_dist :distance of the start of the curve from the vertex ahead.

cnlinkl, cnlink2 : points to the start and the end of a curve

marklink : points to the last node of a line section.

Results of train runs are stored in a matrix structure very similar to the time/route table described in Section 5.4. In this structure, each element of the matrix represents a vertex and has the fields described below :

rnlinkl, rnlink2 : right and left pointers

cnlinkl, cnlink2 : up and down pointers

run_route : route identifier for profiles (i.e. from vertex N to vertex M).

Profiles, which are separated by signal block head nodes throughout the line section, are inserted between these table elements. The fields of a block head node are described below :

rnlink1, rnlink2	: right and left pointers
run_time	: number of time increments to clear the block
run_dist	: distance of the block entrance from the vertex ahead
block_number	: identification number of the signal block
block_aspect	: signal aspect that governs train movement within the signal block
entry_speed	: speed of the train at the block entrance.

It is possible to copy a block to block run if the same run has been done by an identical train before. This optional facility can be used to speed up the simulation run when the interaction between trains is only through multi-aspect line-side signalling. If the dynamic storage area of the computer is not large enough to keep all runtime data produced then they are periodically transferred to sequential output files. In the simulator, management of this table is handled together with time/route table.

5.6 CONCLUSIONS

Data structure design and implementation has been the first activity conducted during the simulation model design and implementation process. The activity has involved the identification of the minimum amount of data that represents a rail transit system and the logical relationships required between those. Thus, data structures have been designed considering the operations to be performed upon them. This chapter has described the data structures required to model a rail transit system. Chapter 6 will describe some of the processing methods which operate on them. These structures, however complex, have been based on a limited number of basic building blocks available for organising information i.e. scalar items, sequential vectors, matrices and linked lists. All these structures are created and deleted dynamically during a simulation run. Their representational details can be changed without any consequential effects in the software.

The rail network has been viewed as a hyperdigraph. Thus, structures like terminals, stations, junctions have been modelled as vertices connected by weighted line sections representing the features between them. The adjacency multi-list representation of this graph has been found more suitable than other alternatives for its software realization. Timetables and routes of trains has been represented by a modified sparse matrix which incorporates time and route lists in a matrix like structure. Trains have been represented by using two levels of circular lists for general (class) and specific (individual) data. Results of simulation runs are held in linked lists which have also been arranged as a matrix like structure.

CHAPTER 6

PROCESSING METHODS

6.1 INTRODUCTION

In this chapter, tractive effort models and train movement calculation and train traffic regulation methods that operate on the data structures will be described. Traction equipment models are largely independent of the data representations chosen to represent trains and their development has been isolated from the design of the simulation model. Three different models will be presented.

There are two types of calculations performed by two different modules prior to train movement calculations. The first of them transforms the given track geometry to a more appropriate form for more efficient manipulation of data. The rail network representation changes simultaneously to accommodate the new data. In another module of the simulation model, two sets of methods are employed to calculate braking profiles for speed restrictions and scheduled stops. These profiles are held by linked lists in a matrix like structure.

The movements calculations are performed by methods that require access to the tractive effort models, and to the track, train, timetable and route data held in the previously described data structures. The calculations themselves are kept fairly simple. Train sequencing and interactions between trains through the signalling interlocking system are handled by a set of traffic regulation methods.

6.2 TRACTION EQUIPMENT MODELS

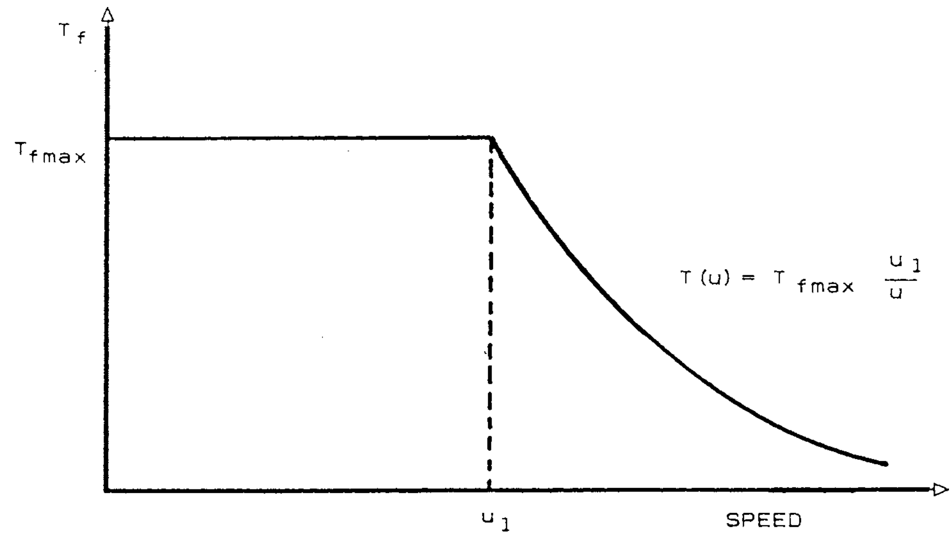
6.2.1 Basic Locomotive Model

The tractive effort produced by a locomotive is generally a non-linear function of speed and controller settings and is usually in distinct regions. In this subsection a simple traction equipment model is suggested. It is used for initial system tests and when more accurate data are not available.

For most classes of train, the initial tractive effort is held constant over the range of zero to a speed which is typically less than the half the maximum operating speed. The nett acceleration resulting from this tractive effort depends on the local gradient, the frictional drag (i.e. train resistance) and the weight of the train.

At higher speeds the tractive effort is limited by the equipment operating at constant power and decreases with increasing speed. The speed at which full power is exerted and below which the tractive effort is relatively constant is called 'base speed' (or sometimes 'loading speed'). The tractive effort versus speed characteristic is shown in Figure 6.1a. The tractive effort function in motoring is:-

$$T_f(u_c) = \begin{cases} T_{fmax} & u_c < u_L \\ T_{fmax} \dfrac{u_c}{u_L} & u_c \geq u_L \end{cases} \qquad (6.1)$$



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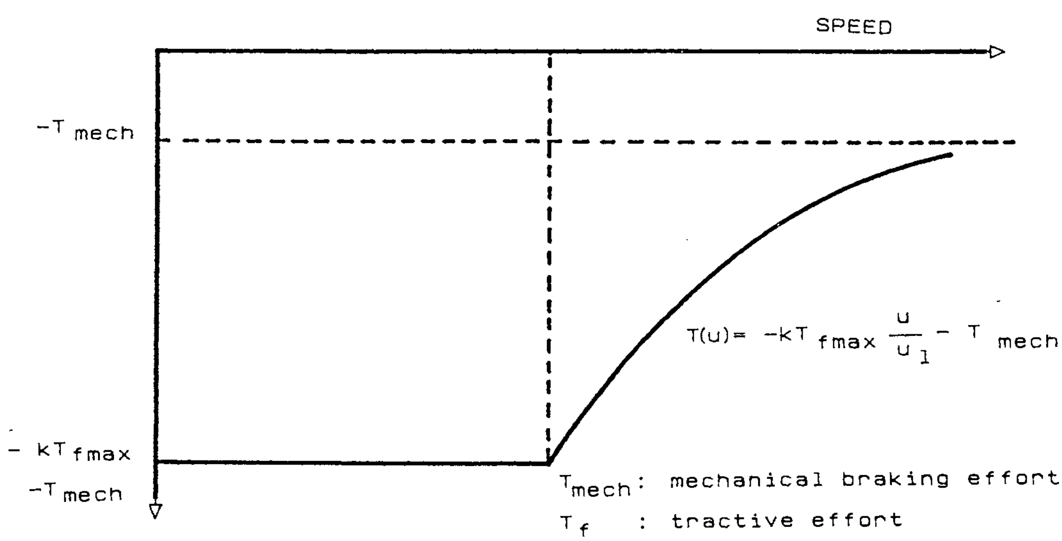

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FIGURE 6.1 _ TRACTIVE EFFORT CHARACTERISTICS
A _ MOTORING MODE
B _ BRAKING MODE

where u_c and u_L are train and base speeds respectively.

The deceleration characteristic is broadly similar with two additional considerations. When braking, the maximum steady state power rating of the traction equipment may be exceeded for short periods of time and mechanical brakes can be used. In this basic model, the function defined to calculate deceleration rate is shown in Figure 6.1b :

$$T_f(u_c) = \begin{cases} - k\, T_{fmax} - T_{mech} & u_c < u_L \\ - k\, T_{fmax} \dfrac{u_c}{u_L} - T_{mech} & u_c \geq u_L \end{cases} \qquad (6.2)$$

where $1 \leq k \leq 2$

In the model maximum tractive effort T_{fmax}, mechanical braking effort T_{mech}, base speed u_L and k are locomotive dependent constants.

6.2.2 DC Traction Equipment Model

This subsection describes the model of a chopper controlled separately excited DC machine interfaced with the simulator for traffic control experiments on Dockland Light Railway System and Waterloo & City Line reported in Chapter 7. The objective of this exercise is to develop a software module capable of generating tractive effort and volt-ampere (V-I) models as functions of train speed for any given loading and line voltage, and during motoring and braking. This is an essential facility since in a comprehensive study of a rail transit system account must be taken of varying train mass and line voltages.

The module generates profiles for tractive effort and line current versus speed. For the latter, V-I models are formulated for all modes of operation, and for line voltages varying between allowed limits. The electrical models are in the form of a voltage source connected in series with a resistance and are derived using a piecewise linearisation technique. This facility can be used to calculate the energy consumptions of the trains at a specified line voltage.

6.2.2.1 Tractive Effort in Motoring

For a chopper controlled separately excited DC machine, independent control of the following variables is possible:-

1. Field current
2. Armature Current

In practice, different control strategies can be fabricated by suitably controlling these two variables. In the motor modelled, the control passes through four stages as the speed is increased:-

Region 1A : The armature and field currents are held constant. For this purpose, the motor voltage is varied by controlling the mark/period ratio of the chopper. The mark/period ratio is increased as the machine speed is increased. The tractive effort remains relatively constant in this region.

Region 1B : The field current is kept constant while the armature current is decreased with a slope s_1. The mark/period ratio still increases as the speed increases.

Region 2A : The mark/period ratio is held constant at the maximum while the armature and field currents are decreased as the speed increases.

Region 2B : Similar to Region 2A, except that the slope of the armature current is s_2.

In the actual traction equipment, a microprocessor based controller has made the implementation of above control strategy possible [101].

The main circuit diagram for each car is given in Figure 6.2a. For modelling purposes, a simplified circuit (i.e. a logical motor) is used, which takes into account the equivalents of the principal components and their losses. This circuit is shown in Figure 6.2.b. The modelling technique used extracts the basic machine parameters from the characteristics supplied by the manufacturer, and incorporates these parameters into a model of the control scheme to obtain the terminal characteristics. In this way it is possible to derive the tractive effort at a particular speed. Knowing the tractive effort, the track geometry and drag forces acting on the train, the resulting nett acceleration and hence the speed can be determined as described in Section 6.3. To achieve this objective, the modelling process described in Appendix 3 is used. The process can be summarized as follows. Firstly, the energy balance for the circuit of Figure 6.2b is written as :

$$I_L V_L = I_L^2 R_L + R_T I_A^2 + (E + V_b)\ I_A + \alpha I_A V_T + (1-\alpha)\ V_D I_A \tag{6.3}$$

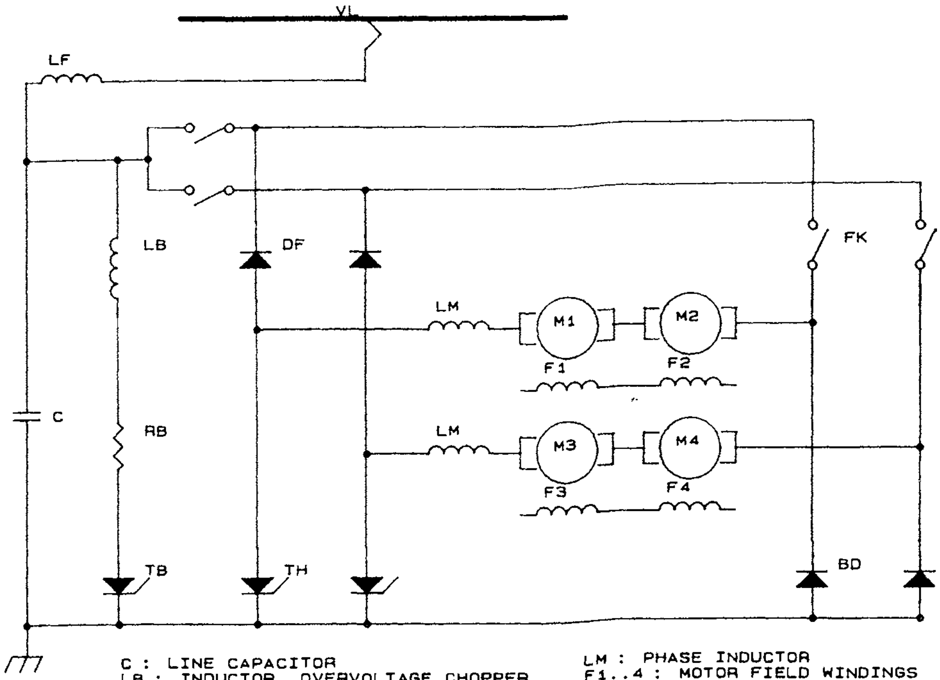
where α : chopper mark/period ratio, I_A : armature current,

V_L : line voltage, I_L : line current, E : induced voltage,

V_b, V_D, V_T : voltage drops in brushes, diodes and choppers

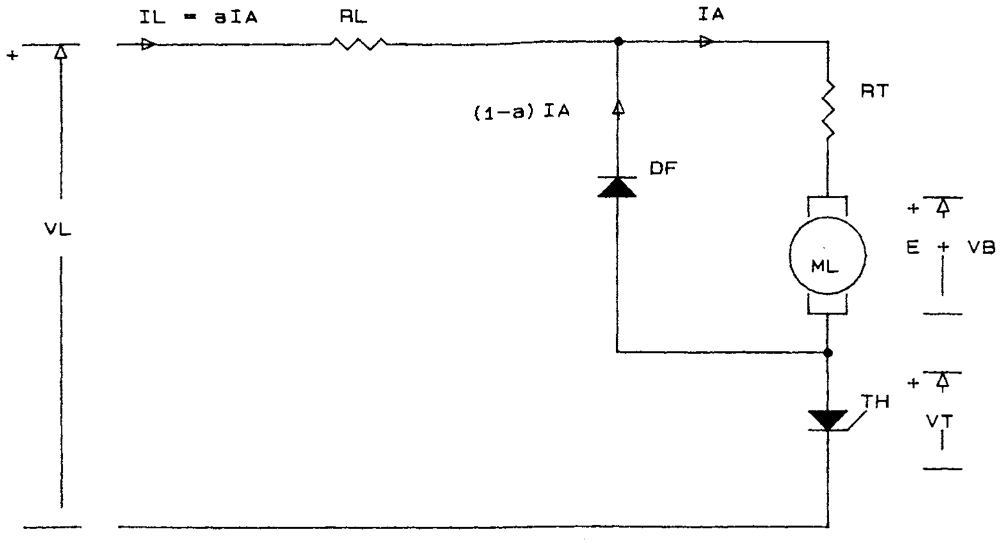
R_L, R_T : line resistance and total resistance

The above equation leads to a practical formula for the mark/period ratio of the chopper in the regions 1A and 1B. The armature current I_A for all



C : LINE CAPACITOR
LB : INDUCTOR, OVERVOLTAGE CHOPPER
RB : BRAKING RESISTOR
TB : OVERVOLTAGE CHOPPER
DF : FREEWHEEL DIODE
TH : MOTORING CHOPPER
VL : LINE VOLTAGE (+ 750 V nominal)

LM : PHASE INDUCTOR
F1..4 : MOTOR FIELD WINDINGS
M1..4 : MOTOR ARMATURES
FK : MOTORING CONDUCTOR
BD : BRAKING DIODE



VL : LINE VOLTAGE
IL : LINE CURRENT
a : CHOPPER MARK/PERIOD RATIO
IA : ARMATURE CURRENT

RL : LINE RESISTANCE
RT : TOTAL RESISTANCE
ML : LOGICAL MOTOR ARMATURES
TH : LOGICAL MOTORING CHOPPER

FIGURE 6.2 _ DC MOTOR CIRCUIT DIAGRAMS
A _ MAIN CIRCUIT DIAGRAM FOR EACH CAR
B _ CIRCUIT DIAGRAM OF A LOGICAL MOTOR UNIT

control regions as a function of speed and line voltage as defined by the manufacturer is shown in Figure 6.3a. Flux variation in the regions 1A and 1B is extracted from the magnetisation characteristics also supplied by the manufacturer and shown in Figure 6.3b. Using a standard least squares curve fitting technique, the module then calculates the flux (ϕ) corresponding to the field and armature current values. In the field weakening regions 2A and 2B, flux can be obtained, using the basic equation :

$$\phi = E \;/\; k.n \qquad (6.4)$$

where E: induced voltage $E = V_L - I_A\,(R_L + R_T) - V_B - V_T$

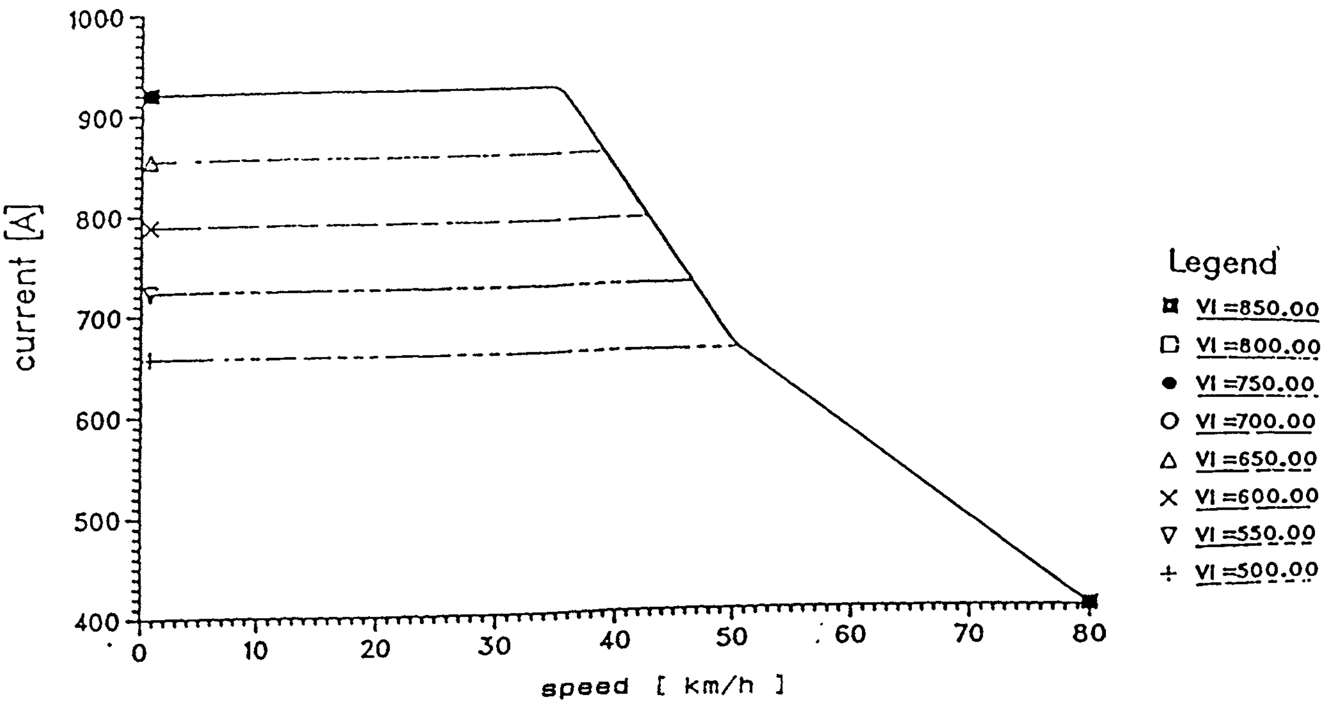
k : DC motor constant, n : motor speed [rpm]

Once the armature current I_A, the flux ϕ, and induced voltage E of a logical motor are known, the tractive effort is calculated using the motor equations given by the manufacturer. The resulting tractive effort characteristics are shown in Figure 6.4a.

6.2.2.2 Tractive Effort in Braking

The tractive effort versus speed curve for service braking characteristic is shown in Figure 6.4b. The curve is valid also on down gradients and the deceleration can be maintained until a specific gradient.

At low speeds the armature current is set to produce the tractive effort required for the given braking rate with occasional or no blending with mechanical brakes. At higher speeds where the tractive effort decreases, mechanical brake assistance is usually required.



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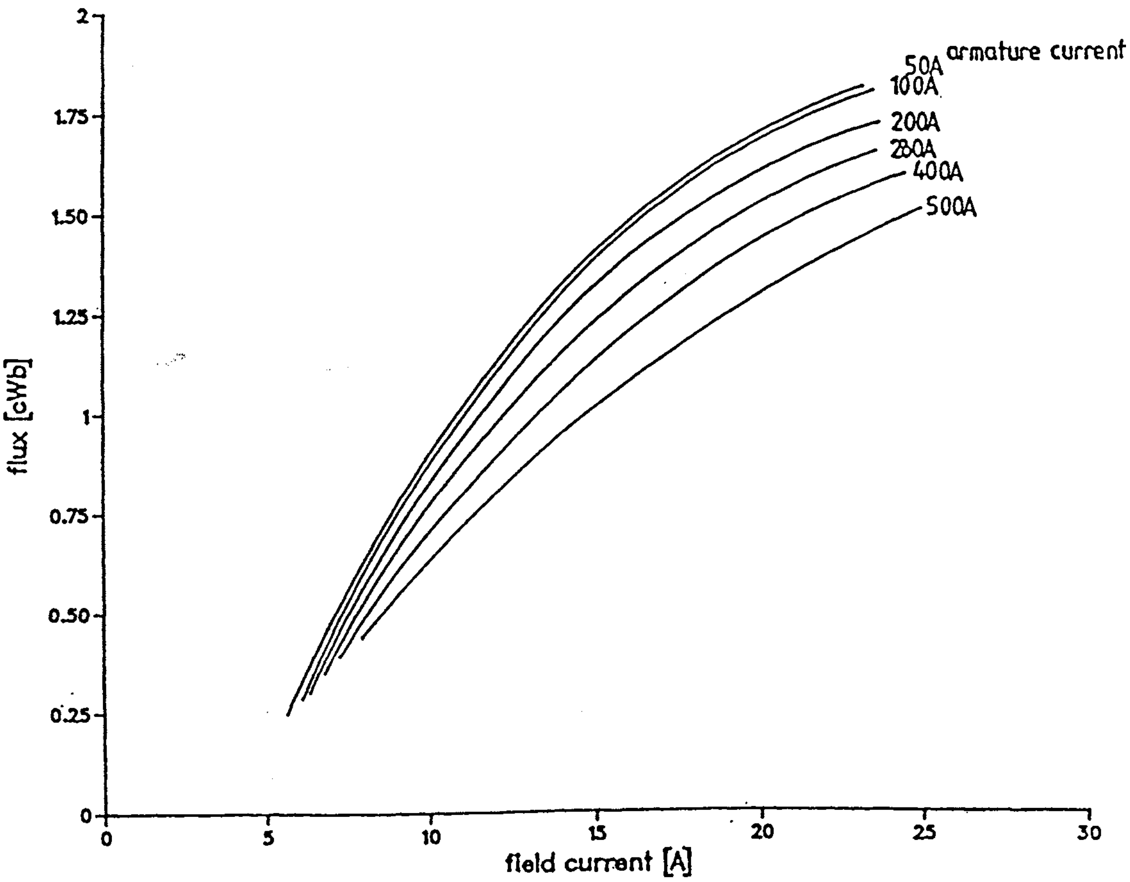

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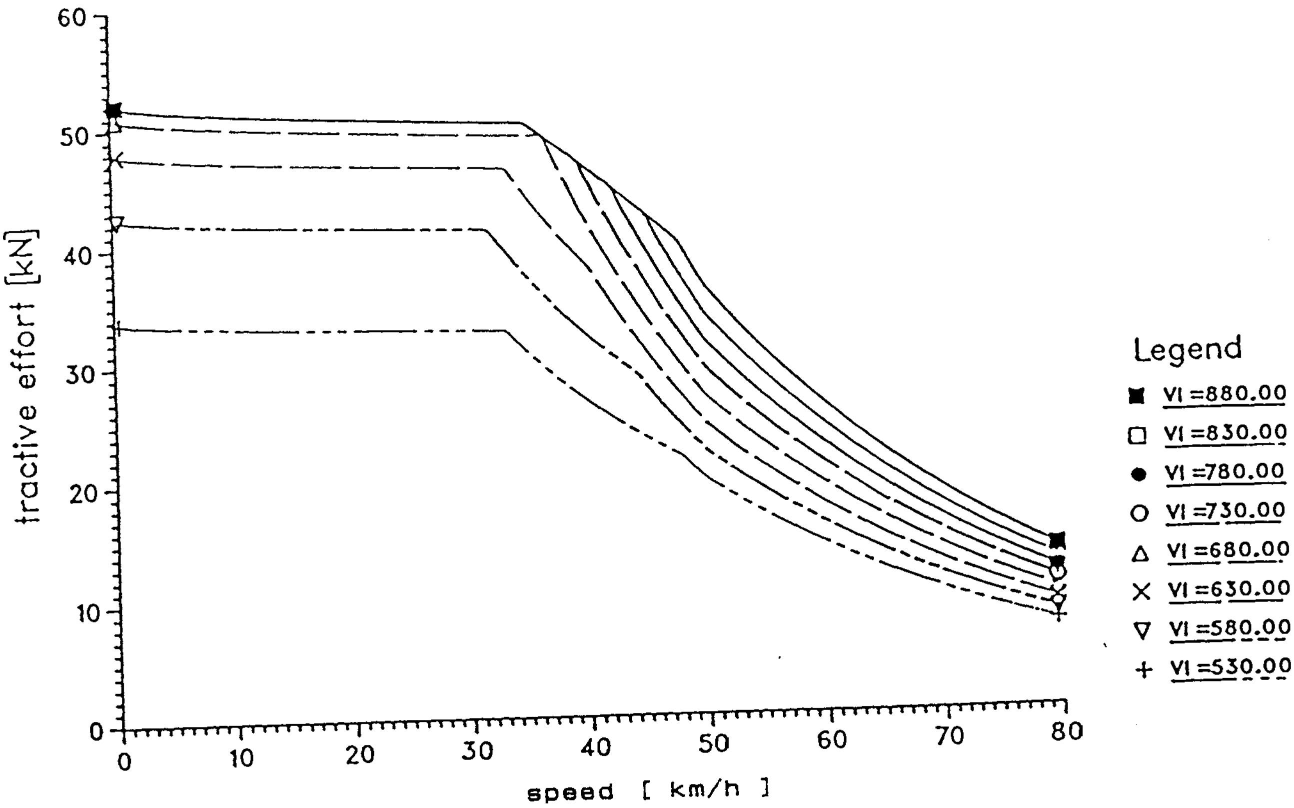
FIGURE 6.3 — ARMATURE CURRENT AND MAGNETISATION CHARACTERISTICS.
A — ARMATURE CURRENT AS A FUNCTION OF TRAIN SPEED AND LINE CURRENT
B — MAGNETISATION CHARACTERISTICS AS A FUNCTION OF FIELD CURRENT AND ARMATURE CURRENT



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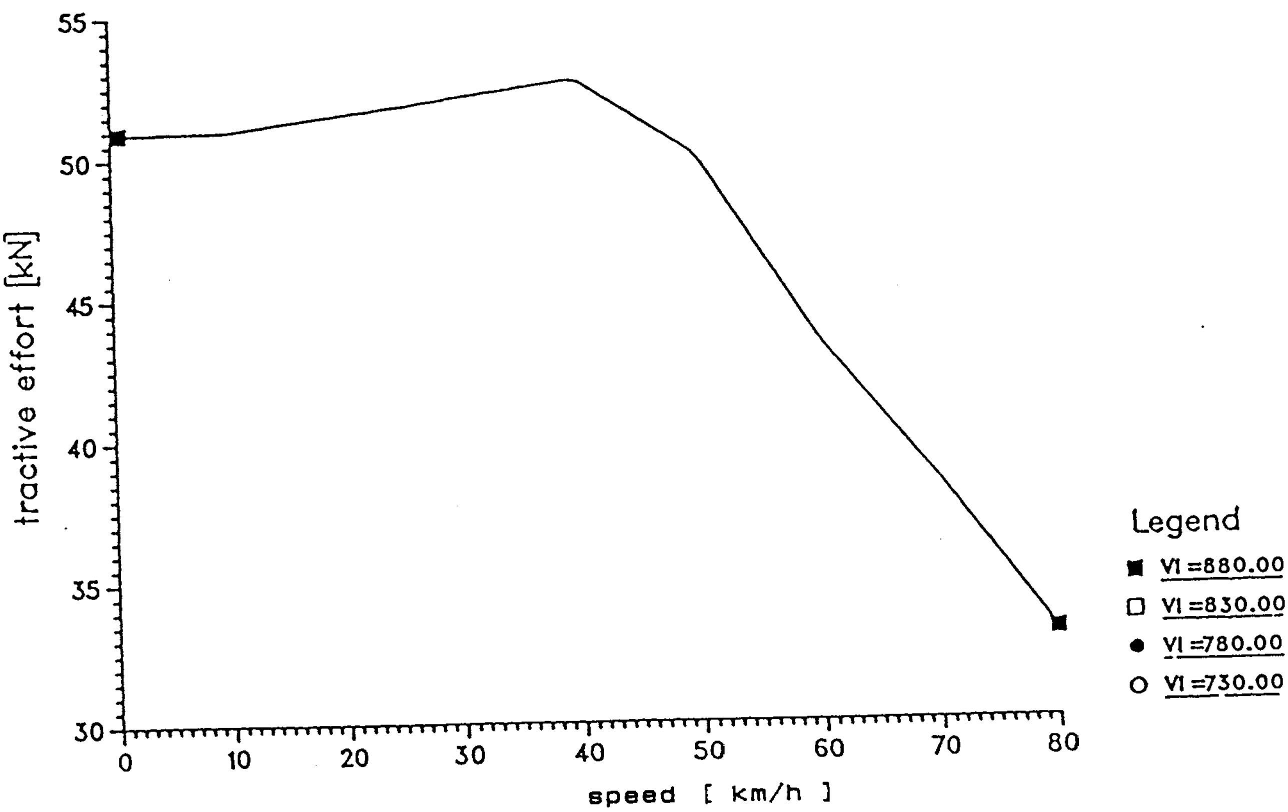

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FIGURE 6.4 _ TRACTIVE EFFORT CHARACTERISTICS.
A _ TRACTIVE EFFORT AS A FUNCTION OF TRAIN SPEED AND LINE VOLTAGE IN MOTORING
B _ TRACTIVE EFFORT AS A FUNCTION OF TRAIN SPEED IN BRAKING

chanical brake assistance is usually required.

6.2.3 AC Locomotive Model

A model has been developed for the coal trains of Queensland Railways of Australia (QR) for the maximum energy demand estimation and control study reported in Chapter 8. The traction equipment terminal characteristic data of tractive effort versus speed has been supplied for 19.5, 25 and 27 kV line voltages.

There are ten tractive effort versus train speed characteristics (i.e. notches) for each line voltage value. After extracting a sufficient number of data points from these tractive effort curves, standard least squares curve fitting techniques are used to define tractive effort functions for different regions of operation. Points of discontinuity are carefully specified and then used to separate the characteristics into 2 distinct regions of operation in motoring. Thus, a better fit is assured.

Once these functions are defined , their coefficients and boundary values are transferred and held in real arrays in the motor model module. The simulator simply calculates the tractive effort by checking the region of operation of the motor and choosing the right function. Then, the corresponding accelaration rate can easily be calculated. The deceleration rate is considered constant for this application.

The model is voltage dependent between 19.5 - 27 kV. The electrical power input of a train is calculated by using the total tractive effort of the active locomotives. This facility is used to predict the trends in train or system energy consumption under different operating conditions.

6.2.3 AC Locomotive Model

A model has been developed for the coal trains of Queensland Railways of Australia (QR) for the maximum energy demand estimation and control study reported in Chapter 8. Three sets of traction equipment terminal characteristic data of tractive effort versus speed have been supplied by the operator for 19.5, 25 and 27 kV line voltages. Each set is consist of ten tractive effort versus train speed characteristics corresponding to ten different acceleration setting on the onboard speed controller. After extracting a sufficient number of data points from these tractive effort curves, standard least squares curve fitting techniques are used to define tractive effort functions for different regions of operation. Points of discontinuity are carefully specified and then used to separate the characteristics into 2 distinct regions of operation in motoring. Thus, a better fit is assured.

Once these functions are defined , their coefficients and boundary values are transferred and held in real arrays in the motor model module. The simulator simply calculates the tractive effort by checking the region of operation of the motor and choosing the right function. Then, the corresponding accelaration rate can easily be calculated. The deceleration rate is considered constant for this application.

The model is voltage dependent between 19.5 - 27 kV. The electrical power input of a train is calculated by using the total tractive effort of the active locomotives. This facility is used to predict the trends in train or system energy consumption under different operating conditions.

6.3 CALCULATIONS PRIOR TO MOVEMENT CALCULATIONS

6.3.1 Transformation of Track Geometry

6.3.1.1 Representation Techniques Avaiable

One of the critical features of a movement simulator is its ability to manipulate efficiently the data describing track geometry. During the simulation run, it is necessary to calculate the resistance due to the track geometry at each simulation cycle (time increment). As a train can lie simultaneously on a number of different gradient or curvature blocks over its length, this calculation involves establishing the mass of the train acting on each block at the instant of calculation.

The approaches to this problem can be divided into two categories. In the first approach the mass of the train is assumed to be concentrated at a single point (usually in the middle) and track geometry changes through the train are ignored, so that the transition from one block to another is not smooth [102]. This approach is simple to program and minimises the amount of calculations. However, as this simplification may introduce significant errors in the predicted train performance there is a necessity to calculate their effect more carefully [102]. This is especially true for rail transit systems like the ones studied in this thesis. QR's AC fed coal trains are almost 2000 m long and therefore lie on several track geometry blocks simultaneously. Dockland Light Railway system aimed to make the most economical use of land in a congested urban environment. Although the trains are short the rail network has very tight curves, steep gradients and a frequently changing track geometry .

In the second category, the distribution of the mass along the length of the train is accounted for, but at the expense of computing time, as the distribution of the train has to be established at each time increment in the calculation.

The effective gradient technique adopted in this simulator was developed to increase the efficiency of movement calculations while preserving its ability to account for changing gradients over the length of the train [103]. In this technique, prior to the simulation run, the data describing the track geometry are transformed to permit the train to be treated as having its mass concentrated at the nose of the train. The transformed track is described by the effective track geometry function. During the simulation, the track geometry effect is calculated at any point with relative ease by evaluating this function. In this section only the effective gradient technique for trains with uniform mass distribution is described. To avoid confusion the following terminology is defined :-

real gradient : physical gradient of the track.

equivalent gradient : the real gradient compensated for track curvature (a technique used by some manufacturers).

effective gradient : the gradient at a point which has been calculated to be the uniform gradient which would produce the same resistance as the combined effects of equivalent or real gradients acting simultaneously along the length of the train.

In the following subsection only effective gradient calculations are described. If the real gradients are supplied instead of equivalent ones seperate, but similar, effective curvature calculations must also be performed.

6.3.1.2 Effective Gradient Technique

Figure 6.5 illustrates the effective gradient technique in operation. The gradient profile of a section of track is shown in Figure 6.5a. It consists of three sections with equivalent or real gradients g_s, g_{s+1} and g_{s+2}. The breakpoints occur at d_s, d_{s+1}, d_{s+2} and d_{s+3}. The head of the train is shown in Figure 6.5b at d_{s+1}. New coordinates defining a transformed set of breakpoints are introduced in Figures 6.5c to 6.5f. The first x_n, coincides with d_s. In the example, x_{n+1} and d_{s+1} or x_{n+2} and d_{s+2} also coincide but it will become obvious that this is not necessary. In Figures 6.5b and 6.5c it can be seen that, as the head of the train progresses from x_{n+1} to x_{n+2}, a proportionally greater mass moves onto the gradient between x_{n+1} and x_{n+2} until the head reaches x_{n+2}. The effective gradient will, therefore, increase linearly as the head travels between x_{n+1} and x_{n+2}. Similarly between x_{n+2} and x_{n+3} (x_{n+3} is the point where the rear of the train reaches d_{s+1}), there is a linear change in the effective gradient. This new breakpoint x_{n+3}, marking the current position of the head of the train, will be called a virtual breakpoint to differentiate it from the actual track breakpoints. Similarly, in Figure 6.5e a further breakpoint x_{n+4} is introduced when the rear reaches the point d_{s+2}. The next breakpoint which is passed by either the head or rear of the train is d_{s+3} which is transformed to x_{n+5}.

Hence, the original track breakpoints are transformed to a new set in which a breakpoint is created at the position of the head of the train whenever the rear or head of the train passes an original breakpoint. It can be

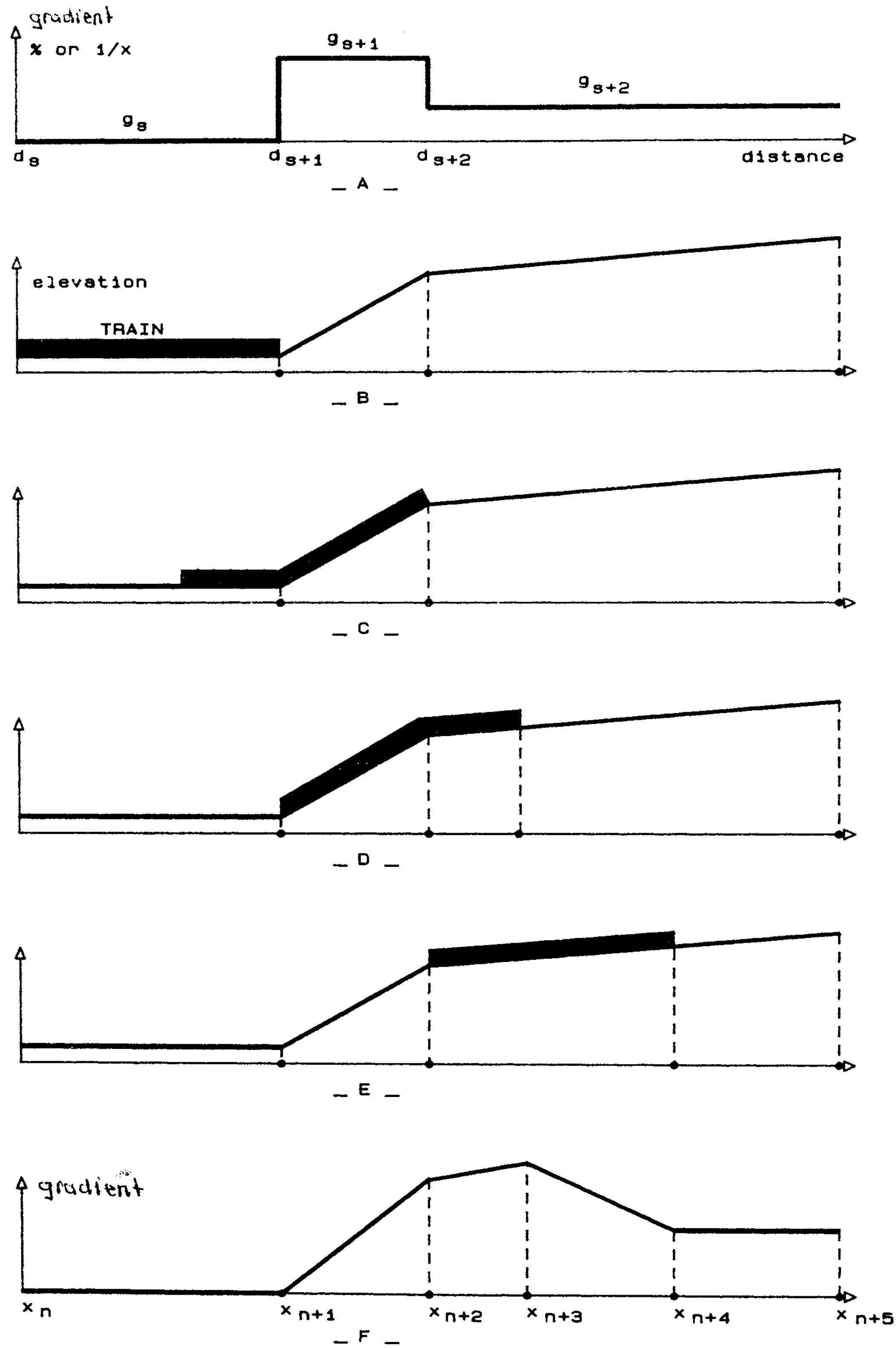


FIGURE 6.5 _ THE DEVELOPMENT OF THE EFFECTIVE GRADIENT.

seen that as all of the original breakpoints are retained in the new set of breakpoints. The derivative of the new profile with respect to distance is constant unless the distance between two breakpoints is longer than the train. Such an effective gradient profile for the track defined in Figure 6.5a is shown in Figure 6.5f. Vertical axis shows the elevation in Figures 6.5b, 6.5c, 6.5d, 6.5e and 6.5f.

If a train of uniform mass in per unit is considered the equation for the gradient force due to the equivalent gradient under the i th section of train is :-

$$F_i = g_{n+i-1} \, m \, \Delta x_{n+i-1} \, g \tag{6.5}$$

where Δx_{n+i-1} is length of track under the i th section of train

m is mass of train per unit length

g is gravitational constant.

It follows that the effective gradient G_{n+p-1} for a train of uniform mass with its rear wagon in track section n and its head at x_{n+p-1} is :-

$$G_{n+p-1} = \sum_{i=1}^{P} \frac{F_i}{Mg} = \sum_{i=1}^{P} \frac{g_{n+i-1}}{L} \Delta x_{n+i-1} \tag{6.6}$$

where L is total train length

M = mL is total train mass.

During the simulation run, the effective gradient at any point on the line section is found by interpolating linearly between the stored values of the effective gradient at the adjacent breakpoints. For example, if the head of the train is at a point y in Figure 6.5 between x_{n+2} and x_{n+3} then the effective gradient function is :

$$G(z) = \left[G_{n+2} + (G_{n+3} - G_{n+2}) \frac{y-x_{n+2}}{x_{n+3} - x_{n+2}} \right] \qquad (6.7)$$

for $x_{n+2} < y \leq x_{n+3}$

6.3.2 Precalculation of Braking and Stopping Profiles

Two similar sets of methods are employed in the simulator to calculate the braking profiles for the trains braking for track speed restrictions (i.e. braking profiles) and scheduled stops (i.e. stopping profiles). If there is a train of a certain class running from vertex X to Y, the profiles are calculated by running it from Y to X in reverse direction. Only one set of profiles for each class of train is calculated between X and Y. The calculations stop when all possible routes and train classes are exhausted.

For braking profiles the calculations start from the last more restrictive speed restriction from X to Y. The train is run backward until all speed restrictions are checked. If any train of the class is scheduled to stop at vertex Y, computations start from the vertex Y and proceed by moving the train backwards to vertex X. The stopping profile calculations calculations take the signalling scheme into account as will be described in Section 6.5.

The aim of these precalculations is to reduce the amount of calculations performed during the simulation run. The precalculated profiles have the additional advantage of handling peculiar speed restrictions. Referring to Figure 6.6; even though the braking distance to d_1 is less than the train distance away from it and hence may be disregarded, for the class of train and speed, the braking distance to d_2 is much longer. Under these conditions d_2 is more restrictive than d_1 even though it is further away. Since the braking profiles are calculated in reverse direction (i.e. from 2 to 1 if the train route is from 1 to 2) this problem will be intrinsically solved.

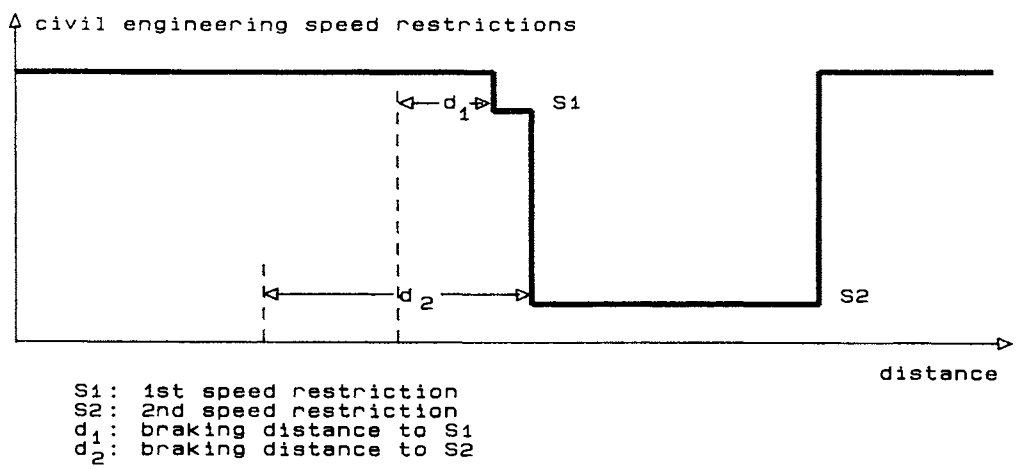


FIGURE 6.6 _ BRAKING DISTANCES FOR TWO CONSECUTIVE SPEED RESTRICTIONS.

6.4 MOVEMENT CALCULATIONS

Simulation of an entire rail transit system's operations is comprised of a number of single train movement calculations. During these calculations the interaction between trains can be considered discrete (i.e. interaction through line side signalling) or continuous (i.e. interaction through power system, cab or continuous signalling) or none according to the aim of the study and type of the rail transit system. This section describes the logical basis of the movement calculations for the trains from which the running patterns may be deduced. In these calculations both discrete and continuous interactions can be taken into account.

There are two aspects of the movement calculations that should be recognised. These are:-

1. **Data Referencing :** The simulation requires access to a substantial amount of data; some actually describing the track, some the trains and some the system. Furthermore some data are fixed and some may vary as the simulation proceeds. This means there is a need for careful definition, structuring and manipulation of the data. The data that the simulation model operates on for the calculation of movements are divided into 3 different sets. All train related data are held in train structures, all rail network related data in a network structure and the operational data (i.e. timing and route data) in a time/route table. The relationships between and construction of these structures have been described in Chapter 5.

2. **Train Movement Control :** During its run, a complex set of influences may require the train to enter a particular tractive mode (i.e. power, brake, coast or wait). The movement of each train is calculated according to its mode. These calculations are affected by the track geometry and train resistance as well as traction equipment performance and speed controller (or driver) behaviour. The methods applied on data structures to move trains and the way various factors affect train movement are discussed in this section.

6.4.1 Calculation of Acceleration Rate

6.4.1.1 Train Position and Speed Referencing

The train position is referenced by the distance of the nose of the train from the vertex ahead. Since the train effectively moves in discrete steps, at the end of each simulation cycle the position recorded at the end of a particular time increment is referred to as the initial position in the following time increment. Similarly, the speed of a train before a time increment is referred to as initial speed.

6.4.1.2 Train Mass

The mass of each train is needed for the movement calculations. Sometimes an allowance is made for the inertia of rotating parts when accelerations are being deduced and this is based on the tare train weight. The tare train weights, passenger or coal weights and if applicable locomotive weights are thus given separately.

6.4.1.3 Train Resistance

The value of train resistance is very important in movement calculations but reliable data is difficult to obtain. For the DC articulated light rail transit vehicle modelled for traffic control experiments, the train resistance is calculated from the empirical equation [25] :

$$F_r = c_0 + c_1 u_i + c_2 u_i^2 \tag{6.8a}$$

where u_i is the train speed at the beginning of a simulation cycle
c_0, c_1, c_2 are coefficients obtained by fitting an analytical curve to experimental results.

The train resistances of QR's AC fed trains are computed from the following empirical Equation 6.8 supplied by the operators. The train resistance of a loaded train is taken as a starting resistance, decreasing linearly to cut the rolling resistance curve. The rolling resistance curve is :

$$F_r = (c_0 + c_1/w + c_2 u_i + c_3 u_i^2/wn_x)\ m_t \tag{6.8}$$

where u_i is the train speed at the beginning of a simulation cycle.
c_0, c_1, c_2, c_3 are coefficients, w is weight per axle, n_x is number of axles per car, m_t is total train mass.

Empty trains use the same equation at all speeds with a different set of coefficients.

6.4.1.4 Effective Gradient and Curve Drag

In calculating the gradient affecting train performance, the train weight is considered as acting at the nose of the train. The current gradient value is calculated by evaluating the effective gradient function given in Equation 6.6. The current effective gradient value is converted into a gradient equivalent force by using the equation:-

$$F_g = m_t \, g \, G_e \tag{6.9}$$

where m_t is total train mass,

g is acceleration due to gravity,

G_e is effective gradient.

Value of a curvature block is expressed by the radius of the circle representing the curve. This value can then transformed to the effective curvature if required. Curve drag refers to the force exerted on the train when it is going through a curved section on the track. This is only taken account for coal trains using the equation supplied by QR :

$$F_c = m_t \, c_0 \, C_e \tag{6.10}$$

where c_0 is a given coefficient,

C_e is the effective curvature.

6.4.2 Control of Acceleration

6.4.2.1 Target Speed Assignment

The aim of a speed controller is to reduce the error between the current train speed and the target speed (i.e. the speed the train aims for). If several speed restrictions are in force the train will be instructed to take into account the one with the minimum value. There are four types of speed restrictions generally encountered in train operation :

1. Track speed restrictions
2. Signal speed restrictions

3. Dynamic speed restrictions
4. Scheduled train stops

Unlike other speed restrictions,track speed restrictions are normally permanent. Signal restriction depends on signal indication and maximum allowable speeds are usually different for each class of train. Dynamic speed restrictions are temporary, train dependent and specific to some trains and/or sections of the rail network. It is common to have temporary speed restrictions for track work etc.. The dynamic speed restriction concept can also be used for various other purposes in the simulator. For example, the effect of approach released signals can be simulated by assigning a short speed restriction at an appropriate position before the signal. Each train will be forced to slow down until it has passed the restriction. This approximates to the action of approach released signals, which normally show a restrictive aspect until the train is within a specific distance and then revert to proceed aspect. Scheduled stops are train dependent and indicated in the time/route table.

A look-ahead method, which calculates a braking profile, is used to ensure that correct train speed can be achieved at the entry to signal restrictions. Track and dynamic speed restrictions and scheduled stops are normally known before the simulation run. The braking profiles for all different classes of trains are calculated and stored in doubly linked run profile lists prior to the simulation run, as described in Section 6.3.1. All the profiles indicate the positions where the continuous braking must commence (i.e. braking point) and end (i.e. start of the track speed restriction). They also define the braking envelopes.

During the movement calculations a target speed decision process is executed at every simulation cycle. The actions for this process are :

1. Receive the current train speed and position.

2. a. If there are braking envelopes enclosing the current train position then choose the dominant (i.e. the smallest corresponding speed value) braking or stopping profile if not already chosen before. If the train is enclosed by a profile then it will be in the continuous braking mode.

b. Else assign the minimum of all enclosing speed restrictions as target speed.

6.4.2.2 Nett Acceleration Calculations

At the beginning of each simulation cycle before the calculations start, the lowest of the speed restrictions is chosen as the target speed with the decision process described above. The tractive mode (i.e. powering, coasting, braking or waiting) is then chosen by comparing the train speed with the target speed and speed controller regions. Once the mode of the train is known, it is possible to deduce the nett tractive effort as described below :

Powering mode : The available gross tractive effort is calculated by using the appropriate traction equipment model, as described in Section 6.2. Train resistance and track geometry equivalent force also act upon the train and the available nett force for acceleration is thus:-

$$F_n = T_f - F_r - F_g - F_c \qquad (6.11)$$

The acceleration itself is thus given by Newton's Second Law :

$$a = \frac{F_n}{m_e} \tag{6.12}$$

where m_e is total effective mass (i.e. the total train weight plus a fraction of the tare train weight allowing for rotary inertia)

Braking mode : In the applications described in Chapter 7 and Chapter 8 a constant nett acceleration in braking can be maintained independent of track geometry and train resistance. But there may be cases where the behaviour in braking is generally similar to that in powering. That is, the nett acceleration in braking is calculated by taking train resistance and track geometry equivalent forces into account for all values or after a threshold gradient value.

Coasting mode : When coasting the train performance is affected only by train resistance and track geometry equivalent force.

6.4.2.3 Acceleration Controller Design

The nett acceleration rate is controlled in order to minimize the oscillations of the train speed around the target speed. Various nett acceleration control strategies are described below :

Bang-bang controller : In the most basic form of the control, if it is desired to increase speed, maximum acceleration is applied until the target speed is reached from the standstill. The train speed is then checked at each simulation cycle against the target speed. If greater, full service brake is applied, otherwise full acceleration continues. This would correspond to what is known as 'bang-bang' control shown in Figure 6.7a. Starting at A, speed will increase, thereby reducing the error. Acceleration will diminish under the action of train resistance and/or tractive effort characteristic while the target speed is being approached. This has a natural smoothing effect but there will still be the possibility oscillation of the train speed around the target speed during the short powering and braking periods.

Proportional control with dead band : In practice, the driver (or the ATO) senses the difference between the target and current train speeds and adjusts the rate of acceleration accordingly. This action is modelled by introducing a 'proportional controller with saturation' outside the dead band as shown in Figure 6.7b.

A typical form of this function for acceleration is:-

$$a = \begin{cases} 0 & u_c \leq (e_1+1)\ u_t \\ a_{max} & u_c > (e_2+1)\ u_t \\ a_{max}\ \dfrac{u_c - u_t(1+e_1)}{(e_2 - e_1)\ u_t} & \text{otherwise} \end{cases} \qquad (6.13)$$

where a is nett acceleration, u_c is current speed, u_t is target speed,

e_1 and e_2 are user defined values between 0 and 1,

A similar function with a constant slope would be :

$$a = \begin{cases} 0 & u_c \leq (e_1 + 1)\ u_t \\ s\ (u_c - u_t)a_{max} & u_c < \dfrac{T_n}{m_e s} + u_t \\ a_{max} & \text{otherwise} \end{cases} \qquad (6.14)$$

where s is the slope of the proportional band.

With a constant error band the upper limit of the first part of the function would be $u_c < u_e + u_t$ where u_e is the speed error permitted without any corrective action.

These functions moderate the intensity of acceleration around the target speed but have no effect outside the proportional band. When the train clears a speed restriction to enter a new one, maximum acceleration will be applied to approach the new target speed. To simulate the actual service situation, it is necessary to specify a maximum permissible rate of charge of acceleration (jerk limit). It is also necessary to specify a minimum value of jerk, so that acceleration distance is not increased excessively. Since the simulation cycle is not less than 1 second for the majority of possible applications, no allowance has been made for jerk.

This type of controller works well if the gross acceleration (i.e. the acceleration calculated from tractive effort alone) is usually close to nett acceleration rate. It is used for traffic control experiments on Dockland Light Railway and Waterloo & City Line. In these applications allowance is made for the reaction delay (i.e. hysteresis effect) of the ATO subsystem.

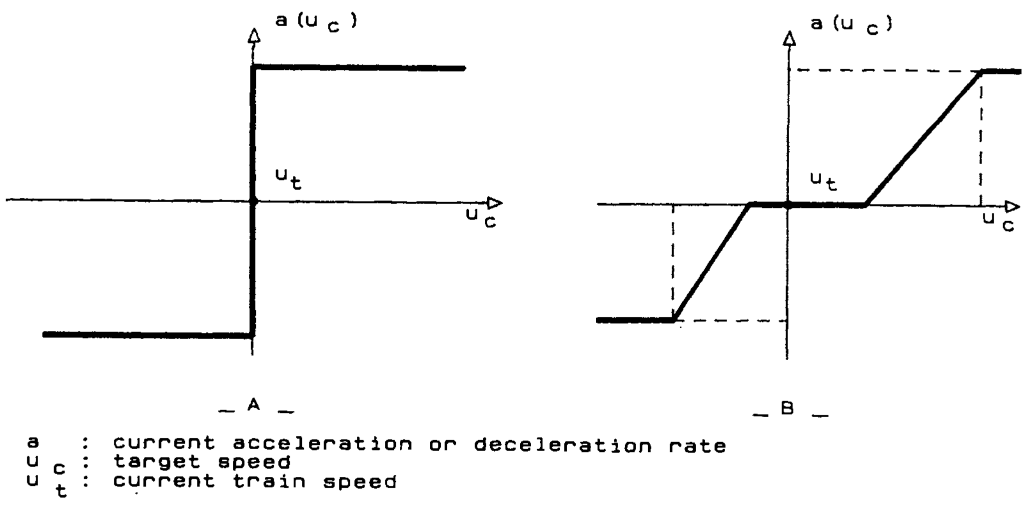


FIGURE 6.7 _ TWO DIFFERENT CONFIGURATIONS OF THE SPEED CONTROLLER
A _ BANG-BANG CONTROLLER
B _ PROPORTIONAL CONTROLLER WITH AN ERROR BAND

Notch control with error band : In practice, the speed of QR trains are controlled by choosing one of the ten tractive effort characteristics. This process is known as 'notching' and each control position is called a 'notch'. For the initial runs different maximum notches were used for empty and loaded trains which can then be reduced proportionally. This strategy has been found unsatisfactory because of its inconsistency with the way these trains are controlled in practice. A new controller has been developed which utilises the different tractive effort characteristics and assigns the number of active locomotives.

The deceleration rate of a braking train is prescribed and constant. The train operates under the 'notch control' if it is in powering mode. Given the maximum notch and the number of active locomotives, the driver senses the difference between the target and current speeds and notches down or coasts if he feels that the target speed will be exceeded soon. This is the behaviour which the speed controller emulates when the train is in the 'notch control' region. The maximum notch and the number of active locomotives can be specified according to the location and load of the trains. A 'driver reaction time' to the changing target speed and a 'speed error recovery time ' independent of the 'simulation cycle time' are also specified.

After the 'required' nett acceleration, which is needed to make the train speed equal to the target speed at the end of the speed error recovery time, is calculated one of the following actions is taken :

1. If the required nett acceleration is negative, which means the partial acceleration due to the current gradient is sufficient to reach the target speed, then the train will coast.

2. If the required nett acceleration is positive but smaller than the

net acceleration corresponding to maximum notch, then the nett acceleration is reduced by notching down from the specified maximum notch until the required acceleration is greater than the new nett acceleration. Thus, a new notch is chosen.

3. If the required nett acceleration is greater than the maximum nett acceleration available then the maximum nett acceleration is used.

4. If the train speed is above the error band around the target speed then full or controlled braking is applied.

5. If train speed is within the error band the train coasts.

6.4.3 Calculation of Train Displacement and Speed

Once the nett acceleration is calculated, the calculations proceed by incrementing the displacement. The constant simulation cycle (i.e. time increment) can be specified in such a way that the error due to computation and the coincidence with the changing track parameters are acceptable.

Firstly, displacement - acceleration relationship is used :-

$$\Delta d_n = u_{n-1} \Delta t + 0.5 a_n \Delta t^2 \qquad (6.15)$$

where a_n is the acceleration, Δd_n is the displacement,

u_{n-1} is the initial speed for time increment n,

Δt is the time increment in seconds.

The final speed at the end of the current time increment can then be deduced from :-

$$u_n = u_{n-1} + a_n \Delta t \qquad (6.16)$$

The resulting change in train position then follows from :-

$$d_n = d_{n-1} + \Delta d_n \qquad (6.17)$$

6.4.4 Organisation of Movement Calculations

The organisation of train movement methods in the simulation model can be summarized as below:

1. Choose the tractive mode of a train by checking the train speed against the target speed (Subsection 6.4.2.1) and the acceleration controller regions (Subsection 6.4.2.3). There are 4 possible modes : motoring, braking, coasting, waiting.

2. **a.** If the mode is 'waiting' then calculate the time when the train will become active. No further action until this 'scheduled' time.

   b. If the mode is 'coasting' then calculate the nett tractive effort affected only by train resistance and track geometry.

   c. If the mode is 'motoring' or 'braking' then calculate gross tractive effort from the appropriate tractive effort model module (Section 6.2).

3. Calculate the available nett acceleration by deducing the effects of track geometry and train resistance from the gross tractive effort (Subsection 6.4.2.2).

4. Calculate the controlled nett acceleration according to the acceleration control strategy chosen (Subsection 6.4.2.2).

5. Calculate the train displacement and the final speed at the end of the simulation cycle (Subsection 6.4.3).

6.5 REGULATION OF TRAIN TRAFFIC

6.5.1 Train Sequencing

The train sequencing methods perform the following actions :

1. enter a new train on the simulated system according to a specified headway time or timetable. Train entrance times are sorted and kept in a list in order to reduce the number of checks.
2. remove the train from the system at the end of its run.
3. update the train structures should any of the above events occur.

6.5.2 Automatic Signal Setting For Double Track

In multi-aspect signalled rail transit systems signal setting and release can be done automatically except in conflict areas, as explained in Chapter 3. In the line section structure of the simulator a boolean variable is defined to indicate the existence of a train in a signal block section (or in a track circuit). When a train occupies a signal block this variable is set to 'true' and remains so until the rear of the train leaves the block (and the overlap). There is also an integer to hold the identification number of the train which reserves the signal block so that only that train can occupy it. This route setting feature has proved useful in the Waterloo & City Line simulation , later described in Chapter 7. The automatic multi-aspect signal setting methods of the simulation model should be able to cope with majority of existing schemes. The automatic signal setting actions are described below :

1. Set the next signal aspect to 'stop' at a predetermined distance from the end of the current signal block i.e. at the sighting point.

2. a. Check the appropriate signal block (or track circuit) ahead of the train starting from the adjacent one. The number of blocks is one more than the number of signal blocks determined for service braking e.g. maximum 3 blocks are checked for BR type 4-aspect signalling scheme.

b. Check also the interdependencies between the current and the other signal blocks. In some cases the same track circuit can be shared by different signal blocks.

c. If there is a conflict area on the route switch to 'conflict area controller' (Subsection 6.5.3).

d. Reserve the signal block for the train

3. Repeat step 2 by reducing the severity of the aspect and by checking the next signal block ahead until all restrictive aspects are exhausted if the signal block is not occupied or reserved.

4. Set the new signal aspect.

5. Move the train as described in Section 6.4. If the aspect is restrictive calculate a braking profile.

Application of these methods to the BR type 4 aspect 3 block signalling scheme is illustrated in Figure 6.8. In this scheme 3 unoccupied blocks ahead sets the current signal aspect to 'green', 2 to 'double yellow', 1 to 'yellow' and none to 'red'.

SITUATION AHEAD	LINESIDE SIGNAL ASPECT	TRAIN SIGNAL MODE IN THE MODEL
1st block occupied	RED	0
2nd block occupied	YELLOW	1
3rd block occupied	DOUBLE YELLOW	2
1st, 2nd and 3rd blocks free	GREEN	3 (maximum line speed)

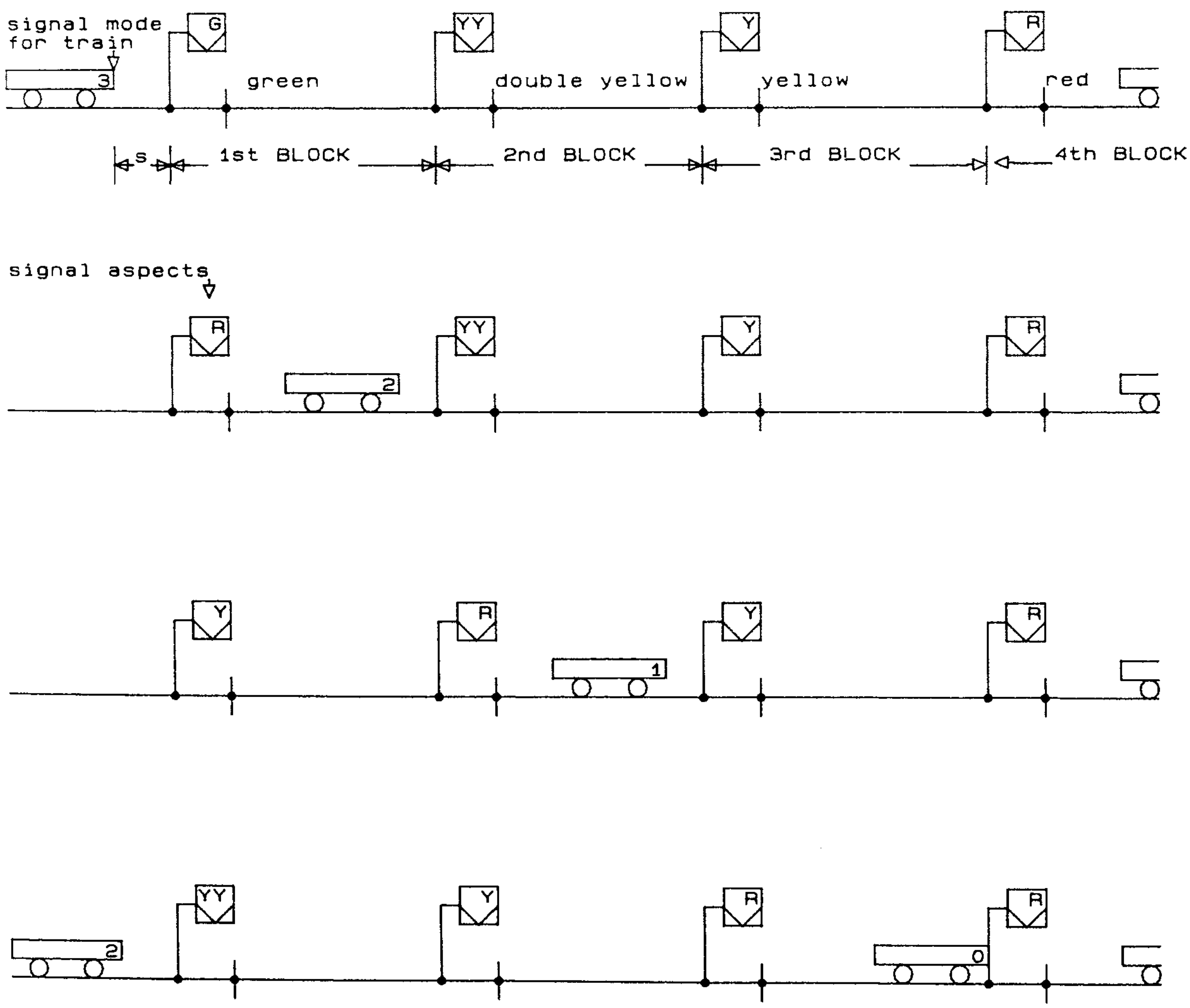


FIGURE 6.8 _ AUTOMATIC SIGNAL SETTING SEQUENCE OF THE SIMULATION MODEL FOR BR'S 4 ASPECT 3 BLOCK SIGNALLING

The methods of signal setting (i.e. automatic route setting) is readily applicable to all n aspect n-1 block schemes but, overlap distance must be set to zero metres for the conventional European practice. Singapore MRT or French TGV type n aspect n block signalling schemes with a forbidden block can be modelled as n aspect n-1 block with an overlap distance equal to the full block length.

By creating interdependencies between signal blocks (or track circuits) it is possible to set and release them simultaneously. It is also possible to reserve a signal block (or a track circuit) in advance for a particular train. These features are shared by the conflict area control methods and well suited to the particular logic of the two systems simulated for the traffic control experiments reported in Chapter 7. A signal block which is reserved for or occupied by a train can be released after the train clears the overlap. The signal block release times are sorted and kept in a list to avoid redundant checks.

6.5.2 Stopping Profile Calculations

This subsection describes the stopping profile calculation methods employed in the simulation model. The methods can easily be adopted to various multi-aspect signalling schemes or continuous control imposed on fixed block multi-aspect signalling schemes.

Route signalling schemes : The profile calculations take into account the maximum recommended restrictive speed of the train in each signal block. A different set of restrictive speeds is assigned for each class of trains. The calculations are initialized at the sighting point prior to the least restrictive signal aspect. If the signals are indicated in the cab then the train and signal interaction will be continuous, therefore the time-oriented mode of the simulation model should be used. In the case of line side signalling, if the sighting distance is negligible or is not specified then the train and signal interaction is at the block entrances and the simulation model can run in its combined mode i.e. block to block with or without on-line movement calculation. If the sighting distance is significant then the part of the block to block run after the sighting point must be time-oriented. Examples : Queensland Railways 3 aspect signalling, BR 4 aspect signalling, BR 5 aspect high speed train signalling on the East Coast Line.

Speed signalling schemes : The profile calculations take into account the speed restriction of each signal aspect. The braking profile calculated covers only the adjacent signal block. The profile calculations are initialized at the sighting point prior to the restrictive signal aspect. The braking rate can be adjusted in order to obtain a continuous stopping curve occupying the full signal block length if required. If the signal block is longer than the required braking distance, train can either coast then brake or brake then coast according to the adopted signalling philosophy. The simulation mode is application dependent like route signalling schemes. Examples : American 4 aspect signalling, French TGV Southeast 5 aspect, Atlantic 6 aspect signalling, Italian 3 and 4 aspect signalling, Hong Kong and Singapore 5 aspect mass rail transit signalling.

Continuous signalling schemes : The signal blocks are retained for train detection but a continuous stopping profile is calculated using the maximum service braking speed. The calculations are initialized at a safe braking distance specified by the number of clear signal blocks between the consecutive trains. Unlike the step supervision of speed signalling schemes, the train speed supervision is continuous. As the train and signal interaction is continuous, the simulation run has to be time-oriented. Examples : German high speed train signalling and the new French TGV line will use a similar continuous control scheme. A comparison of the step speed supervision for TGV Atlantic type 6 aspect cab speed signalling and for TGV Northern type continuous speed supervision is given in Figure 6.9.

6.5.3 Conflict Area Control

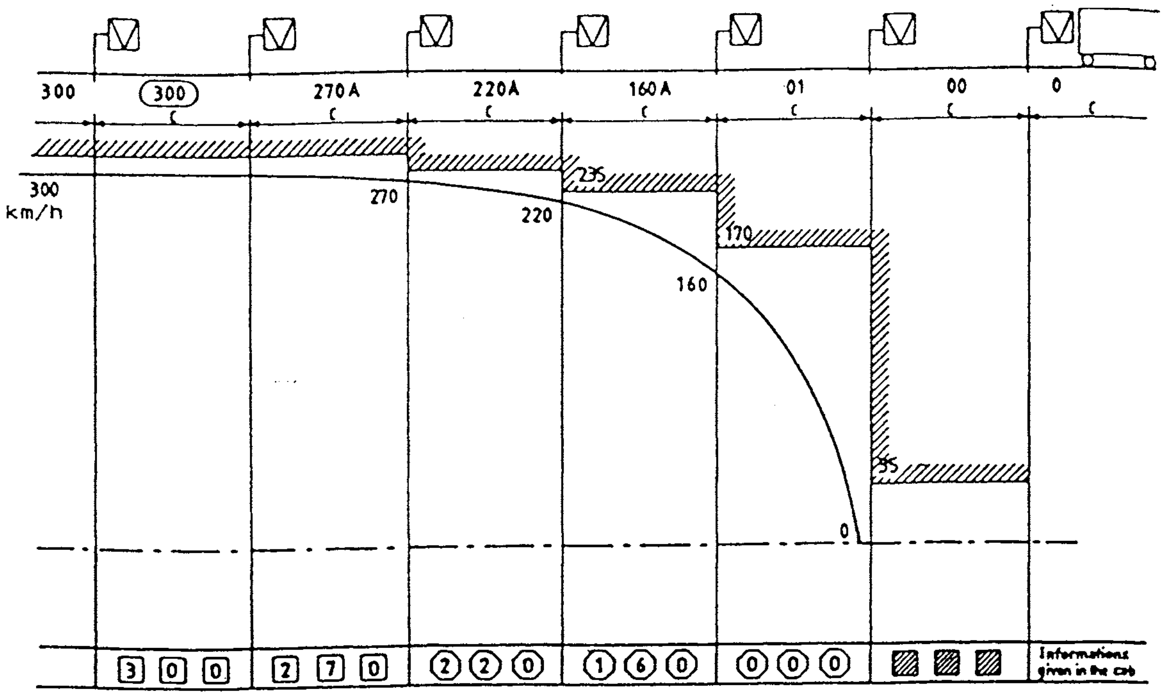
To resolve the conflicts at a junction the two best known strategies of decision making are implemented. These are known as 'first come first served' and 'scheduled sequence', which are defined in Chapter 3. A typical junction exchange method using one of these strategies would be :

1. At a predetermined point from the entrance of the junction detect the approaching train. Get the next vertex number from the time / route table. Activate the chosen strategy. This involves checking all conflicting routes (and trains for the 'scheduled sequence').

2. a. If the train has the right of way set the route. This involves blocking all the conflicting routes.

   b. If the right of way is not issued be prepared to bring the train to a halt before the conflict area. Repeat steps 1 and 2 until the right of way is issued.

3. When the train arrives at a vertex connect the train to the new line section lists on the route.

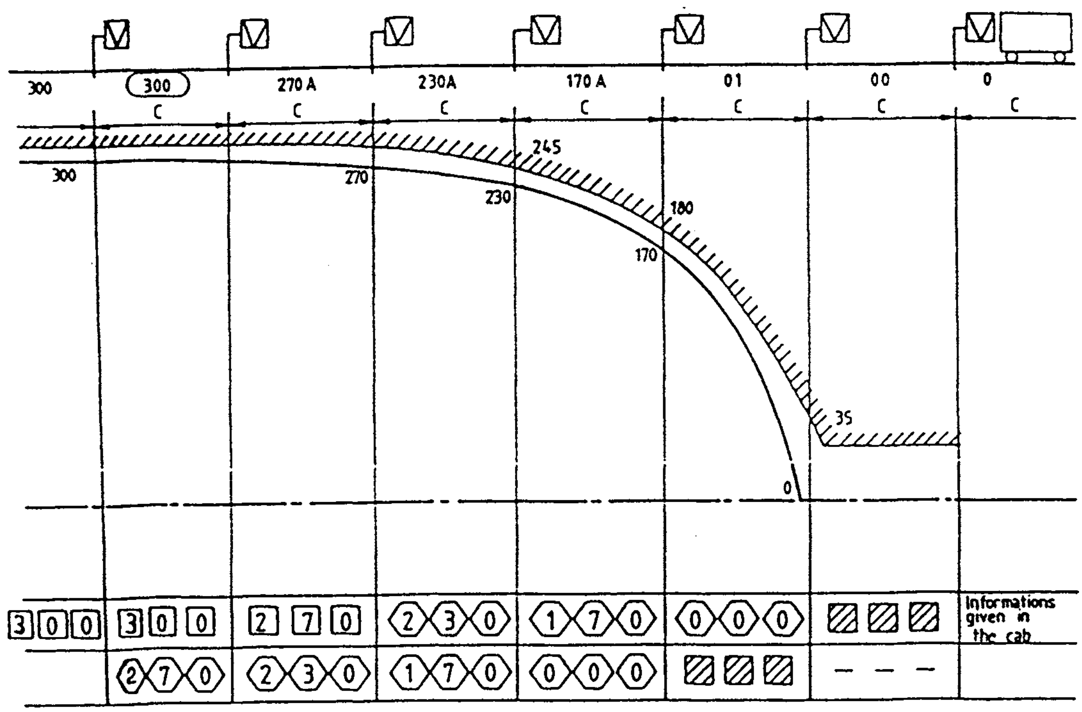


forbidden speed section (automatic braking system operative)

F

signal block section marker

— A —



1500 m signal block section instead of 2000 m

— B —

FIGURE 6.9 — BRAKING AND STOPPING SEQUENCE FOR SIGNAL BLOCK SECTIONS.
A — UNDER STEP SPEED SUPERVISION
B — UNDER CONTINUOUS SPEED SUPERVISION

4. Move the train on its route releasing the route partially if applicable.
5. After the train clears the exit signal release the route completely.

6.6 OVERALL STRUCTURE OF THE SIMULATION MODEL

The described data structures and the processing methods operating on them have provided inherent modularity to the software. The simulation model has been divided into 8 main modules. The interconnections (i.e. coupling) among these modules are limited and usually only through the data structures described in Chapter 5. The exceptions are the coupling between Module 8 (traction equipment models) and Module 6 (profile precalculations) and between Module 8 and Module 7 (movement calculations) which are through well-defined argument lists. The data flow structure of the simulation model is shown in Figure 6.10.

Module 1 : The module reads in the data common to all trains of a class. It also read in the number of trains in each class. The train structures described in Chapter 5 are created by this module. An example input file is given in Appendix 4.

Module 2 : This module reads in the network configuration file. This file defines the configuration of the network including the identifiers and their interconnections. After the network frame is set up, track geometry and speed restrictions for each line section and for each direction are read from a data base. Examples are given in Appendix 4.

Module 3 : This module reads in the timetable and route information of the trains. The input file has a block of data for each train which contains the order of the vertices the train passes through (i.e. train route) and, entry, exit, re-entry, vertex arrival and waiting times, where available (i.e. timetable). The route/timetable structure described in Chapter 5 is created and linked to the train structures simultaneously.

Module 4 : The inclusion of traffic control is an optional feature of the simulation model. Where it is included, signal block data (i.e. positions of signal block (or track circuit), overlap, sighting point and interdependencies) is read in by this module. Otherwise dummy signal blocks, which are equal to the line section in length, are created. The signal block lists are created and linked to the network model simultaneously.

Module 5 : This module transform the track geometry as described in Section 6.2. The network model is also modified to hold the new lists as described in Chapter 5.

Module 6 : This module calculates and arranges the expected braking and stopping profiles as described in this chapter.

Module 7 : This module is responsible for the movement of trains and management and control of train traffic according to the route and timetable information and traffic control strategies. It also selects and arranges the variables for output files.

Module 8 : This module consists of traction equipment models described in Section 6.2 and acceleration controllers described in Section 6.4. Naturally, this module is application dependent and purpose-written versions must be interfaced to the simulation model for each different application.

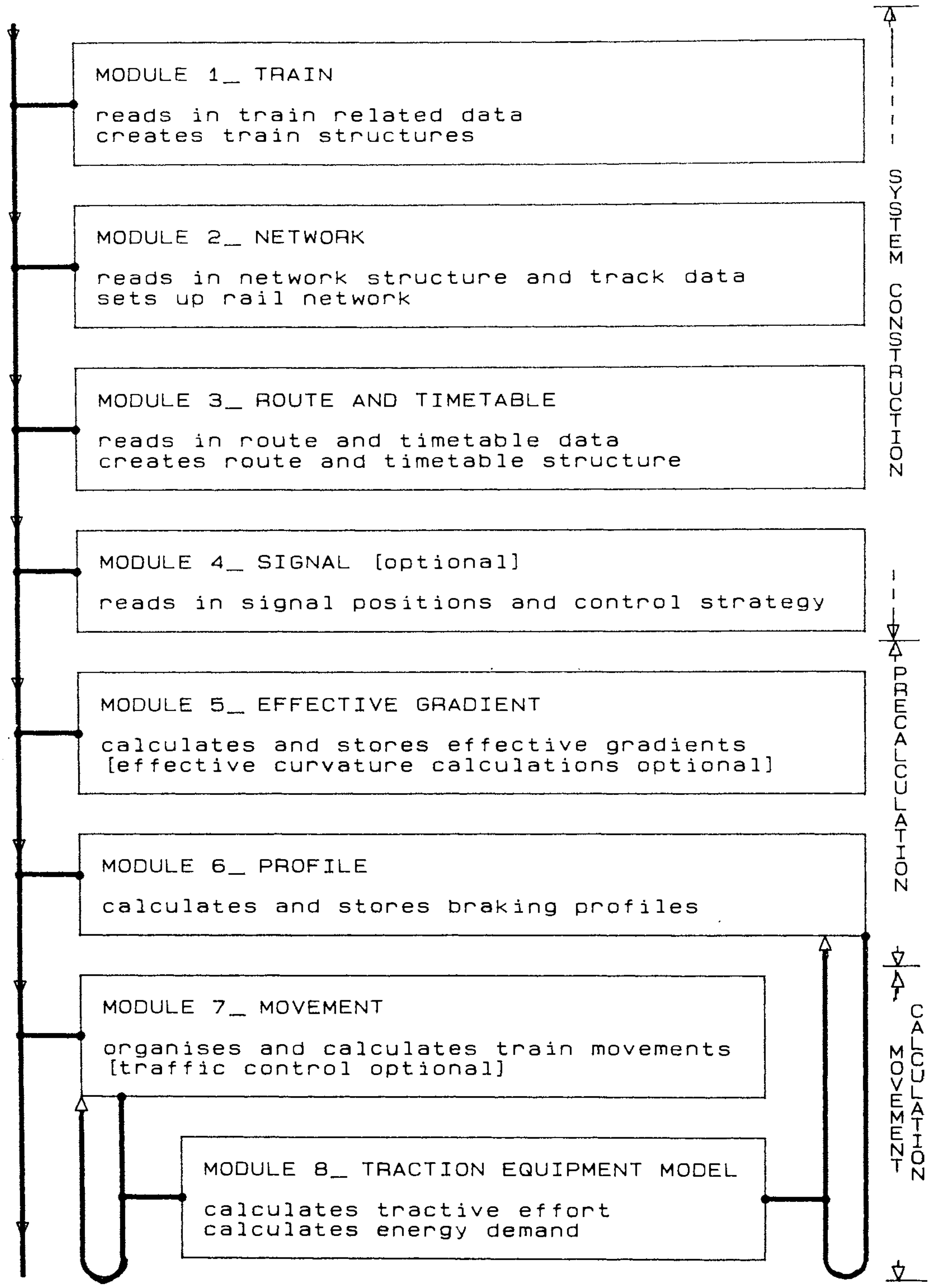


FIGURE 6.10 _ DATA FLOW STRUCTURE OF THE SIMULATION MODEL.

CHAPTER 7

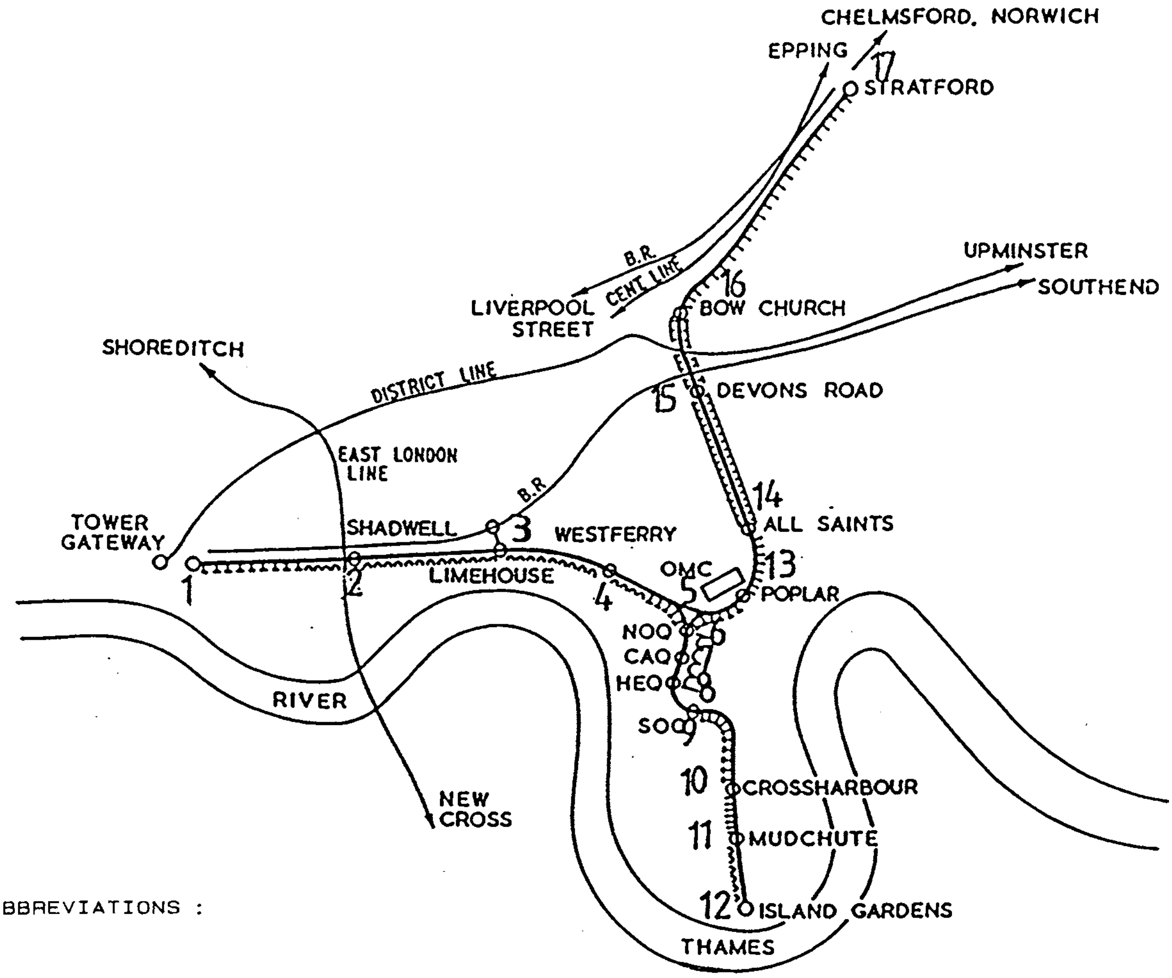
TRAFFIC ANALYSIS EXPERIMENTS

7.1 INTRODUCTION

After the simulation model had become fully operational, in order to demonstrate the simulation model's capabilities, and its independence of any particular track layout and signalling scheme, a series of system tests were carried out by simulating two different systems. These tests have been based on London Docklands Light Rail Transit System (DLR) and Waterloo & City Line track data and train traffic regulation concepts. The DC traction equipment model described in Chapter 6 has been used to power the trains in both systems. This chapter will summarize these system tests.

System 1 : The Docklands Light Rail System is an automated intermediate capacity transit system serving the redeveloped Docklands area to the east of Central London. A fixed headway time down to 240 seconds is provided, using automatically driven light rail trains. The system makes use of some former BR railway alignments so it is single track between some stations. The rail network has relatively closely spaced stations, a 'delta' junction and single and double track sections as shown in Figure 7.1a.

System 2 : Further testing of the simulation model has been carried out to examine terminus turnaround and crossover situations on British Rail's



KEY & ABBREVIATIONS :

1 GATEWAY	7 CAQ CANARY QUAY	13 POPLAR
2 SHADWELL	8 HEQ HERON QUAY	14 ALL SAINTS
3 LIMEHOUSE	9 SOQ SOUTH QUAY	15 DEVON ROAD
4 WESTFERRY	10 CROSSHARBOUR	16 BOW CHURCH
5 WYE TYPE JUNCTION	11 MUDCHUTE	17 STRATFORD
6 NOQ NORTH QUAY	12 ISLAND GARDENS	

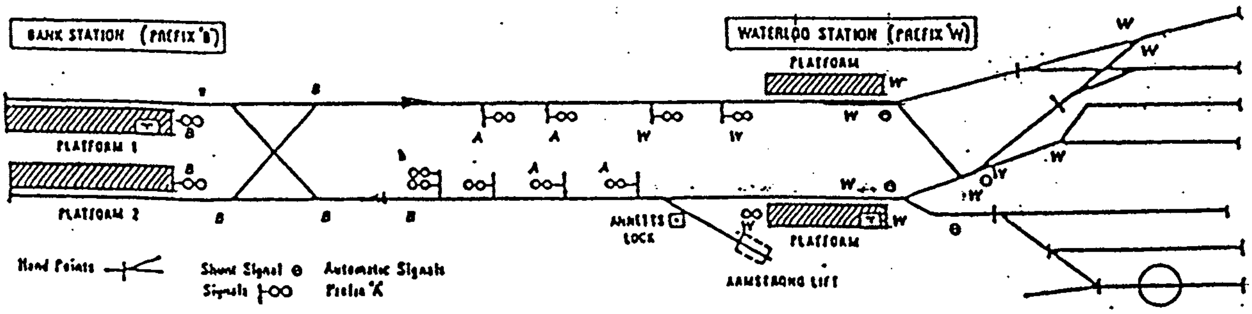


FIGURE 7.1 _ TWO SMALL SCALE RAIL TRANSIT SYSTEMS
A _ LONDON DOCKLANDS LIGHT RAIL SYSTEM ROUTE MAP
B _ ORIGINAL TRACK DIAGRAM OF THE WATERLOO & CITY LINE

Waterloo and City Line. The original track diagram of this system is given in Figure 7.1b. The signalling and interlocking installation on this system dates from 1940 when track circuits, colour light signals etc. were first brought into use. The service is operated by 4 manually driven trains and all of them are in service during the peak hours. The service used to be operated to a 150 second headway time but a problem of drivers becoming hypnotised by the constant short shuttle led to a decision to extend the headway time to 180 to 240 seconds until the system is fully automated.

7.2 LONDON DOCKLANDS LIGHT RAIL SYSTEM SIMULATION

7.2.1 System Control Concepts

7.2.1.1 Automatic Train Supervision Functions

A central Automatic Train Supervision (ATS) system initiates and regulates all traffic movement on the system [104] [105]. It issues route requests to the BR Solid State Interlocking (SSI) system, which sets points and energises Automatic Train Protection (ATP) transmitters if it is safe to do so.

Trains receive commands via Docking Data Links (DDL) at each station platform. The data sent to the trains include vital start information from the interlocking, as well as non-vital information about the identity of the station, the performance level that is required for the run to the next stations, the request from ATS to start the train etc.

7.2.1.2 Automatic Train Operation Functions

An Automatic Train Operation (ATO) computer on the train looks up the appropriate speed profile data for the route in its memory, and starts and runs the train in accordance with the stored speed profile. If a lower performance level has been requested by the ATS, the ATO initiates coasting at a predetermined location on each route.

Much of the rail network is signalled on a station-to-station block system, which is adequate for the headway time required. In certain sections, where the station-to-station distance is long, intermediate stopping points are provided to enable trains to leave stations while the line section to the next station is still occupied by another train. In these sections the train will start to follow a speed profile bringing it to a halt at an intermediate point if the rest of the line section is still occupied, but will change to a profile continuing to the next station as soon as the route section ahead is released.

7.2.1.3 Automatic Train Protection Functions

Whilst the train is running, the ATP equipment on board checks continuously that the train has permission to run in that section of track, and that the speed of train is correct. Provided that the ATO runs the train correctly, the ATP system does not intervene. The ATO computer also stops the train in alignment with the stop mark on the next station platform.

In the event of ATO failure, trains can be driven at line speed in ATO Manual mode with full protection. The facilities provided by the ATP system are described below :

Train Detection : Train detection is by means of high frequency track circuits which employ audio frequency tones generated and detected by double-tuned 'reed' filters.

Speed Monitoring : The solution adopted on the DLR system makes use of cable loops laid in the track throughout the system. The cables forming these loops are fed by audio frequency current and transposed at intervals, so as to allow a train travelling at the maximum safe speed to pass over one transposition per second. By varying the spacing of the transpositions, any civil speed limit can be monitored, and the correct deceleration of trains approaching speed restrictions can be proved safely.

Trainstop Function : Before any obstruction, such as an occupied track circuit or unlocked route, an overlap track circuit without safety tone is provided, of sufficient length to enable a train to stop from line speed. Loss of safety tone on a moving train causes an ATP trip, bringing it to a halt short of the obstruction.

Interlocking : On the DLR system, BR Solid State Interlocking is used to ensure the safe movements of trains. The DLR application is the first use of this system for an urban railway with ATP and ATO systems, as well as being the first use with an Automatic Route setting (ARS) and Automatic Train Regulation (ATR) system. One interlocking installation controls the area around the junction and the Depot (not modelled) while the other interlocking installation controls the outer portions of each of the three routes. The interfaces between signalling and interlocking system elements occur in automatically signalled parts of the railway. The DLR ATP/ATO system block and control flow diagrams are given in Figure 7.2.

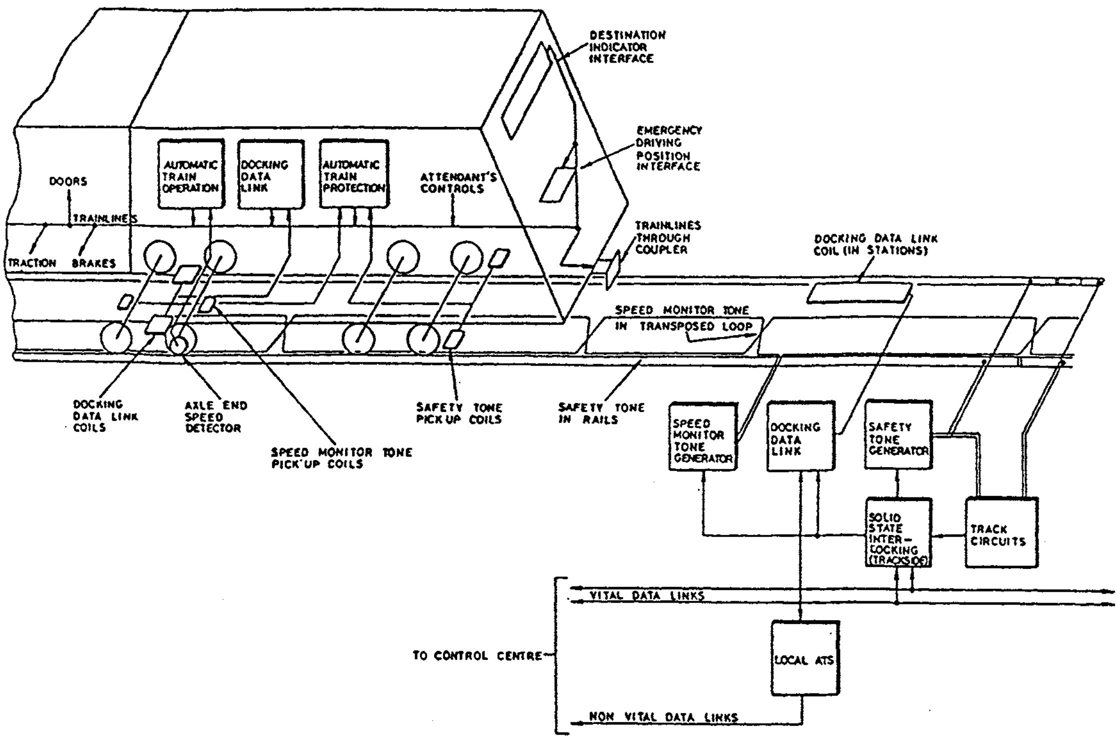


FIGURE 7.2 _ DLR ATP/ATO SYSTEM BLOCK DIAGRAM

7.2.2 Automatic Train Control System Model

7.2.2.1 Modelling Approach

The inclusion of all features of the DLR automatic train control system in the simulation model is not justified. The following functions have been excluded :

1. The ATP function, which ensures train speed is not excessive, is a duplicated safety feature of the real system. Also, there is no direct representation of the transposed loop speed monitoring. However, the 1s update time of the model is equivalent to the speed monitoring frequency of the ATP. The acceleration control methods in the simulation model already guar-

antee that trains do not overspeed.

2. The ATP function 'trainstop' is not modelled since it also is a duplicated safety feature of the real system.

3. The ATS function that takes decisions when unexpected operating conditions arise is not modelled.

4. The ATO function that loads and follows precalculated speed profiles is not modelled. The trains are run by the movement methods in the simulation model which calculates the profiles during the run. However, any speed profile can be generated by imposing coasting points and dynamic speed restrictions.

Although the DLR is a rather special rail transit system in the sense of its unusual traffic regulation installations, the conceptual similarities with train operations in other more conventional systems are not difficult to perceive. Thus, the generalised traffic regulation and movement methods of the simulation model have proved to be adequate to model the ATO/ATP/ATS operations of the DLR after some slight modifications.

7.2.2.2 Modelling of ATC Operations

This subsection describes the ATC system functions and train movements as modelled in the simulator by using the train movement and traffic regulation methods with some minor modifications.

Much of the system is signalled on a station-to-station (i.e. vertex-to-vertex) block basis therefore, unlike conventional multi-aspect signalling schemes, in the majority of the cases all the track circuits between the two vertices (i.e., station or junction) have to be checked before this route section is set. To cope with this peculiarity of the DLR system, interdependencies were created between the track circuits that make up a line section such that they can be set and released simultaneously. The original methods in the simulation model had to be slightly modified in order to cope with this feature of the system.

Having done this, the signalling scheme can be viewed as 2 aspect fixed block type and the automatic signal setting method of the simulation model can be used directly. The route setting process is discrete and performed only before a train enters a new line section.

However, there are some rail network sections where vertex-to-vertex distances are very long. In these sections a train can leave the station before the line section ahead is completely unoccupied, but be prepared to follow an on-line calculated stop profile which will bring it to a halt before the occupied track circuit. In these special cases, the line section is checked continuously and as soon as the rest of the line section is cleared, the stop profile (and if already started the braking application) is cancelled. The type of check, numbers of track circuit to be checked (i.e. number of signalling aspects) and the positions of the coasting points, if given, are held in the extended time/route table structure. The multi-aspect automatic signal setting and continuous train control methods of the simulation model are used to simulate the behaviour of the ATO system in these sections of the network. The number of aspects on these sections depends on the number of interdependent track circuit sets which also determines the positions of stopping points.

Single track line sections of the network are represented as double track sections (i.e. by two sets of linked-lists between vertices, one for each direction) containing identical track circuits and track data for each direction. Interdependencies are created between identical track circuits so that two trains moving in opposite directions cannot occupy the line section at the same time. The lengths of these sections are adequate for two trains moving in the same direction to occupy a single track line section simultaneously provided that they are separated at least by a braking distance. Entrance to these sections is controlled by the 'scheduled sequence' conflict area control strategy methods already defined in Chapter 3 and Chapter 6.

In the real system, stop and brake profiles of trains are independent of the track circuit layout and track circuits are used for train detection only. In the simulation model, all on-line and precalculated stop and brake profiles are therefore calculated independently of the signal aspect of the block and can override the signalling aspects. Thus, the simulation model can cope with some short track circuits existing in the DLR system without any modification to its signal block/track circuit based line section representation.

By these slight modifications, the traffic regulation philosophy of the real system can be modelled with the existing automatic signal setting and conflict area control methods of the simulation model. The movement of a train from a station or junction vertex to another station vertex in the model can be summarized as follows :

1. Activate the train when the dwell time is over (ATO command).
2. Set the route section ahead of the train (ATS operation). The route section will be checked continuously and the train will only be moved when the route section is clear (ATO operation).

3. Move the train by choosing the tractive mode, calculating the required acceleration/deceleration rate and integrating the equations of motion etc. at each simulation cycle (ATO operations).

4. Calculate the new train position and speed at the end of each simulation cycle. If another train is allowed in the same line section route checking is performed at each simulation cycle until the line section is clear. Repeat steps 3 and 4 until the train arrives at the next vertex (ATO operations). These actions will be interrupted if there is an intermediate stop point which brings the train to a halt before it reaches to the next station.

5. Set the next station vertex occupied; read next vertex from the time/route table; find addresses of the new line section and link the train structure to the new line section. (ATS operations)

6. On arriving at the next station, make train inactive until the end of the dwell time (ATS operation).

7. Repeat all the steps for all trains and for all station/vertex to station runs.

For the delta junction to station movement the following actions would be performed by the simulation model :

1. Same as in station/junction to station movement actions above.
2. Same as in station/junction to station movement actions above.
3. Same as in station/junction to station movement actions above.
4. Same as in station/junction to station movement actions above.
5. At a given position (defined by precalculated stop profile) activate chosen conflict area control methods. The delta junction is regulated by the 'first come first served' strategy in this applica-

tion. This strategy and its implementation has already been described in Chapter 3 and Chapter 6.

a. If the train has the right of way then set the junction to occupied; read next vertex from the time/route table; find addresses of new line section, link the train structure to the new line section.

b. If train does not have right of way bring it to a halt, wait until right of way is issued then same as 5.a.

6. Same as in station/junction to station movement actions above.
7. Same as in station/junction to station movement actions above.

7.2.3 DLR System Simulation Runs

7.2.3.1 Simulation Conditions

The trains ran on 4 different routes as in the real system which are defined below. The vertex numbers of the stations and the junction are defined in Figure 7.1a.

Route 1 : 12> 11> 10> 9> 8> 7> 6> 5> 4> 3> 2> 1

Route 2 : 1> 2> 3> 4> 5> 6> 7> 8> 9> 10> 11> 12

Route 3 : 12> 11> 10> 9> 8> 7> 6> 5> 13> 14> 15> 16> 17

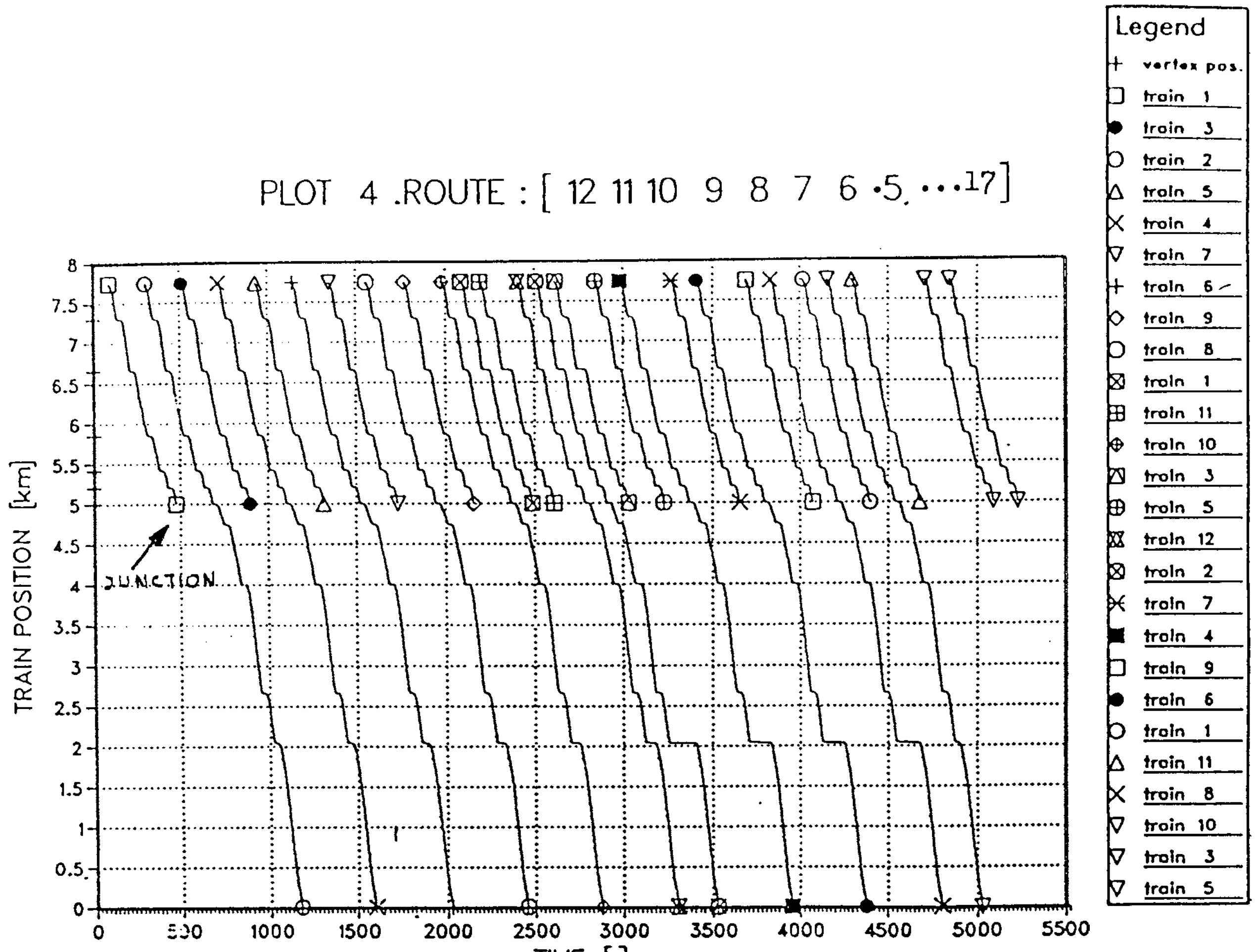
Route 4 : 17> 16> 15> 14> 13> 5> 6> 7> 8> 9> 10> 11> 12

The total number of trains was limited to 12. All the trains entered the network from Island Gardens (vertex 12) according to 3 different fixed headway times i.e. 180, 210, and 240 seconds. The total simulation time was 5400 seconds (i.e. 1 hour and 30 minutes) for every run. As in the real system, the odd numbered trains ran on Routes 1 and 2 while the even numbered trains ran on Routes 3 and 4.

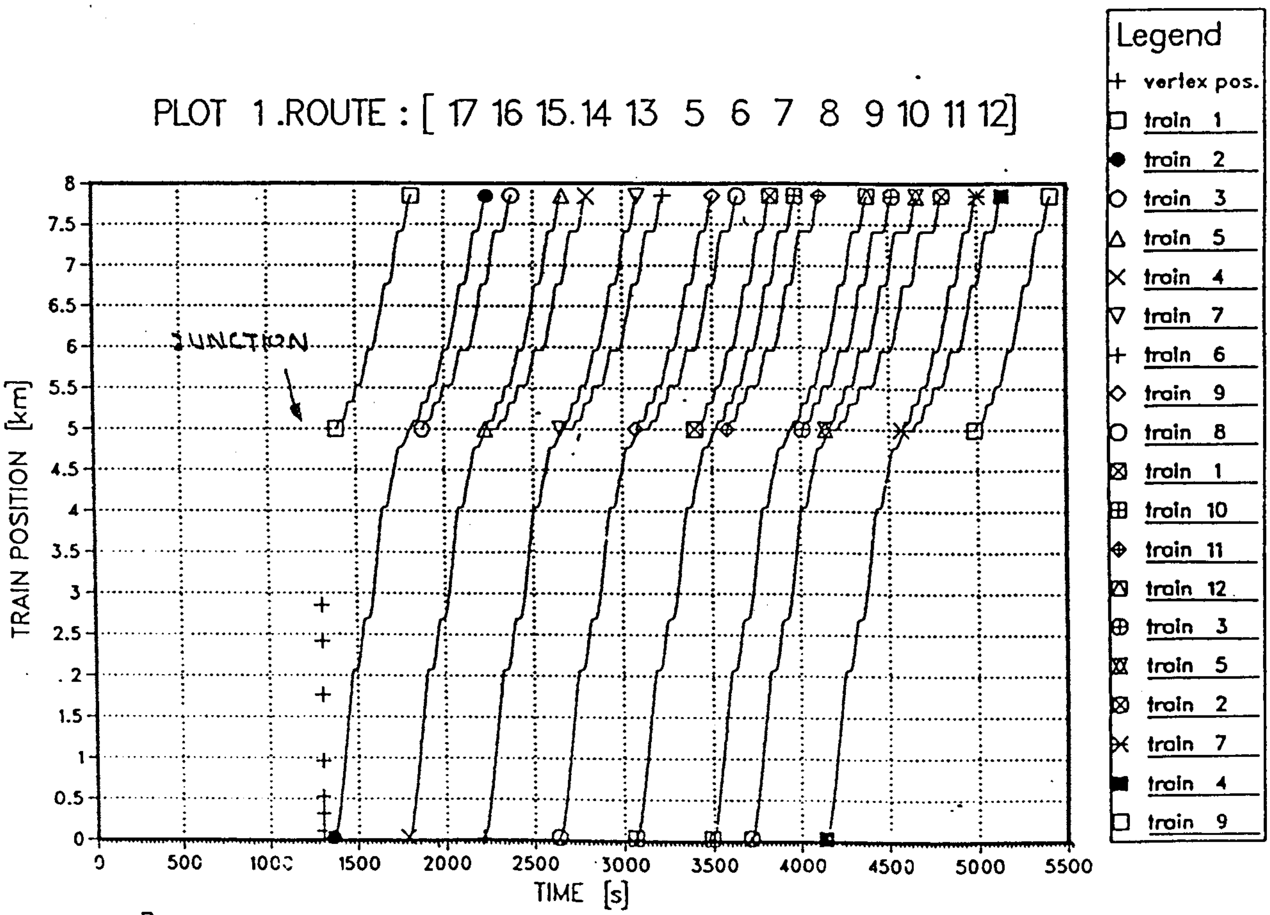
7.2.3.2 Results and Conclusions

Train timing diagrams for 180 seconds headway time i.e., time versus train head position plots, of all possible routes are given in Figure 7.3. Note that the section of the network between Vertex 5 (the junction) and Vertex 12 (Island Garden Station) is common to all train routes. This section is between 5 and 8 kilometres in Figures 7.3a and 7.3b where distances are measured from Vertex 17 (Stratford) and between 3.75 and 6.75 kilometres in Figures 7.3c and 7.3d where distances are measured from Vertex 1 (Tower Gateway). It can easily be seen that e.g. Train 1 of Figure 7.3a runs from Vertex 12 (Island Gardens) to Vertex 1 (Tower Gateway) whereas e.g. Train 2 runs from Vertex 12 (Island Gardens) to Vertex 17 (Stratford). The four plots together give a complete picture of the train operations between 0 and 5500 seconds. Many conflicts occurred in this run although the distances between the trains were more than maximum braking distances in the most of the cases. It can easily be seen that the vertex-to-vertex run philosophy is severely restrictive when considering further capacity increases whilst still using the existing signalling and interlocking subsystem (ATS).

At the time these simulation runs were performed 210 seconds fixed headway time operation of the system was being considered. The train diagrams of all the possible routes, a more detailed picture of the junction


PLOT 4 .ROUTE : [12 11 10 9 8 7 6 •5, •••17]
JUNCTION
TRAIN POSITION [km]
TIME [s]
Legend
vertex pos.
train 1
train 3
train 2
train 5
train 4
train 7
train 6
train 9
train 8
train 1
train 11
train 10
train 3
train 5
train 12
train 2
train 7
train 4
train 9
train 6
train 1
train 11
train 8
train 10
train 3
train 5

— A —


PLOT 1 .ROUTE : [17 16 15.14 13 5 6 7 8 9 10 11 12]
JUNCTION
TRAIN POSITION [km]
TIME [s]
Legend
vertex pos.
train 1
train 2
train 3
train 5
train 4
train 7
train 6
train 9
train 8
train 1
train 10
train 11
train 12
train 3
train 5
train 2
train 7
train 4
train 9

— B —

cont...

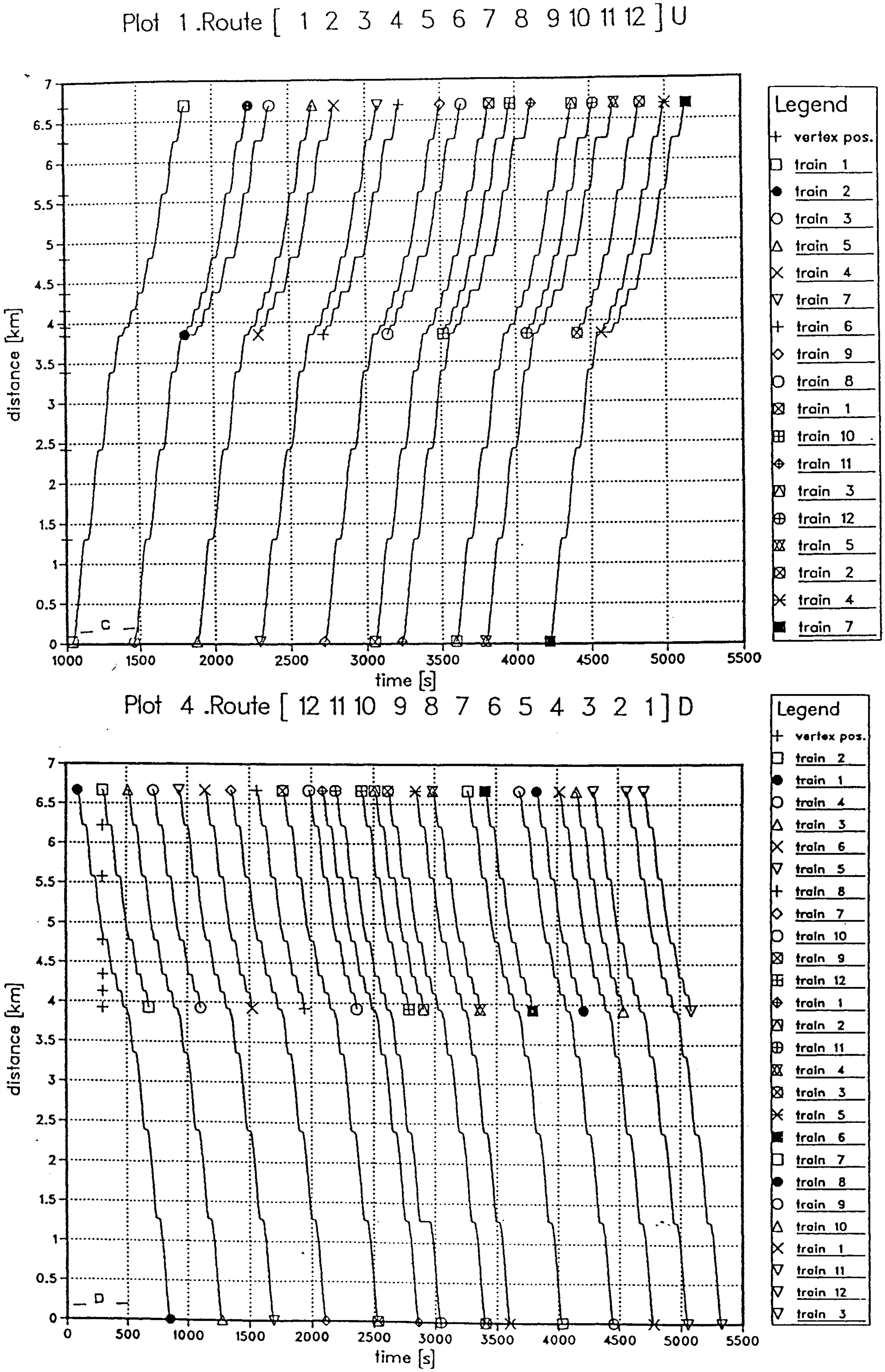
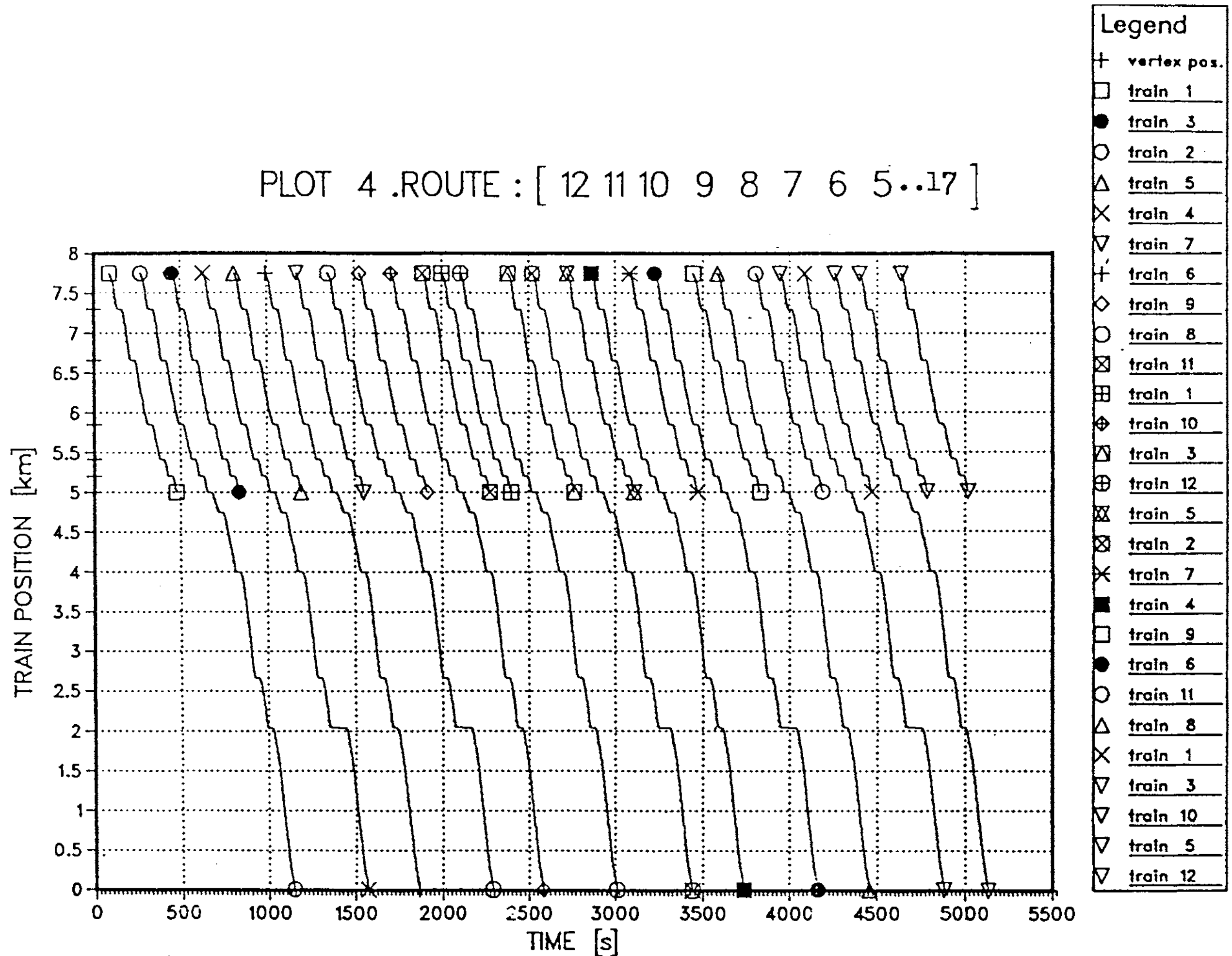


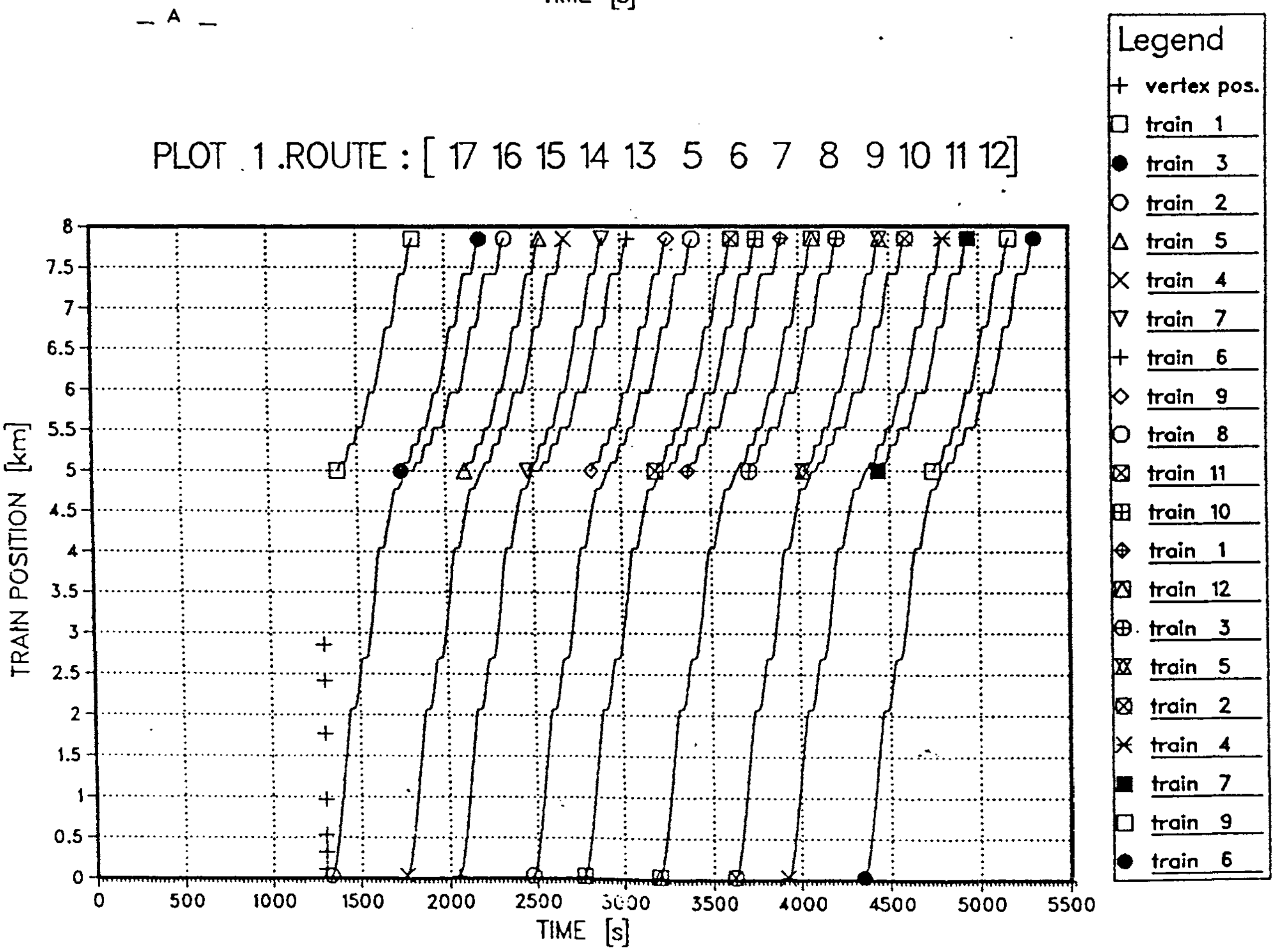
FIGURE 7.3 _ DLR TRAIN TIMING DIAGRAMS FOR 180 s HEADWAY TIME

A _ ROUTE 12...17 B _ ROUTE 17...12

C _ ROUTE 1...12 D _ ROUTE 12....1

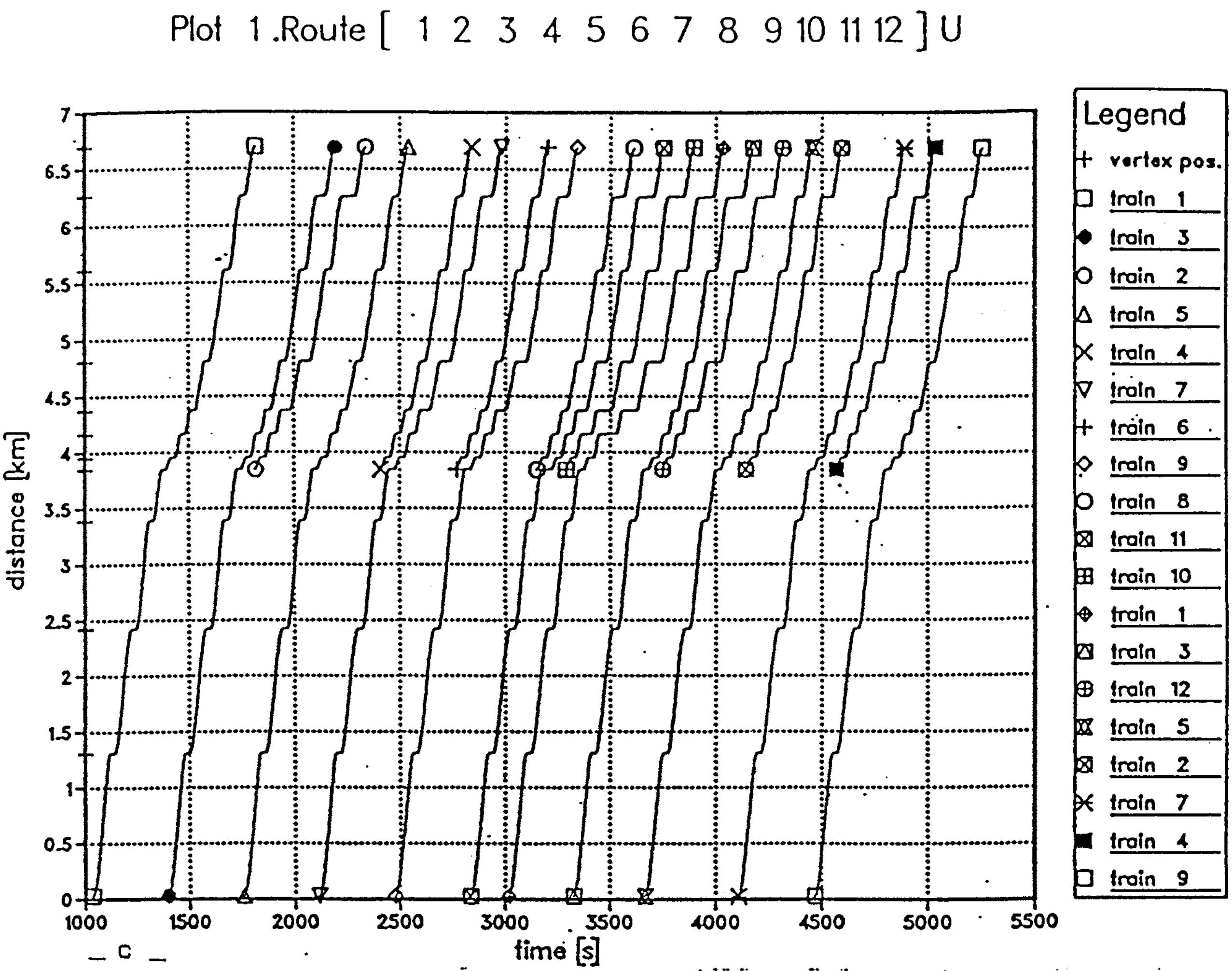

PLOT 4 .ROUTE : [12 11 10 9 8 7 6 5..17]
TRAIN POSITION [km]
TIME [s]
Legend
vertex pos.
train 1
train 3
train 2
train 5
train 4
train 7
train 6
train 9
train 8
train 11
train 1
train 10
train 3
train 12
train 5
train 2
train 7
train 4
train 9
train 6
train 11
train 8
train 1
train 3
train 10
train 5
train 12

— A —

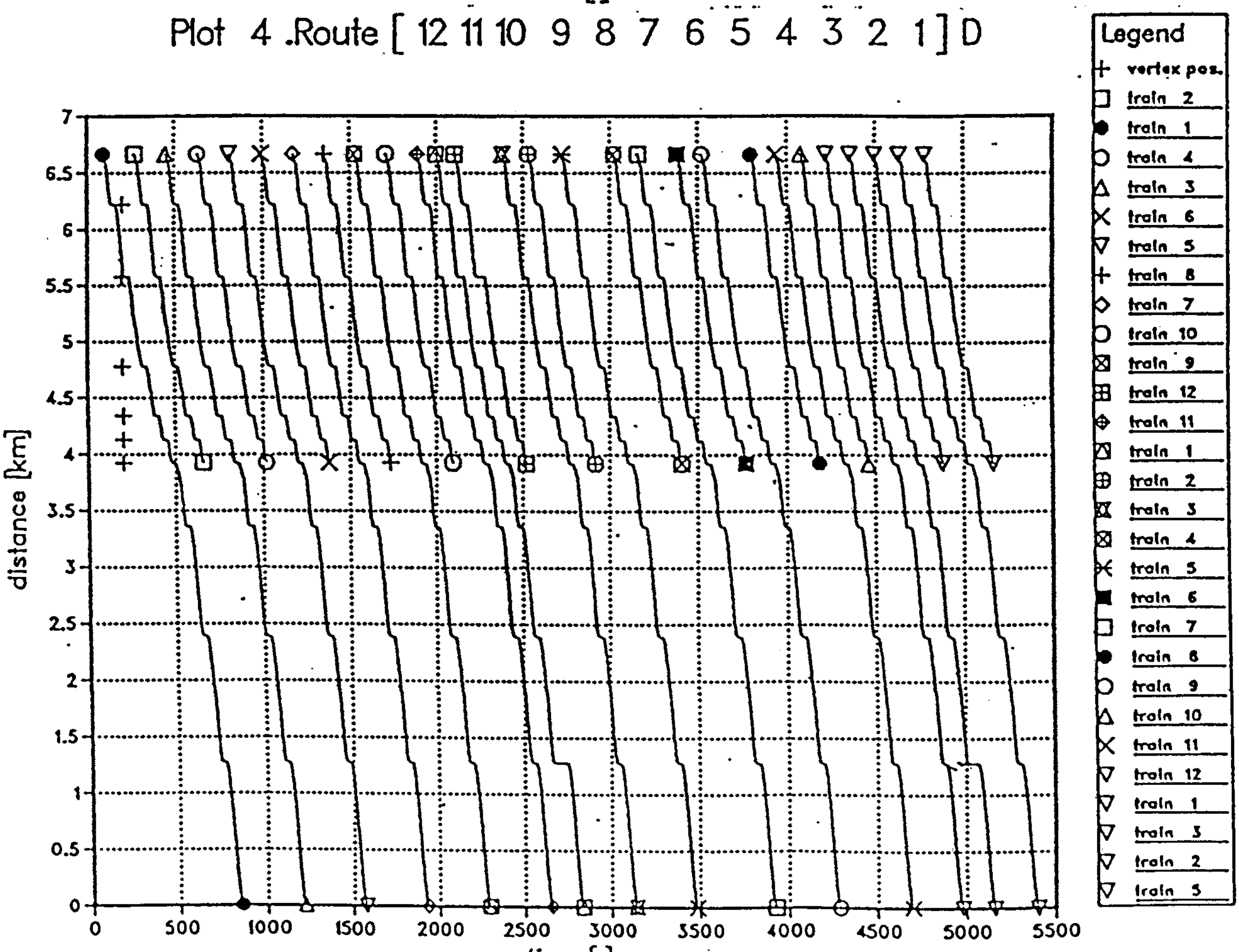

PLOT 1 .ROUTE : [17 16 15 14 13 5 6 7 8 9 10 11 12]
TRAIN POSITION [km]
TIME [s]
Legend
vertex pos.
train 1
train 3
train 2
train 5
train 4
train 7
train 6
train 9
train 8
train 11
train 10
train 1
train 12
train 3
train 5
train 2
train 4
train 7
train 9
train 6

— B —

cont...

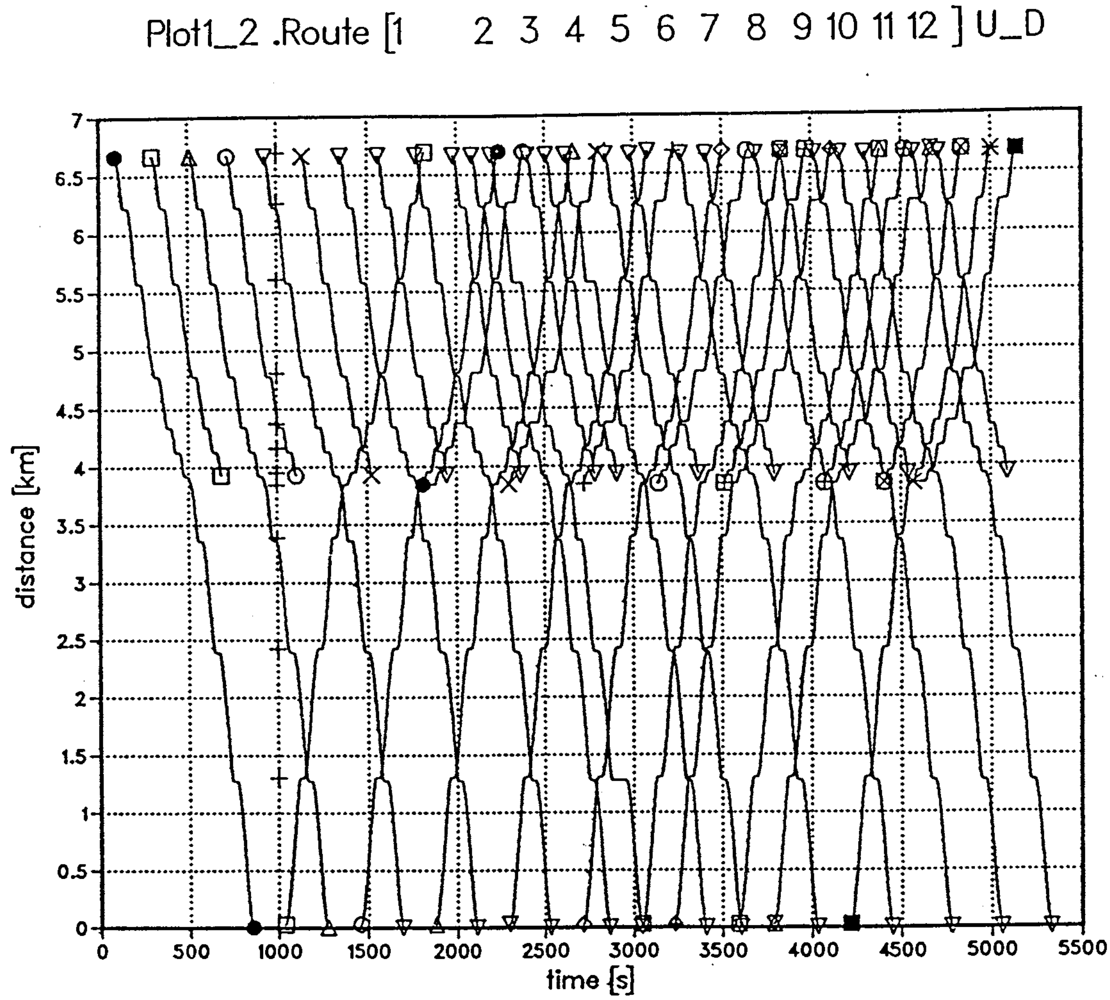

Plot 1 .Route [1 2 3 4 5 6 7 8 9 10 11 12] U
distance [km]
time [s]
Legend
vertex pos.
train 1
train 3
train 2
train 5
train 4
train 7
train 6
train 9
train 8
train 11
train 10
train 1
train 3
train 12
train 5
train 2
train 7
train 4
train 9

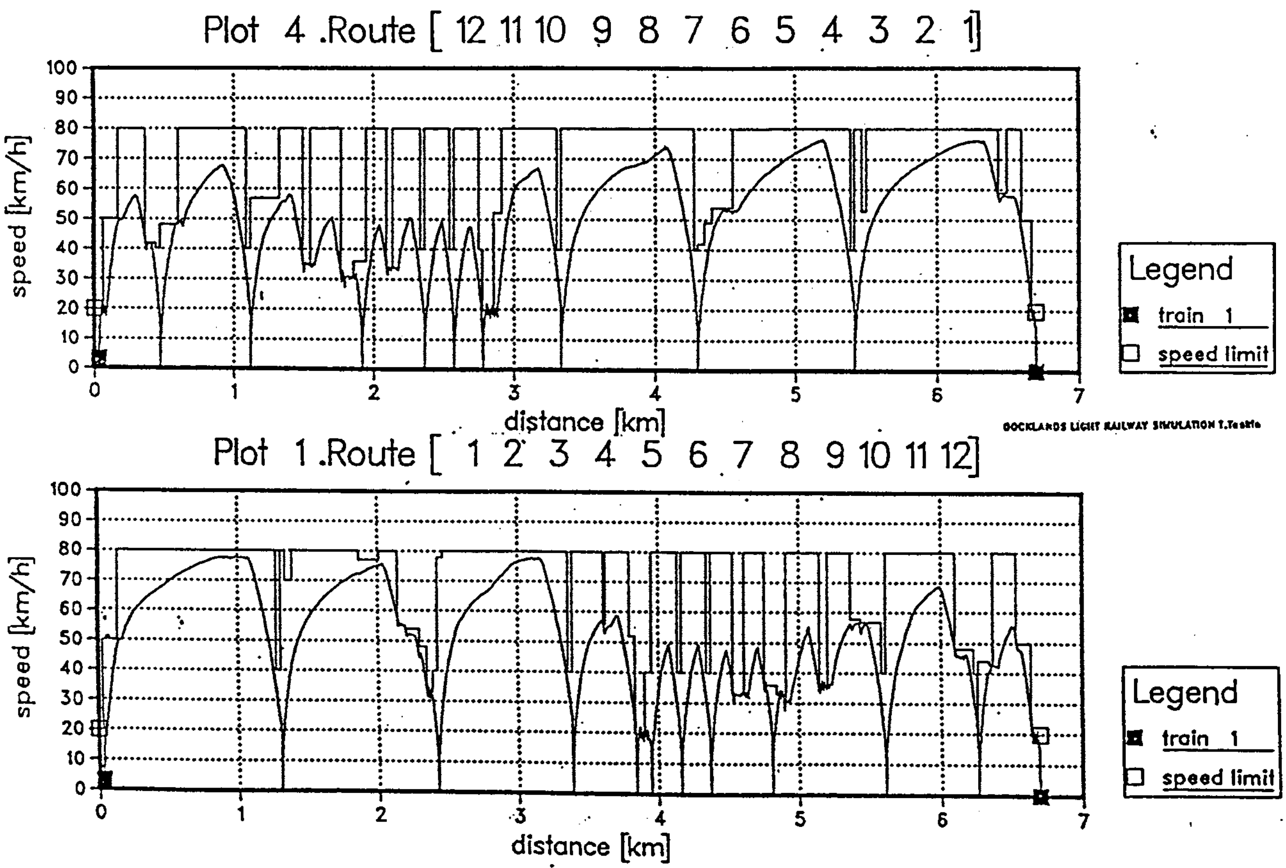
— C —


Plot 4 .Route [12 11 10 9 8 7 6 5 4 3 2 1] D
distance [km]
time [s]
Legend
vertex pos.
train 2
train 1
train 4
train 3
train 6
train 5
train 8
train 7
train 10
train 9
train 12
train 11
train 1
train 2
train 3
train 4
train 5
train 6
train 7
train 8
train 9
train 10
train 11
train 12
train 1
train 3
train 2
train 5

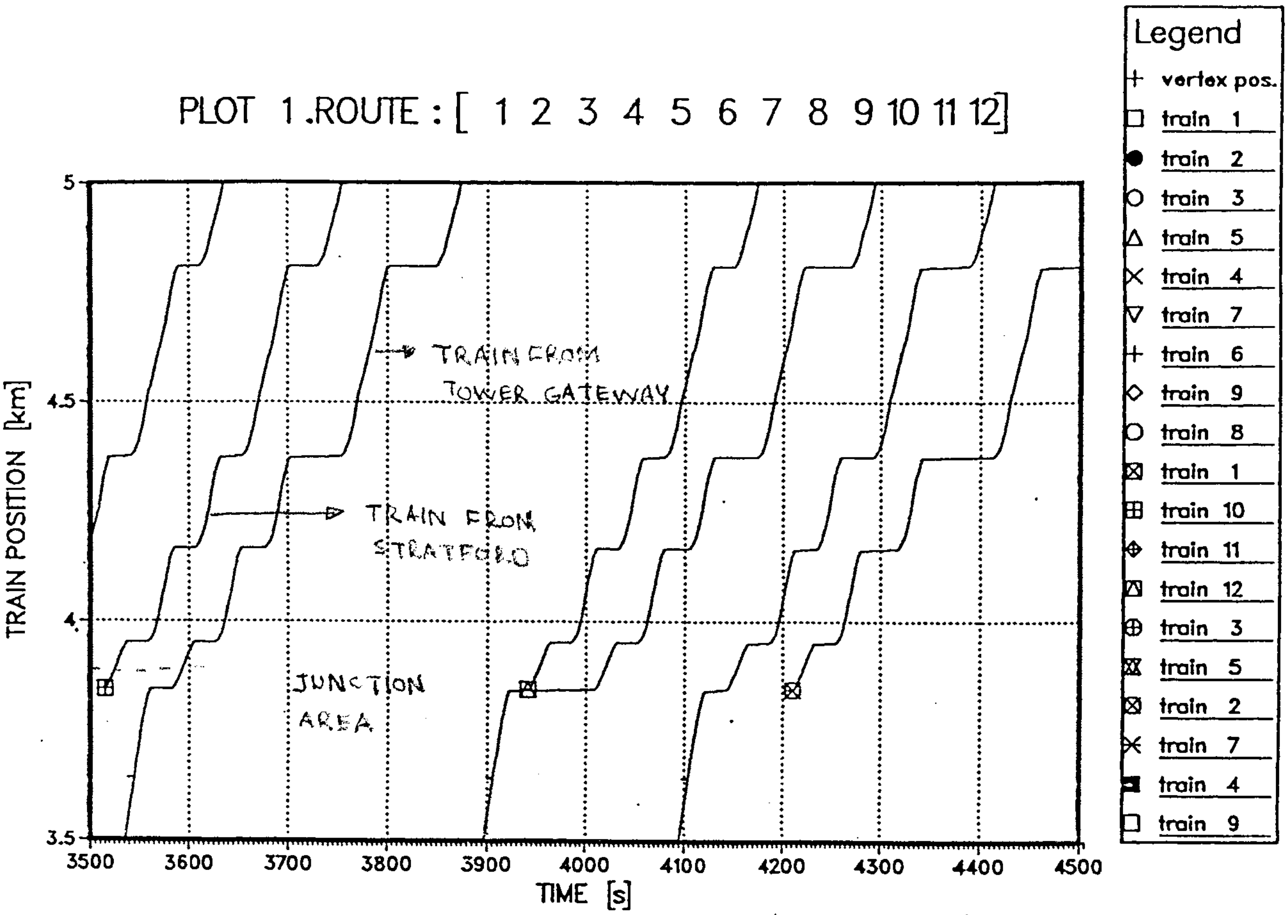
— D —

cont...

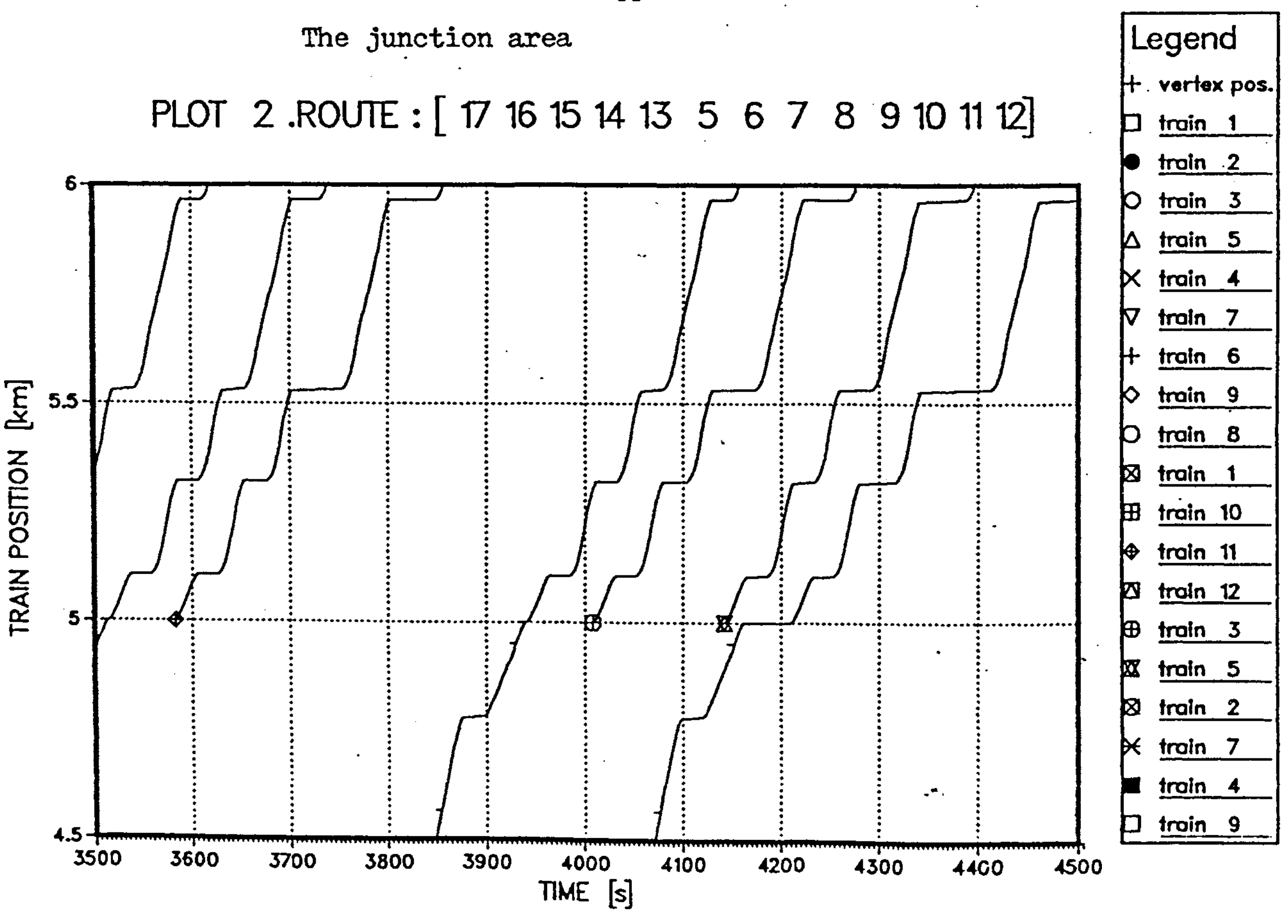




E _ ROUTE 1...12 AND ROUTE 12...1
F _ SPEED VERSUS DISTANCE PLOTS FOR TRAIN 1 ROUTES 1...12 AND 12...1



The junction area



The junction area

G _ ROUTE 1...12 THE JUNCTION AREA
H _ ROUTE 12....1 THE JUNCTION AREA

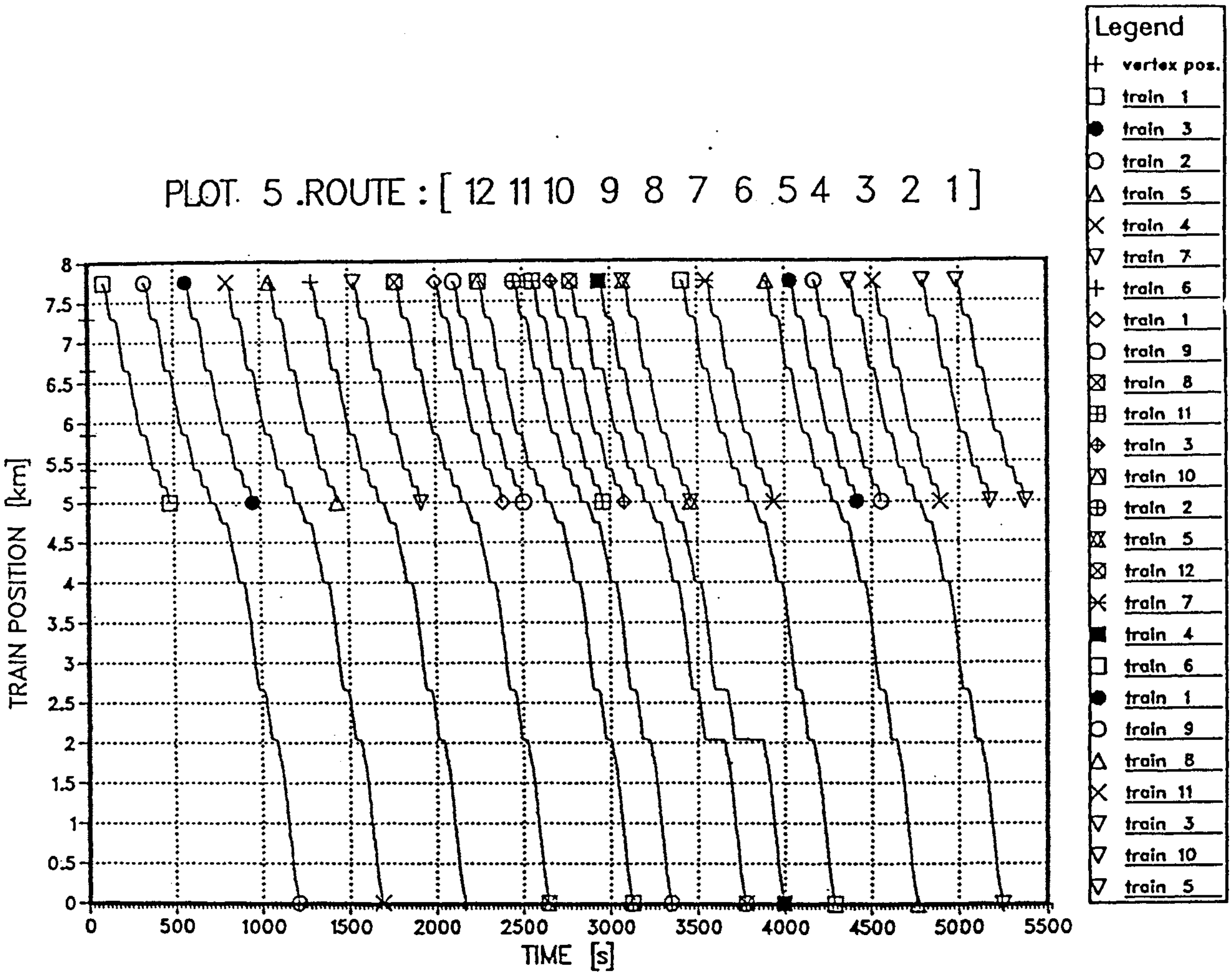
cont...

SIMULATION RESULTS:LIST OF CONFLICTS

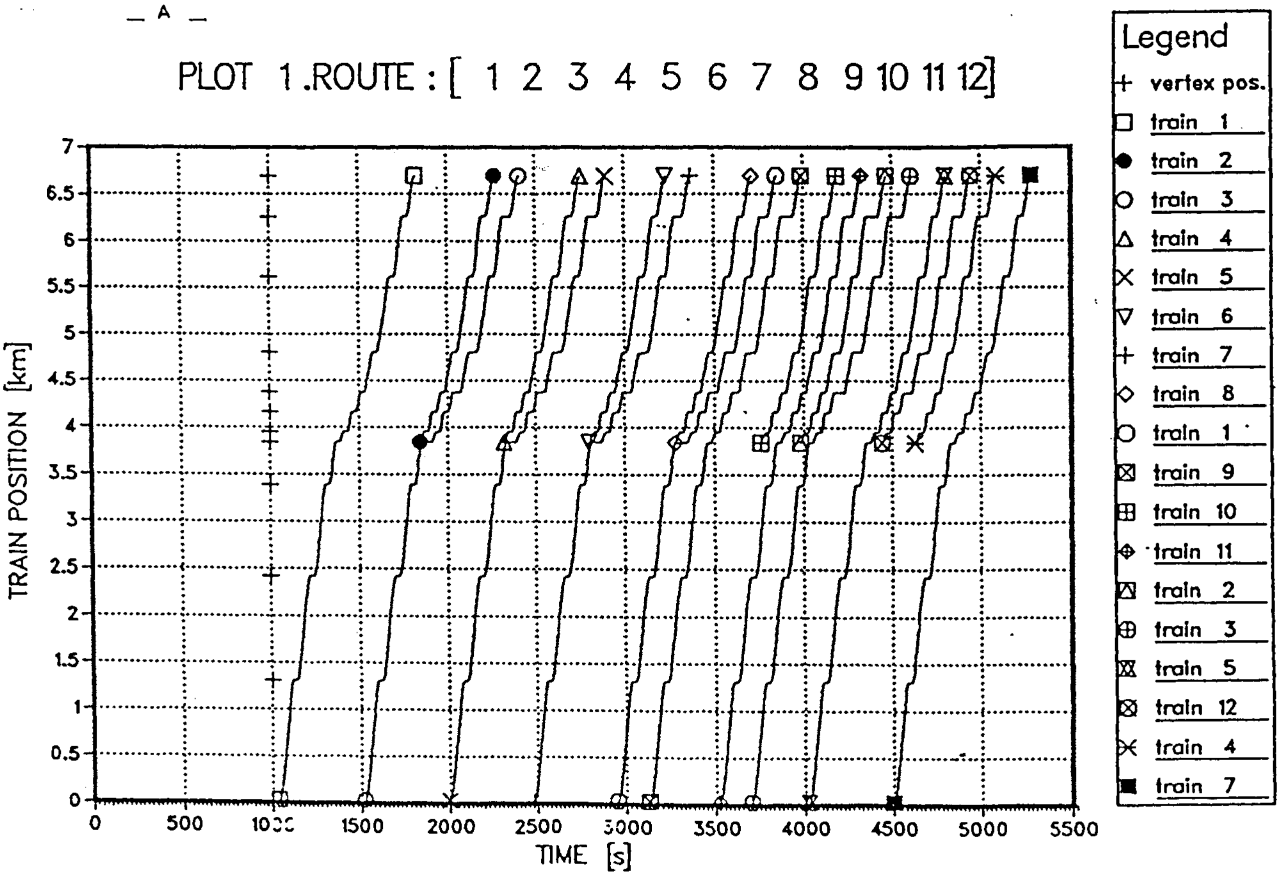
```
T= 1810  TRAIN NO.  3[1] STOPPED BY TRACK CIRCUIT CODE  2_ 4 !!!
T= 1969  TRAIN NO.  3[1] STOPPED BY TRACK CIRCUIT CODE  1_ 6 !!!
T= 2019  TRAIN NO.  3[1] STOPPED BY TRACK CIRCUIT CODE  1_ 7 !!!
T= 2111  TRAIN NO.  3[1] STOPPED BY TRACK CIRCUIT CODE  1_ 8 !!!
T= 2231  TRAIN NO.  1[1] STOPPED BY TRACK CIRCUIT CODE  3_11 !!!
T= 2236  TRAIN NO.  4[1] STOPPED BY TRACK CIRCUIT CODE  2_13 !!!
T= 2263  TRAIN NO. 11[1] STOPPED BY TRACK CIRCUIT CODE  4_12 !!!
T= 2342  TRAIN NO. 11[1] STOPPED BY TRACK CIRCUIT CODE  3_11 !!!
T= 2390  TRAIN NO.  4[1] STOPPED BY TRACK CIRCUIT CODE  1_ 6 !!!
T= 2440  TRAIN NO.  4[1] STOPPED BY TRACK CIRCUIT CODE  1_ 7 !!!
T= 2532  TRAIN NO.  4[1] STOPPED BY TRACK CIRCUIT CODE  1_ 8 !!!
T= 2650  TRAIN NO.  7[1] STOPPED BY TRACK CIRCUIT CODE  2_ 4 !!!
T= 2651  TRAIN NO.  2[1] STOPPED BY TRACK CIRCUIT CODE  3_11 !!!
T= 2662  TRAIN NO.  6[1] STOPPED BY TRACK CIRCUIT CODE  2_13 !!!
T= 2683  TRAIN NO.  3[1] STOPPED BY TRACK CIRCUIT CODE  4_12 !!!
T= 2762  TRAIN NO.  3[1] STOPPED BY TRACK CIRCUIT CODE  3_11 !!!
T= 2815  TRAIN NO.  6[1] STOPPED BY TRACK CIRCUIT CODE  1_ 6 !!!
T= 2865  TRAIN NO.  6[1] STOPPED BY TRACK CIRCUIT CODE  1_ 7 !!!
T= 2899  TRAIN NO. 11[1] STOPPED BY TRACK CIRCUIT CODE  3_ 3 !!!
T= 2957  TRAIN NO.  6[1] STOPPED BY TRACK CIRCUIT CODE  1_ 8 !!!
T= 3070  TRAIN NO.  9[1] STOPPED BY TRACK CIRCUIT CODE  2_ 4 !!!
T= 3088  TRAIN NO.  8[1] STOPPED BY TRACK CIRCUIT CODE  2_13 !!!
T= 3092  TRAIN NO.  2[1] STOPPED BY TRACK CIRCUIT CODE  3_13 !!!
T= 3234  TRAIN NO.  8[1] STOPPED BY TRACK CIRCUIT CODE  1_ 6 !!!
T= 3284  TRAIN NO.  8[1] STOPPED BY TRACK CIRCUIT CODE  1_ 7 !!!
T= 3376  TRAIN NO.  8[1] STOPPED BY TRACK CIRCUIT CODE  1_ 8 !!!
T= 3674  TRAIN NO. 11[1] STOPPED BY TRACK CIRCUIT CODE  1_ 6 !!!
T= 3722  TRAIN NO. 10[1] STOPPED BY TRACK CIRCUIT CODE  1_ 8 !!!
T= 3723  TRAIN NO. 11[1] STOPPED BY TRACK CIRCUIT CODE  1_ 7 !!!
T= 3822  TRAIN NO. 11[1] STOPPED BY TRACK CIRCUIT CODE  1_ 8 !!!
T= 3943  TRAIN NO.  3[1] STOPPED BY TRACK CIRCUIT CODE  2_ 4 !!!
T= 4100  TRAIN NO.  3[1] STOPPED BY TRACK CIRCUIT CODE  1_ 6 !!!
T= 4150  TRAIN NO.  3[1] STOPPED BY TRACK CIRCUIT CODE  1_ 7 !!!
T= 4162  TRAIN NO.  2[1] STOPPED BY TRACK CIRCUIT CODE  2_13 !!!
T= 4242  TRAIN NO.  3[1] STOPPED BY TRACK CIRCUIT CODE  1_ 8 !!!
T= 4280  TRAIN NO.  5[1] STOPPED BY TRACK CIRCUIT CODE  1_ 7 !!!
T= 4301  TRAIN NO.  2[1] STOPPED BY TRACK CIRCUIT CODE  1_ 6 !!!
T= 4361  TRAIN NO.  5[1] STOPPED BY TRACK CIRCUIT CODE  1_ 8 !!!
T= 4363  TRAIN NO.  2[1] STOPPED BY TRACK CIRCUIT CODE  1_ 7 !!!
T= 4481  TRAIN NO.  2[1] STOPPED BY TRACK CIRCUIT CODE  1_ 8 !!!
T= 4485  TRAIN NO.  5[1] STOPPED BY TRACK CIRCUIT CODE  1_ 9 !!!
T= 4566  TRAIN NO.  7[1] STOPPED BY TRACK CIRCUIT CODE  2_ 4 !!!
T= 4588  TRAIN NO.  4[1] STOPPED BY TRACK CIRCUIT CODE  2_13 !!!
T= 4610  TRAIN NO.  2[1] STOPPED BY TRACK CIRCUIT CODE  1_ 9 !!!
T= 4731  TRAIN NO.  4[1] STOPPED BY TRACK CIRCUIT CODE  1_ 6 !!!
T= 4781  TRAIN NO.  4[1] STOPPED BY TRACK CIRCUIT CODE  1_ 7 !!!
T= 4873  TRAIN NO.  4[1] STOPPED BY TRACK CIRCUIT CODE  1_ 8 !!!
T= 5014  TRAIN NO.  6[1] STOPPED BY TRACK CIRCUIT CODE  2_13 !!!
T= 5145  TRAIN NO.  6[1] STOPPED BY TRACK CIRCUIT CODE  1_ 6 !!!
T= 5195  TRAIN NO.  6[1] STOPPED BY TRACK CIRCUIT CODE  1_ 7 !!!
T= 5287  TRAIN NO.  6[1] STOPPED BY TRACK CIRCUIT CODE  1_ 8 !!!
```

FIGURE 7.4 _ DLR TRAIN TIMING DIAGRAMS, SPEED VERSUS DISTANCE PLOTS AND THE LOG OF CONFLICTS FOR 210 s HEADWAY TIME

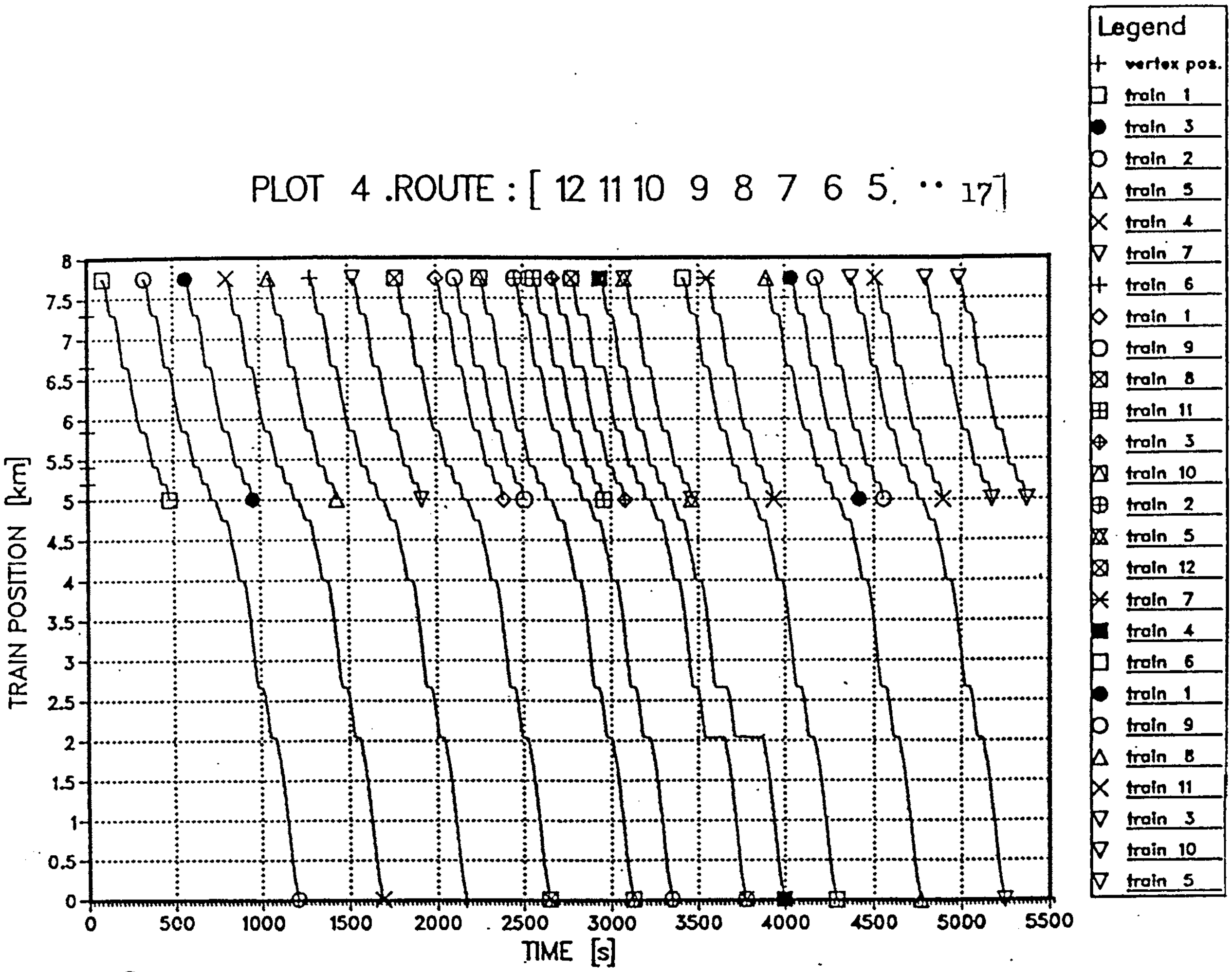
A _ ROUTE 12...17 B _ ROUTE 17...12
C _ ROUTE 1...12 D _ ROUTE 12....1
E _ ROUTE 1...12 AND ROUTE 12....1
F _ SPEED VERSUS DISTANCE PLOTS FOR TRAIN 1 ROUTES 1...12 AND 12...1
G _ ROUTE 1...12 THE JUNCTION AREA
H _ ROUTE 12....1 THE JUNCTION AREA
I _ THE LOG OF CONFLICTS


PLOT 5 .ROUTE : [12 11 10 9 8 7 6 5 4 3 2 1]
TRAIN POSITION [km]
TIME [s]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
7.5
8
Legend
vertex pos.
train 1
train 3
train 2
train 5
train 4
train 7
train 6
train 1
train 9
train 8
train 11
train 3
train 10
train 2
train 5
train 12
train 7
train 4
train 6
train 1
train 9
train 8
train 11
train 3
train 10
train 5

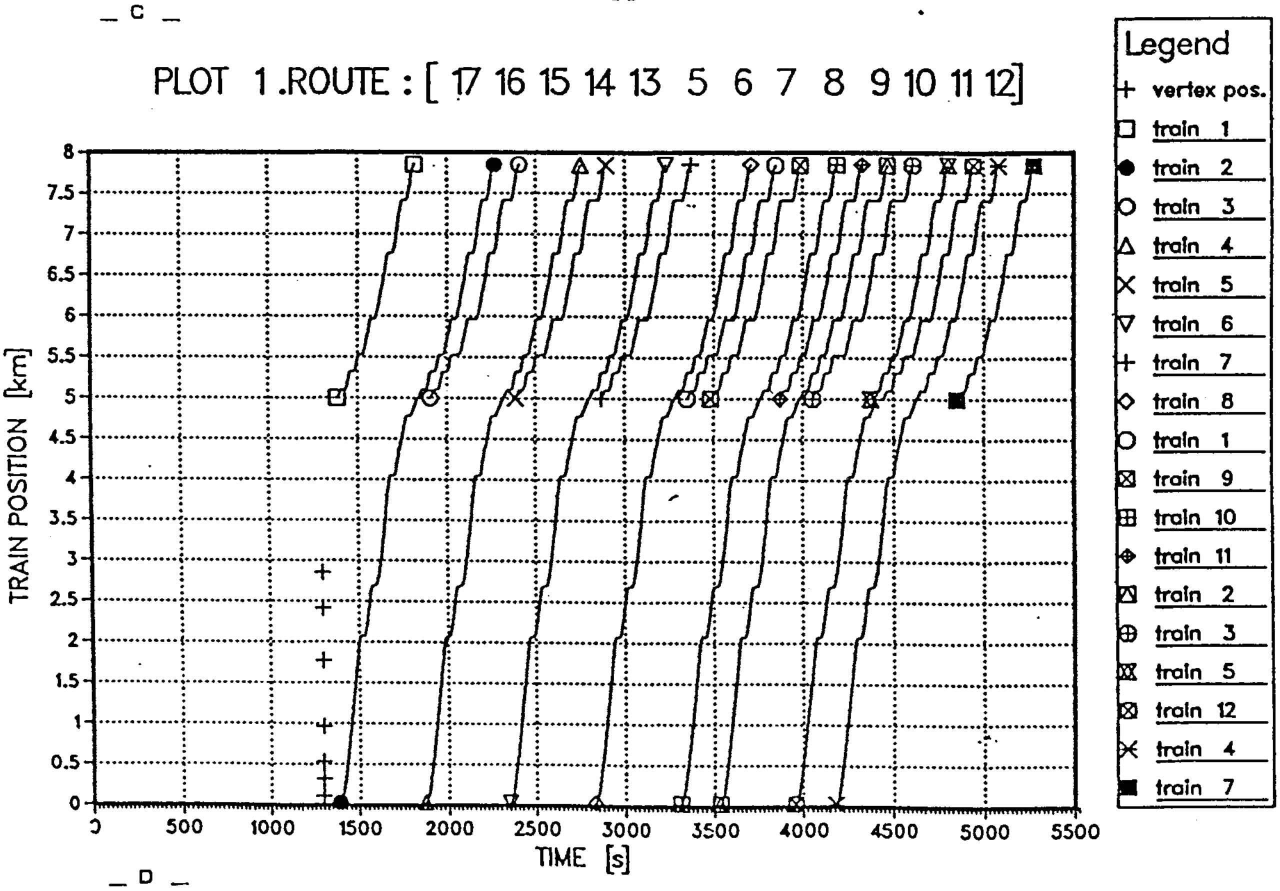
— A —


PLOT 1 .ROUTE : [1 2 3 4 5 6 7 8 9 10 11 12]
TRAIN POSITION [km]
TIME [s]
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
5500
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
Legend
vertex pos.
train 1
train 2
train 3
train 4
train 5
train 6
train 7
train 8
train 1
train 9
train 10
train 11
train 2
train 3
train 5
train 12
train 4
train 7

— B —



_ C _



_ D _

FIGURE 7.5 _ DLR TRAIN TIMING DIAGRAMS FOR 240 s HEADWAY TIME
A _ ROUTE 12...17 B _ ROUTE 17...12
C _ ROUTE 1...12 D _ ROUTE 12....1

area, distance versus speed plots for trains 1 and 2 and a log of the train conflicts that occurred, and were resolved, when the headway time was set to 210 seconds are shown in Figure 7.4. From these results it has been concluded that two alternating fixed headway times for routes 1 and 2 and 3 and 4 should cause less disturbance in the system. It can also be observed that the single track line sections, especially the one between Mudchute (vertex 11) and Island Gardens (vertex 12), are the other major areas of conflict besides the delta junction (vertices 5 and 6).

Incidentally, a major junction conflict occurred when the fixed headway time was increased to 240 seconds. The train timing diagrams for this case are given in Figure 7.5. These results demonstrate that, contrary to what one would expect, a system with greater reserve capacity can be less stable. It shows that in a rail network, train dispatch policies must be planned differently compared to a single line system with no junctions. If the dispatching is done carefully, implementation of sophisticated realtime control strategies should not be necessary for this type of automated rail transit systems.

7.3 WATERLOO & CITY LINE SIMULATION

7.3.1 Modelling Approach

A project is under progress to re-lay the tracks and to resignal this line. Eventually the line will be transformed to a fully automated rail system with headway time down to 60 seconds [106]. Keeping this development in mind the signalling and interlocking system has not been modelled as it exists, but imaginary track circuits around 150m in length have been used, except at the crossover where they are around 25m and from Waterloo Station to the line end where they are around 100m in length. The simplified new rail network and the given routes are shown in Figure 7.6a and Figure 7.6b. Each bidirectional platform of Bank Station is modelled as an individual vertex and called as Bank-A and Bank-B.

Since all four possible routes are known in advance a route approach is adopted for the rail network representation. The resulting representation is shown diagrammatically in Figure 7.6c. In this representation each line section between the vertices is defined independently with its track circuit layout and track data. In the resulting representation all track circuits except one are shared by two or three different routes. To cope with this situation interdependencies are created between physically identical track circuits such that these separately represented track circuits can be occupied and released simultaneously. This approach required only 4 vertices and 3 line section whereas the usual alternative model (i.e. the model that represents all the points as vertices, point approach) which is also shown in Figure 7.6d would have required 11 vertices and 13 line sections to achieve the same level of detail in its representation.

In addition to the interdependencies between identical track circuits another set of interdependencies has been created between the short track circuits of the crossover area and their adjacent ones so that automatic signal setting methods would be valid without modifications.

To avoid any conflicts that this route modelling might create (e.g., a train on route B that passes via the crossover might not be detected by a train on route A which is about to enter to the same track circuit) and to

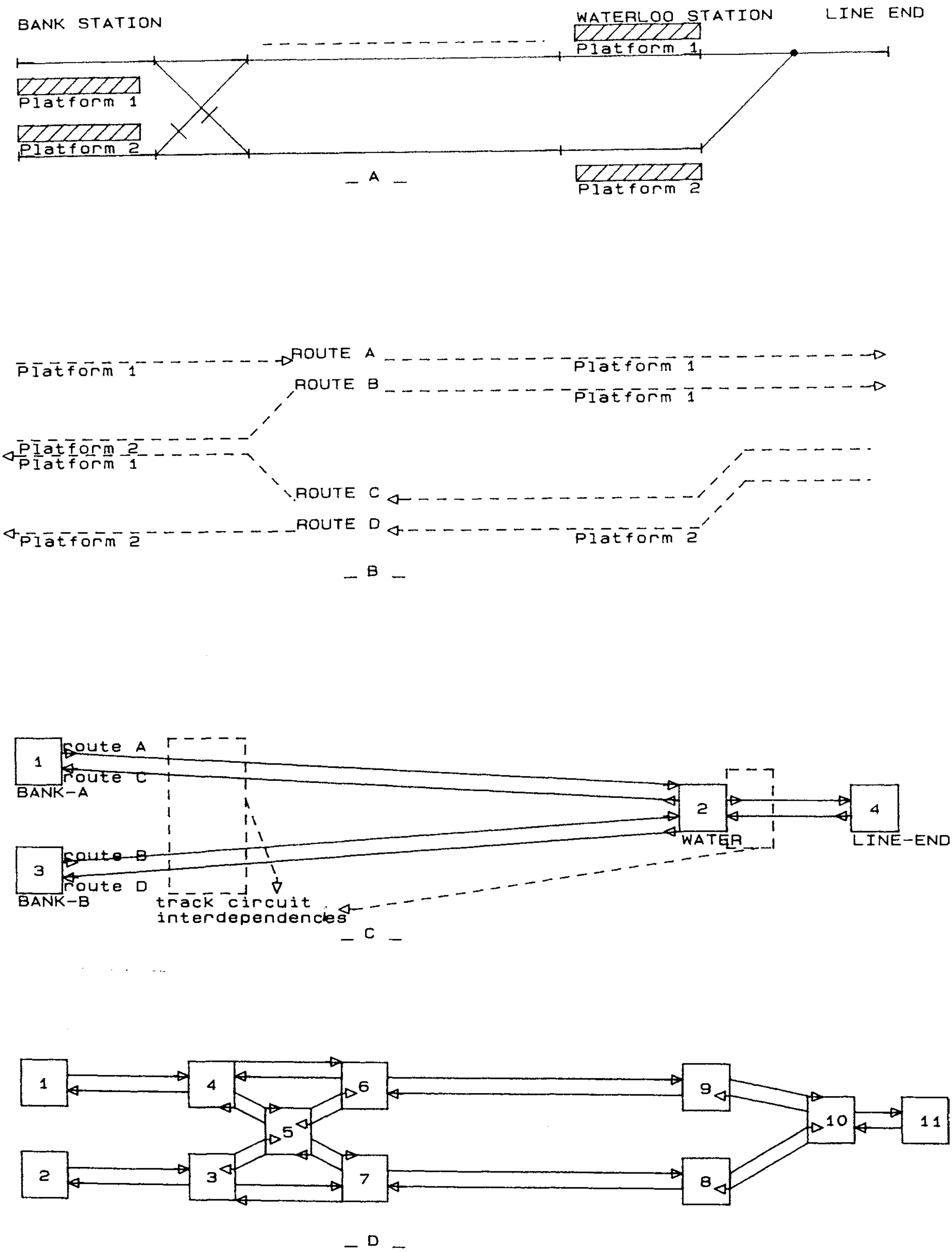


FIGURE 7.6 _ RAIL NETWORK AND ITS REPRESENTATIONS
A _ SIMPLIFIED TRACK DIAGRAM OF THE NETWORK
B _ POSSIBLE TRAIN ROUTES
C _ THE ROUTE APPROACH MODEL
D _ THE POINT APPROACH MODEL

resolve the conflicts that will occur at the crossover which is not modelled by vertices, a new set of methods has been designed. These methods book (or reserve) a sufficient number of track circuits ahead of a train. The booked track circuits can be occupied and released only by the train they are reserved for. These new methods, which are integrated with the automatic signal setting methods described in Chapter 6, have also proved to be adequate to resolve conflicts in a first-come first-served manner at the conflict area.

The signalling system can then be modelled as a conventional 3 aspect fixed-block scheme, the restrictive speed being equal to the maximum line speed. The program actions to regulate the train movements would be :

1. Set the next signal aspect to 'stop' at the end of the current signal block.

2. a. Check the appropriate signal block (or track circuit) ahead of the train starting from the adjacent one. Two track circuits and their interdependencies are checked for 3 aspect signalling.

   b. Check also the interdependencies between this and other signal blocks.

   c. If the checked track circuit is not occupied or booked then book this track circuit by adding it to the newly created booked track circuit list.

3. Repeat Step 2 by reducing the severity of the aspect and by moving to the next signal block ahead until the least restrictive 'proceed' aspect or an occupied or booked track circuit is reached.

4. Set the new signal aspect.

5. Move the train to the end of the track circuit.

7.3.2 Waterloo & City Line Simulation Runs

Train routes were given as :

Route A. From BANK-A (vertex 1) to LINE END (vertex 4) direct

Route B. From BANK-B (vertex 3) to LINE END (vertex 4) via crossover

Route C. From LINE END (vertex 4) to BANK-A (vertex 1) via crossover

Route D. From LINE END (vertex 4) to BANK-B (vertex 3) direct

Ten trains entered to and exited from the line end i.e. vertex 4. The train route sequence was :

Odd trains : Route A and Route C.

Even trains : Route B and Route D.

Crossover movement sequence was :

Train 1 to Bank Station-A, Train 2 to Bank Station-B, Train 1 to Waterloo, Train 3 to Bank Station-A, Train 4 to Waterloo etc.

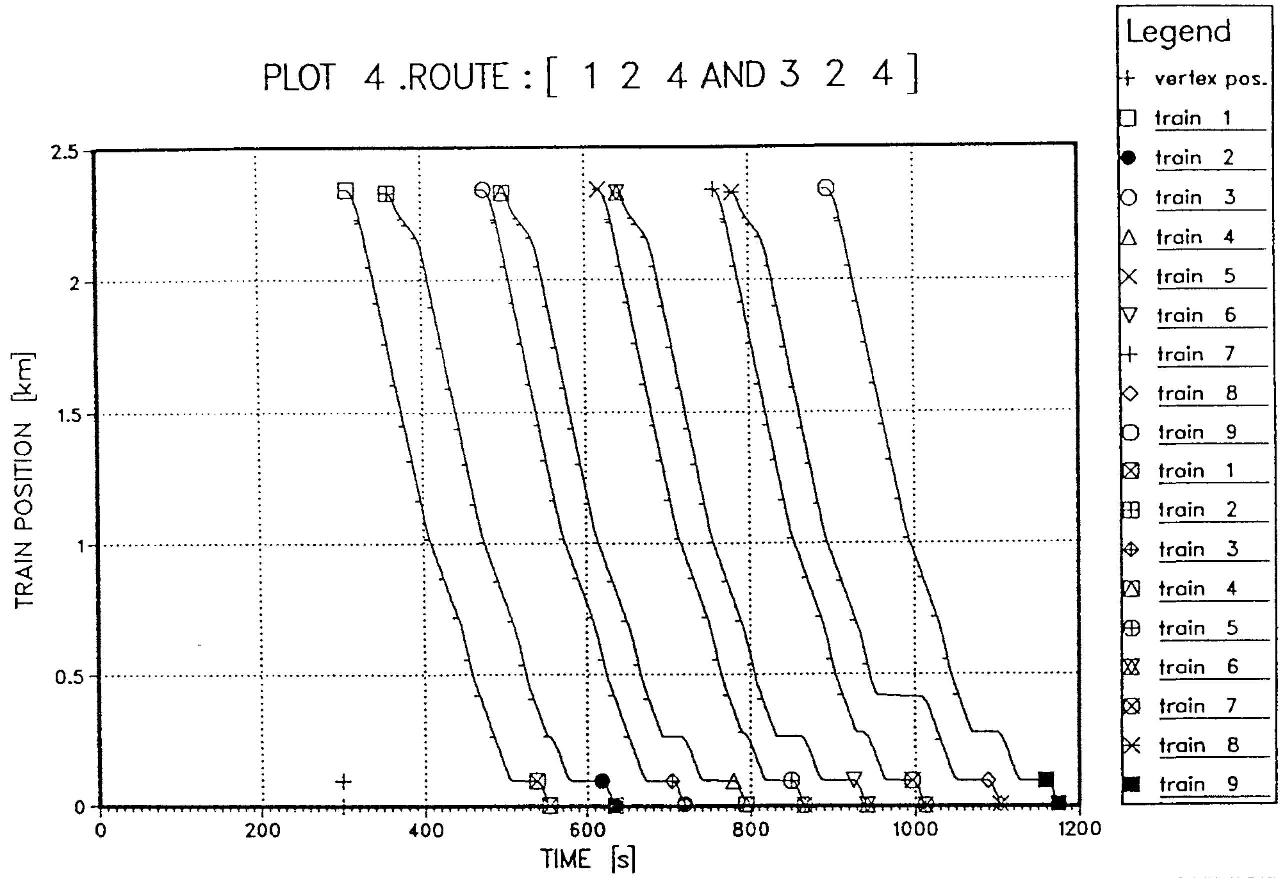
Routes A and B and, Routes C and D share the same tracks sections except the crossover and Bank Station platforms therefore, these routes were plotted on the same train timing diagrams. Plots for 70s, 90s, and 110s fixed headway times are given in Figures 7.7, 7.8, 7.9, respectively. Tags on the train runcurves indicates the times signal block changes are noticed by the trains. The experiments show that this line can support regular 70 s headway time operating practice under the conventional 3-aspect signalling scheme as modelled in this study. This is due to the almost identical track geometry and signal layout of short train routes and the simple train operations which involve only 2 stations.

7.4 CONCLUSIONS

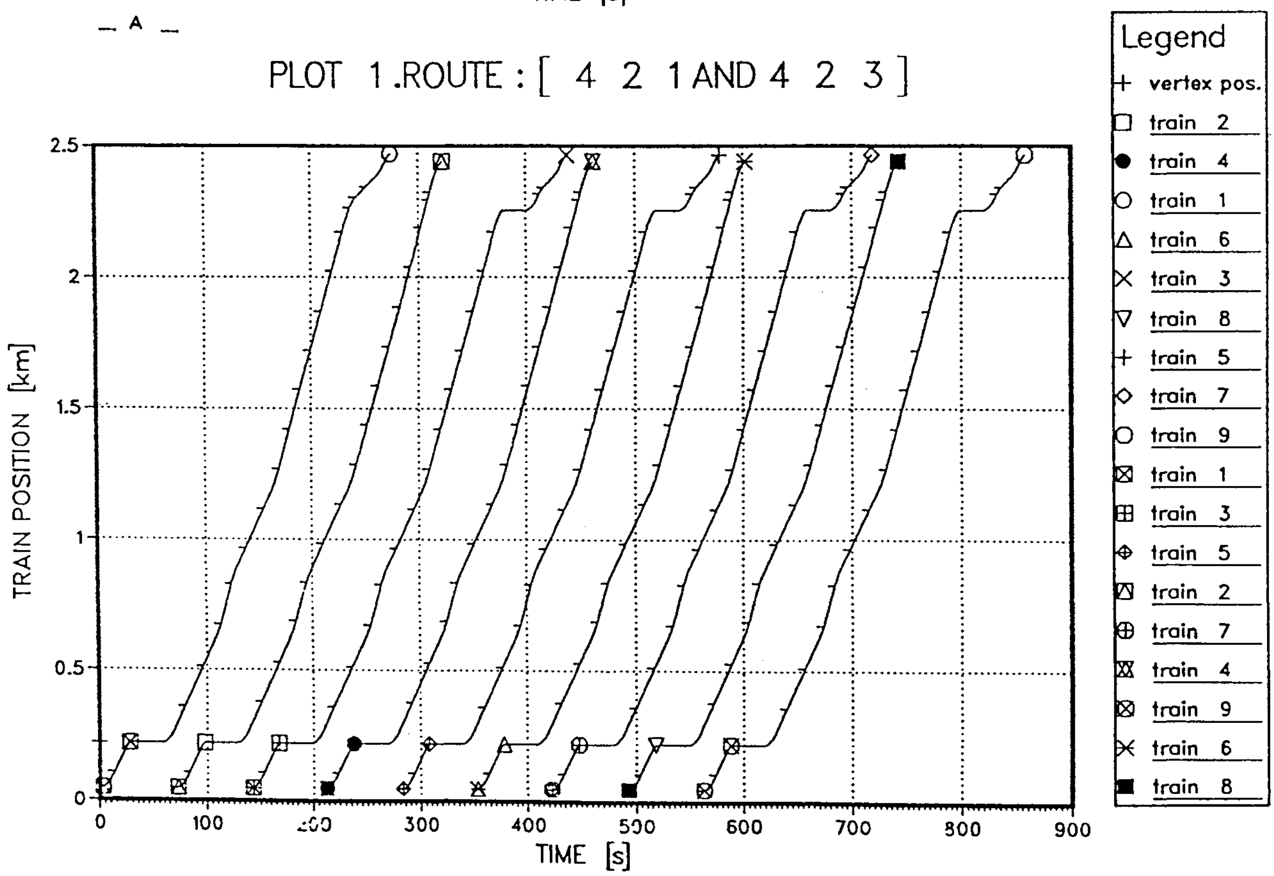
In this chapter, some of the capabilities of the simulation model in modelling different rail networks and signalling schemes have been demonstrated by modelling two small scale systems : The Dockland Light Rail System (DLR) and Waterloo & City Line.

Although the DLR is an unconventional transit system in the sense of its traffic regulation installations, it has been possible to model these features with the traffic regulation and train movement methods of the simulation model after some slight modifications. The most important of these modifications has been the introduction of a signal block/ track circuit interdependency concept. This concept has been successfully used to model both the station-to-station block signalling scheme and the single track operations of the trains. Three sets of simulation runs have been carried out with three different fixed headway times. During the simulation runs it has become apparent that a rail network with greater reserve capacity can become less stable than a tightly scheduled one when the dispatching is not done by using a variable headway time.

The simulation model has been further tested by modelling the terminus turnaround and crossover situations on the Waterloo & City Line. The interdependency concept has been extended to develop an alternative representation of the network which achieves the same level of detail in network representation by using 4 vertices whereas the usual modelling approach would have required 11 vertices. Based on this representation, a 3-aspect fixed block signalling has been modelled by using existing traffic regulation methods.



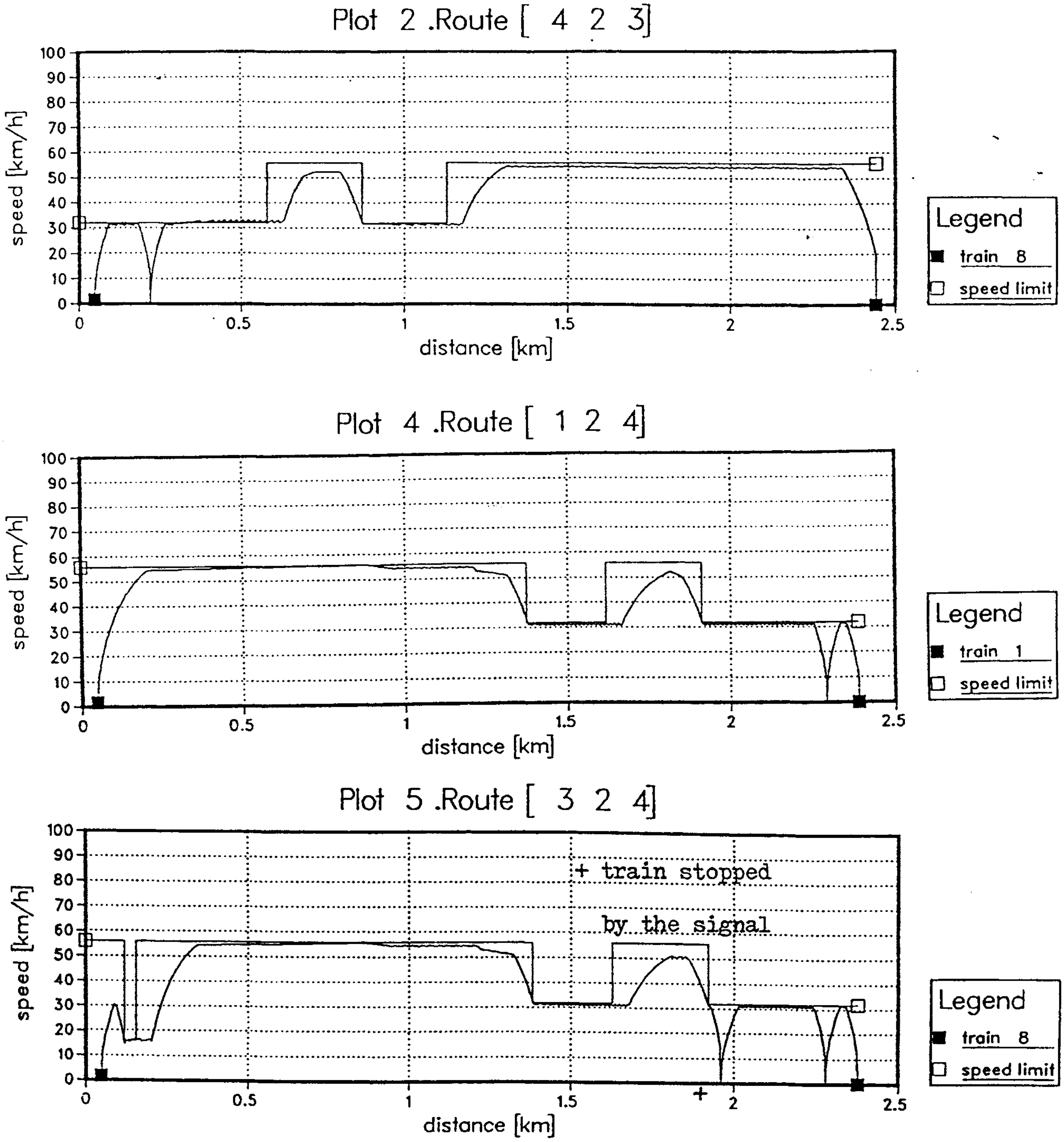
_ A _



_ B _

cont...

A _ TRAIN TIMING DIAGRAM FOR THE ROUTES 1, 2, 4 AND 3, 2, 4
B _ TRAIN TIMING DIAGRAM FOR THE ROUTES 4, 2, 1 AND 4, 2, 3



_ C _ Speed vs.distance plots for trains 8 and 1.

T=	378	TRAIN NO.	3[1]	! STOPPED BY TRACK CIRCUIT CODE 14_ 2 ^ 1[32]
T=	518	TRAIN NO.	5[1]	! STOPPED BY TRACK CIRCUIT CODE 14_ 2 ^ 1[32]
T=	658	TRAIN NO.	7[1]	! STOPPED BY TRACK CIRCUIT CODE 14_ 2 ^ 1[32]
T=	692	TRAIN NO.	4[1]	! STOPPED BY TRACK CIRCUIT CODE 16_ 3 ^ 2[17]
T=	832	TRAIN NO.	6[1]	! STOPPED BY TRACK CIRCUIT CODE 16_ 3 ^ 2[17]
T=	930	TRAIN NO.	7[1]	! STOPPED BY TRACK CIRCUIT CODE 15_ 1 ^ 2[17]
T=	955	TRAIN NO.	8[1]	! STOPPED BY TRACK CIRCUIT CODE 15_ 3 ^ 2[16]

_ D _

FIGURE 7.7 _ TRAIN TIMING DIAGRAMS, SPEED VERSUS DISTANCE PLOTS AND LOG OF TRAIN CONFLICTS FOR 70 s HEADWAY TIME
A _ TRAIN TIMING DIAGRAM FOR THE ROUTES 1, 2, 4 AND 3, 2, 4
B _ TRAIN TIMING DIAGRAM FOR THE ROUTES 4, 2, 1 AND 4, 2, 3
C _ SPEED VERSUS DISTANCE PLOTS FOR TRAINS 8 AND 1
D _ THE LOG OF CONFLICTING TRAIN MOVEMENTS

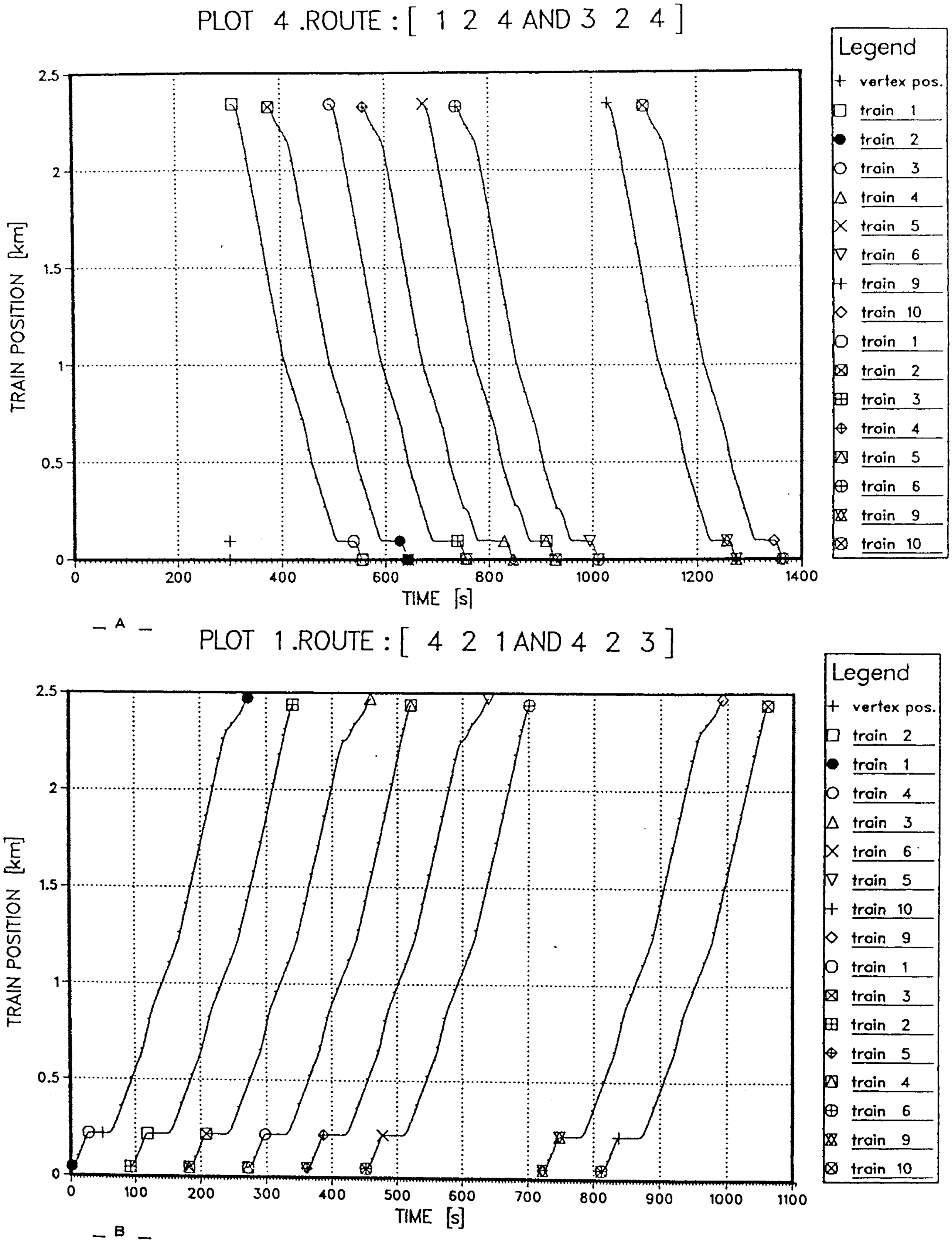
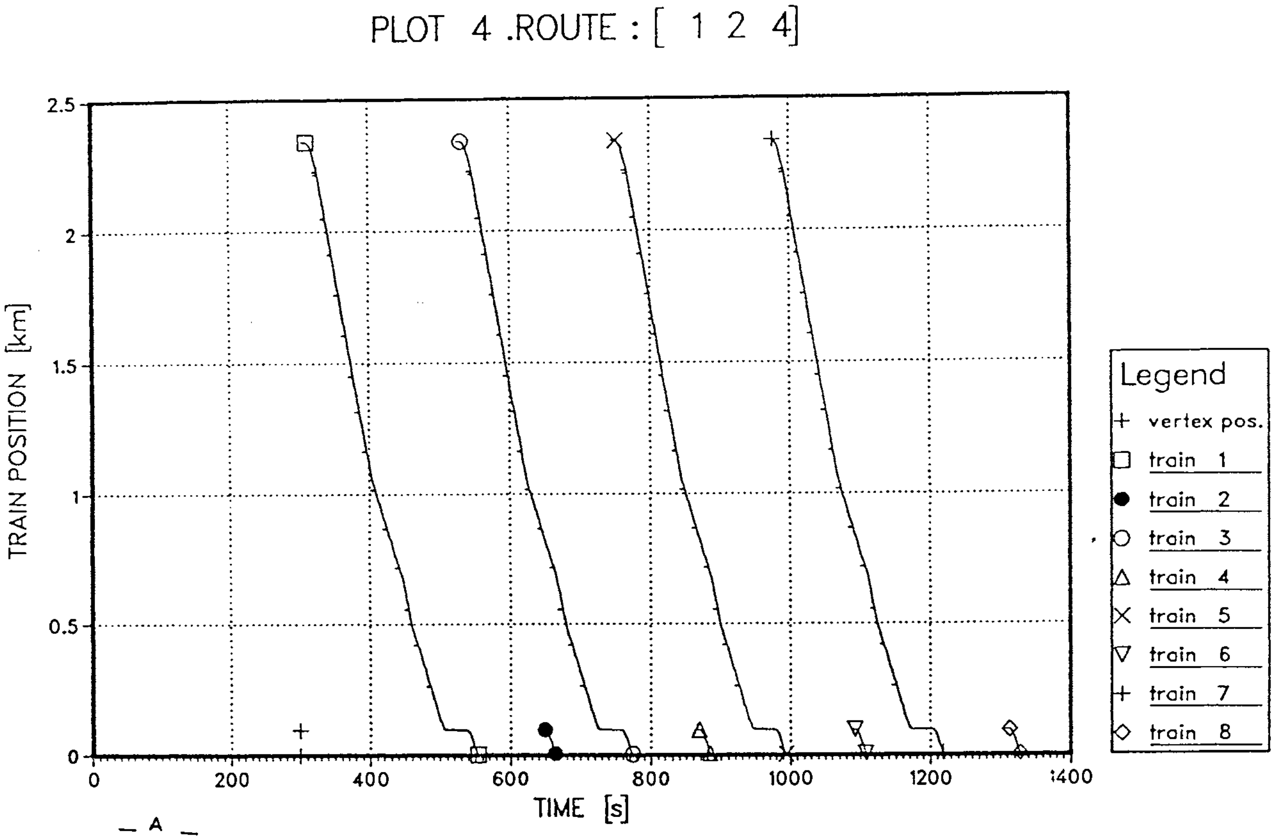


FIGURE 7.8 _ TRAIN TIMING DIAGRAMS FOR 90 s HEADWAY TIME
A _ TRAIN TIMING DIAGRAM FOR THE ROUTES 1, 2, 4 AND 3, 2, 4
B _ TRAIN TIMING DIAGRAM FOR THE ROUTES 4, 2, 1 AND 4, 2, 3



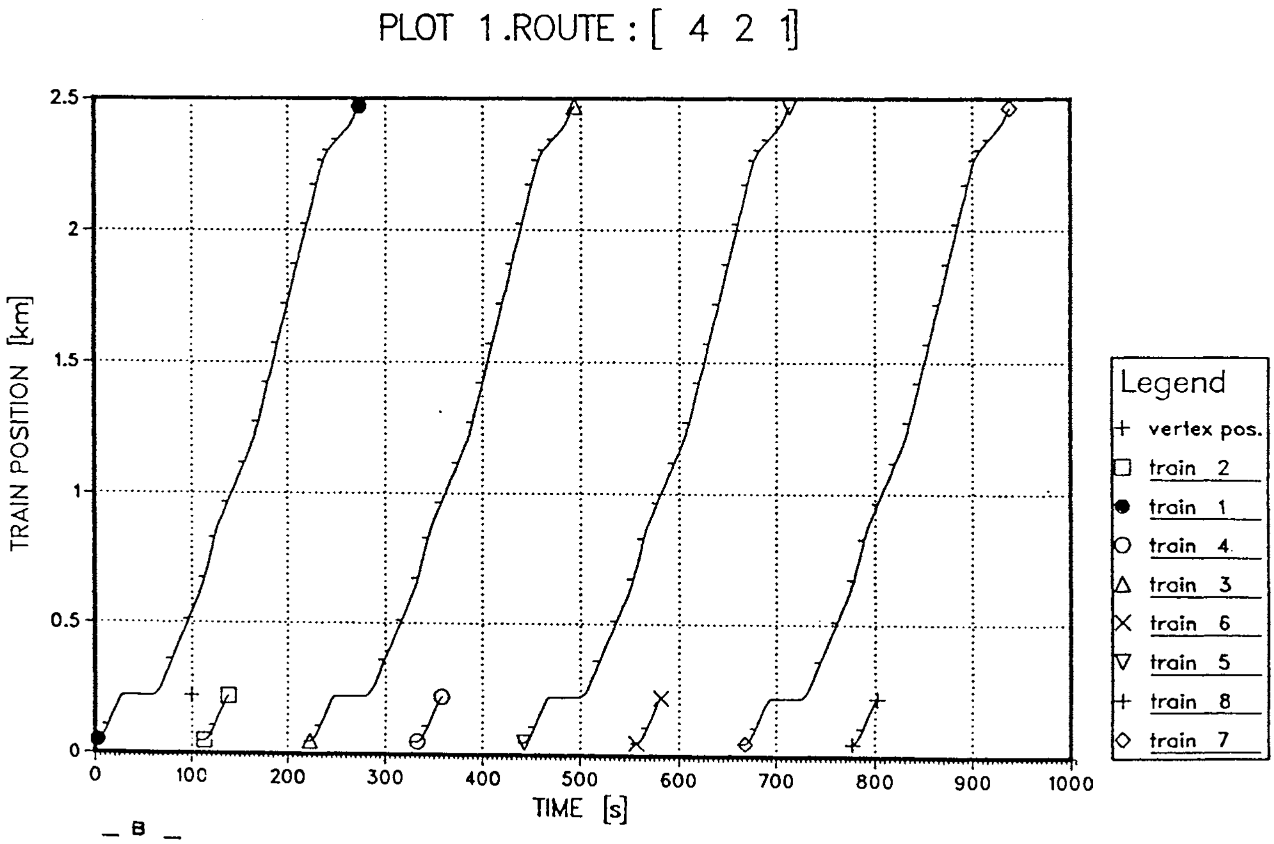


FIGURE 7.9 _ TRAIN TIMING DIAGRAMS FOR 110 s HEADWAY TIME
A _ TRAIN TIMING DIAGRAM FOR THE ROUTE 1, 2, 4
B _ TRAIN TIMING DIAGRAM FOR THE ROUTE 4, 2, 1

CHAPTER 8

MAXIMUM ENERGY DEMAND PREDICTION AND CONTROL

8.1 INTRODUCTION

Queensland Railways of Australia (QR) has electrified its Central Queensland network servicing the mines west of Rockhampton and Mackay (Figure 8.1). Both Blackwater (Stage 1) and Goonyella (Stage 2) systems were commissioned in 1987 and were operating with a fully electric locomotive fleet by early 1989. The Blackwater system is a mixed traffic line which also services mines approximately 250 km inland and hauls coal from the mines to power stations and export facilities on the coast. The Goonyella system is a purpose built railway designed for handling coal from the mines which are approximately 200 km inland from the ports. In total, there are 800 route-km servicing 16 mines.

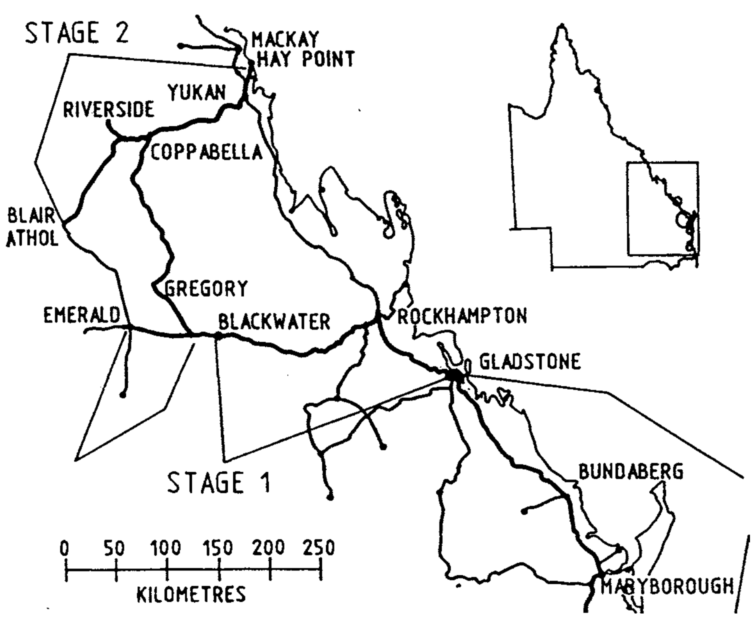


FIGURE 8.1 _ CENTRAL DIVISION OF QUEENSLAND RAIL NETWORK.

Trains on both systems consist of two 4000 kW locomotives in the front and two or three locomotives in the middle. Train loads are 7000-10000 tonnes in the Blackwater system and 6000-7000 tonnes in the Goonyella system. Train lengths are 1500-2000 m. At present, the combined annual tonnage of coal hauled is 53 x 10^6 tonnes which converts to 25.1 x 10^9 km each year.

This traffic task annually consumes 202 x 10^6 kWh for the Goonyella system and 161 x 10^6 kWh for the Blackwater system. Power is provided from a 132 kV distribution system to 13 substations spaced approximately 70 km apart. The power feeding system is the 50 kV (25-0-25) autotransformer scheme [107].

The existing electricity tariff provides a two part structure which offers substantial benefits for a high load factor (i.e. ratio of daily average demand to peak half-hour demand). Considering this level of consumption, it became obvious to QR that minimising the upper limit of the maximum half hour demand for the total system (i.e. Stage 1 and Stage 2) could reduce electricity costs substantially [108]. Because of the great fluctuations which occur in maximum half-hour demand, and the proportion of monthly electricity costs attributable to the demand, the study has concentrated upon the methods of predicting and controlling half-hour demands as a means of reducing electricity costs. Optimisation of total energy consumption is also recognised for its potential savings and has been considered in this study with the expectation that any realtime demand control system implemented would inherently provide the infrastructure for energy minimisation control e.g. by providing continuing movement of trains or by optimising train driving techniques.

In order to estimate future energy demand patterns and to investigate the basic load shifting strategies to reduce and control maximum half-hour demands, it has been decided that the whole of the Central Queensland rail network should be simulated. This study demonstrated that the model is structurally suitable for detailed large scale simulation studies.

8.2 QR RAIL NETWORK STRUCTURE

Most of the track to be represented for Stage 1 and Stage 2 consists of either single track with passing loops or bidirectionally signalled duplicated track with crossovers and passing loops. Terminals at the mines or unloaders are mostly of the balloon loop type. All structural details of the conflict areas have been modelled in full detail except two yards where no information on the movement of trains was available. The types of vertices, combinations of which represent conflict areas, have been identified as below :

Type 1 : 1-branch vertex e.g. line end, balloon loop end (loader or unloader).

Type 2 : 2-branch vertex e.g. intermediate simple single line station, balloon loop entry/exit point (EEP).

Type 3 : 3-branch vertex e.g. single line passing loop EEP, single line junction, duplicated track crossover EEP, single line duplicated unidirectional crossover EEP.

Type 4 : 4-branch vertex e.g. crossover + passing loop EEP, balloon loop + passing loop EEP, centre passing loop EEP.

With bidirectional signalling on the duplicated sections, virtually all the track can be used in either direction under normal operating conditions. Consequently, for each line section joining a pair of vertices in the model, two sets of data describing the section are required, one for each direction of travel. This is made explicit in the small samples of the network structures shown in Figure 8.2. The conflict areas of this network are modelled by 1 to 5 vertices.

Stage 1 was constructed prior to the full development of mining. Its structure suffers to some degree from its early construction when it was not realized what traffic would be operating over it. It has required 158 vertices and 222 line sections for its rail network representation. Stage 2, which was constructed specially to transport coal, is simpler in structure. It has required 77 vertices and 112 line sections in its representations.

8.3 CALCULATION OF ENERGY CONSUMPTION

The main point of interaction between the train movement calculations and the electrical calculations is the calculation of tractive effort as described in Subsection 6.2.3. With the tractive effort known, at an assumed line voltage at the locomotives, the input power can be calculated knowing the speed and efficiency.

$$P_t = T_f \, u_a \, (100 / \epsilon) \, n_l + P_a \, n_l \qquad (8.1)$$

where P_t is total electric power input to train [W],

T_f is Tractive effort output of each locomotive [N],

u_a is average train speed in an update period [m/s],

ϵ is electrical efficiency [%],

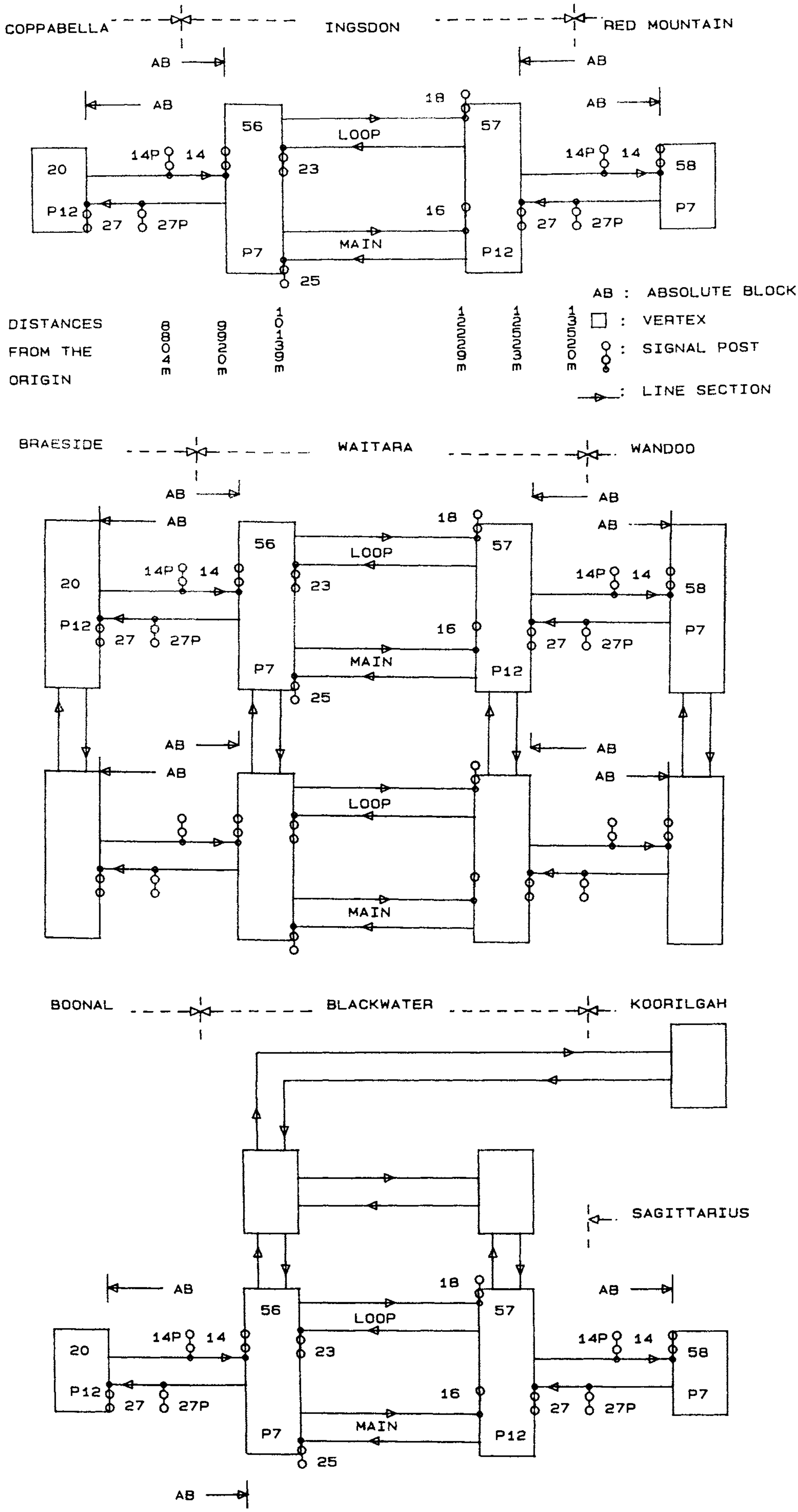


FIGURE 8.2 _ EXAMPLES OF NETWORK ELEMENTS
A _ SINGLE TRACK CROSSOVER
B _ DOUBLE TRACK CROSSOVER
C _ JUNCTION AREA

n_l is the number of active locomotives,

P_a is auxiliary load for each locomotive [W].

Once the electrical power input is calculated its energy equivalent for one simulation cycle can be allocated to a particular substation. When choosing the substation for a particular train the positions of the active locomotives are taken into account.

A new data structure, which represents the substations with a circular linked list, has been added to the model. The substation data fields of this list are detailed enough to hold half-hour energy demand averages of every train. The processing methods that transfer energy demands from run profile structures to substation structures can cope with the event-oriented features of the simulation model. At the end of each simulation run, which usually covers 24 hours of real system operations, a report and histograms of thirty minute power averages of individual and total substation loads are generated.

Although the tractive effort model is voltage sensitive between 19.5 and 27 kV, a more detailed AC railway supply model has not been linked to the simulation model mainly for the following reasons :

1. The trains do not brake regeneratively.

2. The train load is inevitably drawn from particular substations. Therefore, 30 minute average demands can be deduced by superposition.

3. During the validation tests voltage variation has not emerged as a significant factor affecting the train movements and substation loads.

4. The available power supply simulators which could be linked to the simulation model are too detailed and thus consume too much computing time

i.e., even simplified versions slow down the movement simulation by a factor of 8 whereas the energy calculation and substation assignment methods used in this study does not increase the run time greatly i.e. increase in run time is less than 30%. The processing time is important since an on-line version of the simulation model will be necessary in order to implement a realtime maximum demand control system.

8.4 SCOPE AND OBJECTIVES OF THE STUDY

The approach to the maximum energy demand prediction and control problem as a whole can be split into two parts :

1. Feasibility study for maximum demand control using the rail transit system simulation model.

2. Design and implementation of a realtime demand control system in which the rail transit system simulation model will be used for predictive energy calculations.

This chapter covers the results of the feasibility study. A realtime demand control system is also specified. The feasibility study has been carried out with the following objectives :

1. Assure the quality of the software and the credibility of the simulation model by comparing the predicted energy and load demand patterns with the measured ones.

2. Simulate the projected or hypothetical traffic patterns in order to examine and to quantify the load factor trends.

3. Examine the train running and energy demand patterns to establish the parameters which define the maximum half-hour demands.

4. Calculate the load factor changes resulting from some basic strategies of load shifting applied under the given operational constraints.

5. Evaluate the economic feasibility of implementing a real time controller.

6. Establish the possibility of being able to predict the energy demand for a given running pattern fast enough to be able to use the simulation model within a realtime control system.

7. Specify an energy demand control system.

8.5 VALIDATION OF SIMULATION MODEL

8.5.1 Integration Tests

The QR study required the implementation of new methods to model the trains and train driving techniques, and to allocate the energy drawn by locomotives to particular substations. This new code was tested thoroughly before the validation tests commenced.

The output of the tractive effort model, which is described in Subsection 6.2.3, was compared with the supplied tractive effort characteristics. The model was refined until a reasonable match was obtained and then interfaced to the simulation model.

The energy accumulation methods were tested within the simulation model by running single trains to cover all possible routes. The movement of the trains and corresponding energy consumptions were dumped to a debugging file and the half hour demands accumulated at the substations were compared with the manual calculations done on the debugging file. The multi-train situation was tested by running a number of identical trains simultaneously on identical routes.

8.5.2 Single Train Validation Tests

As a part of the validation tests, QR ran a single electric train from/to Haypoint to/from Peak Downs empty/loaded on Stage 2 system with the energy consumption being metered on the train and at the substations. This run was simulated with the objective of comparing simulated and measured results.

Table 8.1 shows the total energy consumption and where available the time taken for the run. Results from QR's own single train movement calculator are also included for comparison. It can be observed that the results show a reasonable correlation. Results on the variation of power by time were not avaiable for comparison.

SINGLE TRAIN TEST	EMPTY RUN		LOADED RUN	
	MWh	Time h: mm	MWh	Time h: mm
measurements	9.57	n/a	14.16	n/a
QR calculations	8.75	3: 20	15.09	3: 28
simulation model	9.84	3: 21	14.96	3: 22

n/a : not available

MULTI-TRAIN TEST	MEASURED	SIMULATED
load factor	0.53	0.52
average demand	13.70 MW	12.48 MW
total consumption	328.80 MWh	299.47 MWh

TABLE 8.1 _ COMPARISON OF SIMULATED AND MEASURED RESULTS

During the runs to produce these results it was noted that the energy consumption is very sensitive to train driving technique, particularly assumptions made regarding regulating the train speed to ruling speed restriction (i.e. target speed). The practical values of acceleration controller parameters that define the controlled acceleration and coast bands around the target speed resulted from this exercise. Refer to Subsection 6.4.1 for a detailed discussion of nett acceleration control methods.

8.5.3 Multi Train Validation Tests

Substation demand patterns for a particular day (referred to as the 1988 run) running to known timetables were provided by QR. A record of daily train movements was also available in the form of the train control clerk's (i.e. signalperson) diagram. Confirmation of these timings was possible by the log printed from the central train control (CTC) computer. By using this information it was possible to simulate the movements of all the electric trains which ran on that day. Independent tests were done for Stage 1 and Stage 2. The loading pattern calculated by the simulation could then be compared with the loadings recorded by the supply authority's meters.

8.5.3.1 Timing Tests

The practical results available for the 1988 run were more comprehensive than those from the single train run. Unacceptable point to point timing mismatches were observed after the initial runs. Considerable development of the driving model was carried out as described in Subsection 6.4.2 until reasonable matches (i.e. within 5 minutes of actual for the great majority of cases) could be obtained after the modifications described below :

Variations in driving technique : All the train driving information provided by QR was implemented into the acceleration controller within the tractive effort module. It was then possible to assign a maximum notch, a number of active locomotives and a dynamic speed restriction for each class of train for particular sections of the rail network. Still the model reflected an average driver behaviour, not the random diversions from it. To cope with individual driver behaviour, a time resetting feature was introduced. The trains can be pulled onto the real timings by moving them forward or backward in time at the points where timings are given.

8.5.3.2 Energy Demand Tests

Separate tests were performed and the following main reasons were identified for the mismatches :

Load shifting due to timing differences : The timing differences which were due to nonstandard driving technique caused load transfer between adjacent half-hour windows. The significance of this effect can be reduced with the time resetting feature mentioned in Subsection 8.5.3.1 if exact timings are known in advance.

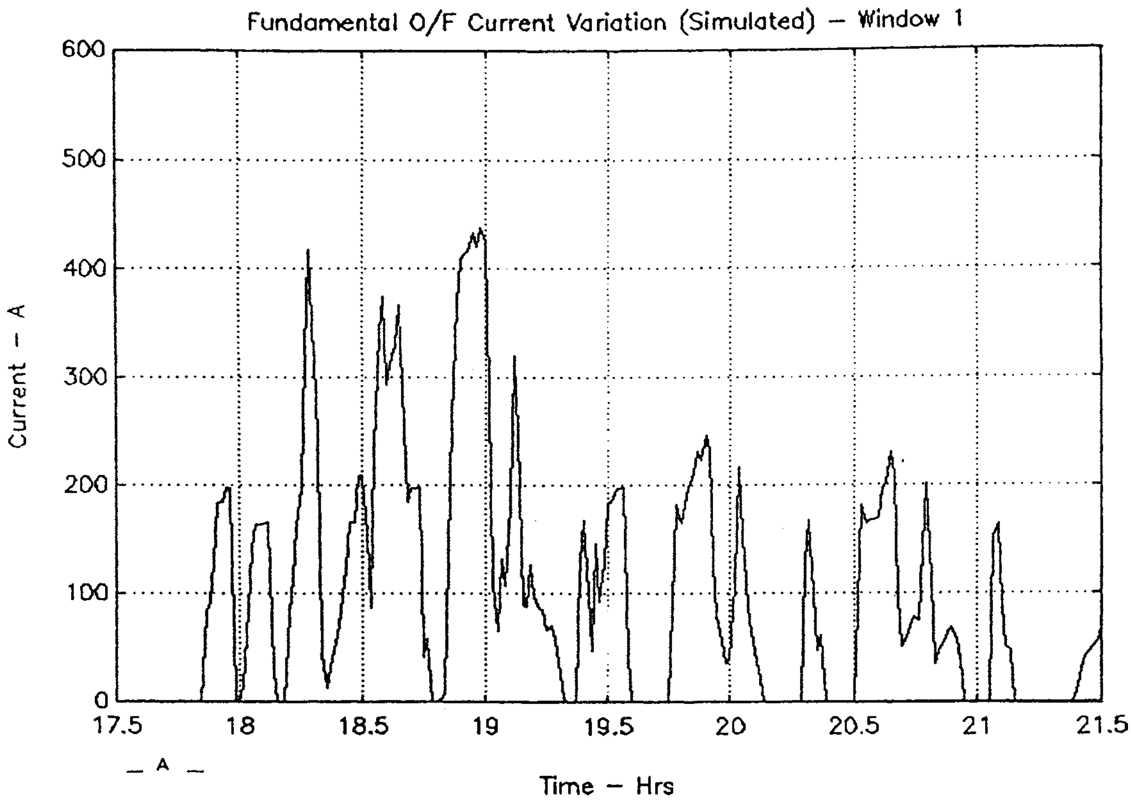
Simplification in rail network representation : The representations of the loaders, unloaders and especially the yards were simplified due to the absence of data. This explains some of the significant mismatches occurring at Oonooie substation which feeds Jilalan yard and Haypoint and Darlrymple unloaders.

Unrecorded train movements : The internal movements in the yards were not recorded in the train control clerk's timing diagrams, therefore could not be simulated. This also explains the mismatches in the Oonooie substation feeding area.

Assumptions about train parameters : Identical average parameters were used for every train of the same class, whereas such standardization does not exist in the real system. Electrical efficiency is assumed constant whereas in practice it is a function of train speed.

Assumptions about train driving technique : The inbuilt driving technique is matched to the expected (standard) behaviour of the drivers whereas it is known that individual drivers handle trains quite differently. Figure 8.3 depicts the actual train operation and the actual current demand of a specific train with the simulated operation and demand of the same train over a four-hour window. Even with the extensive effort made to match closely a 'standard' driving technique, the instantaneous demand differs. However, when considering the average of demand over a half-hour period and when several trains are involved, the variations in driving technique are smoothed out and the half-hour demand becomes predictable.

Substation switching : Between 17:00 and 21:00 approximately the Stage 2 simulation showed substantial loads on Coppabella substation but little on Peak Downs, whereas the measured values were reversed. This is due to the reason that Coppabella Substation was out of service at that time and sections usually fed by that substation were supplied by Peak Downs and Wandoo.



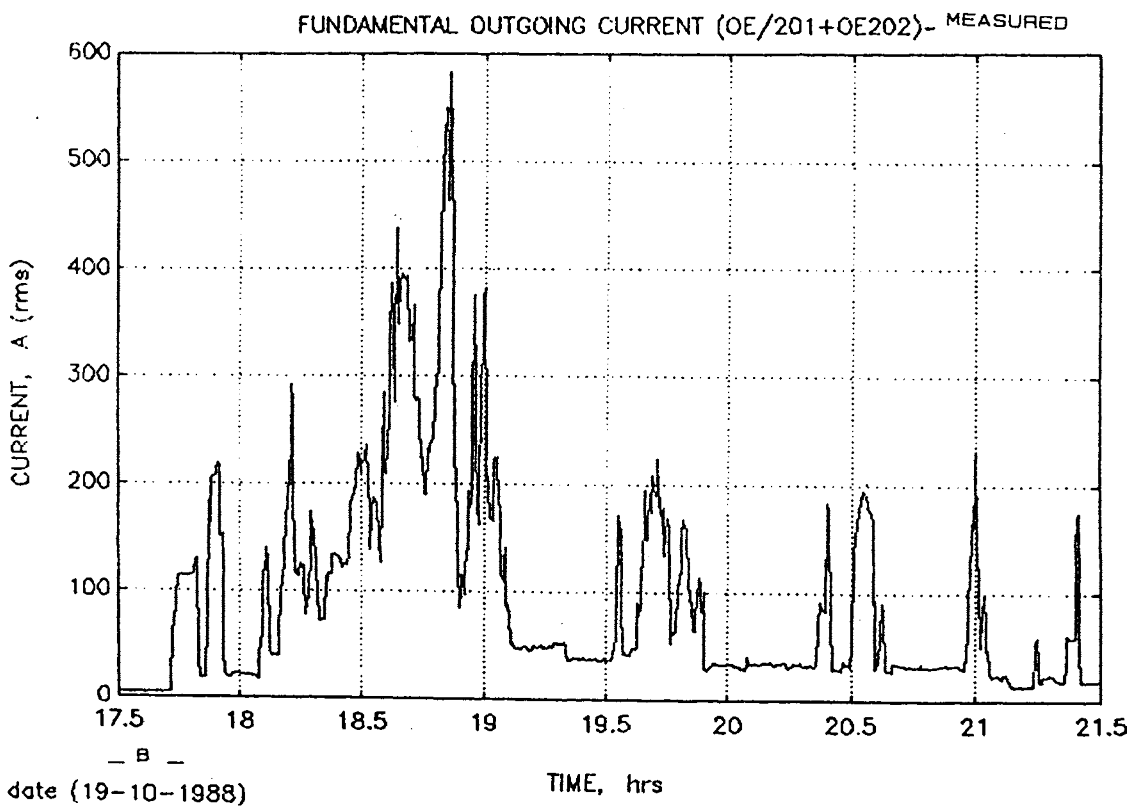


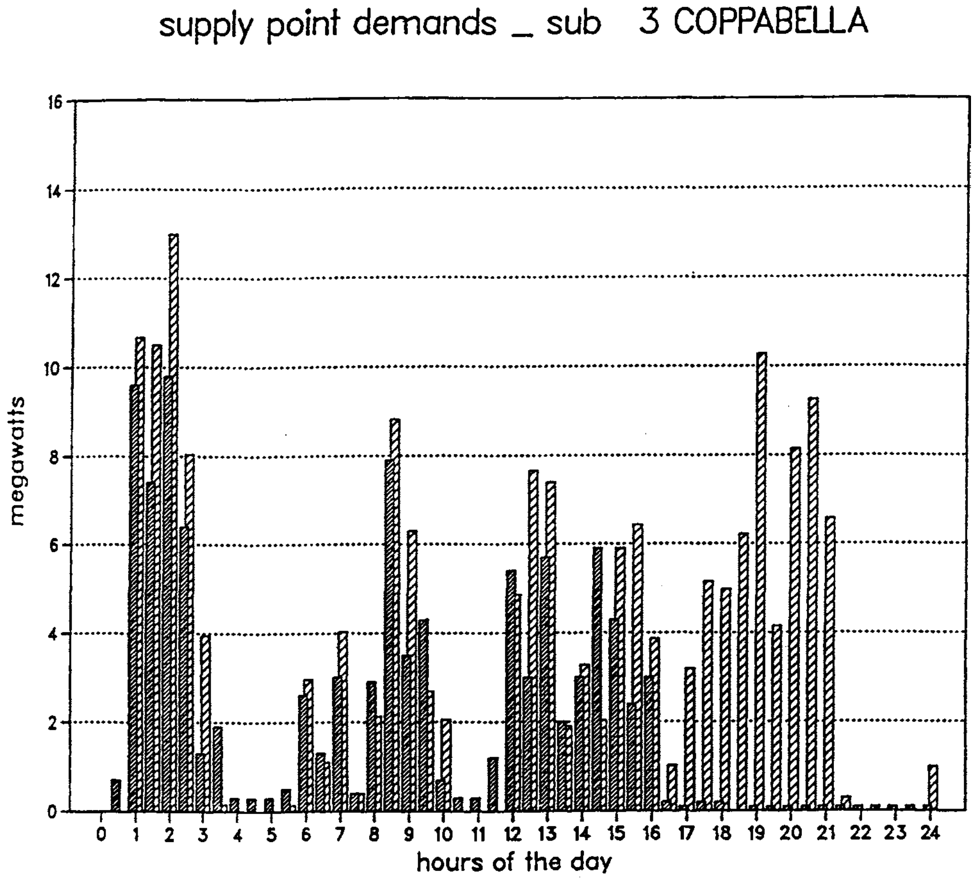
FIGURE 8.3 _ FUNDAMENTAL OUTGOING CURRENT VARIATION AT SUBSTATION

A _ SIMULATED   B _ MEASURED

The effects of the substation switching on the individual substation demands is shown in Figure 8.4.

After the refinements the correlation between the measured and the simulated demands was generally reasonable as can be seen in Table 8.1. The histograms in Figure 8.5a compare the measured and simulated results for Stage 2. No direct comparison is possible for Stage 1 since measured data for a feeding area are not available. This explains the overprediction of peaks between 2:00 and 5:00 hours in Figure 8.5b. Some of the other discrepancies are due to the freight/passenger train operations on Stage 1 which are not modelled at all. There are also some sections of the network around the unloaders where correct track and operational data were not available. Nevertheless, a comparison with the existing measured data are shown in Figure 8.5b. The histograms in Figure 8.5c and 8.5d compare the available measured data with the simulation results for Stage 1 and Stage 2 combined together. Note that Figure 8.5d is manually corrected by adding the simulated results of that particular substation (Rocklands) on to the measured data as solid black bars. This correction improves the correlation between the measured and simulated demands. Comparisons of the individual substation demands for Stage 1 and Stage 2 are given in Appendix 5.

Some discrepancies are bound to occur between the measured and simulated results of such a large scale manually driven system. These do not invalidate the simulated results as long as the simulation model produces the 'correct trends' with reasonable accuracy. Experience with the QR system suggested that great discrepancies rarely occur and small ones were usually balanced without changing the pattern of the total energy demand.

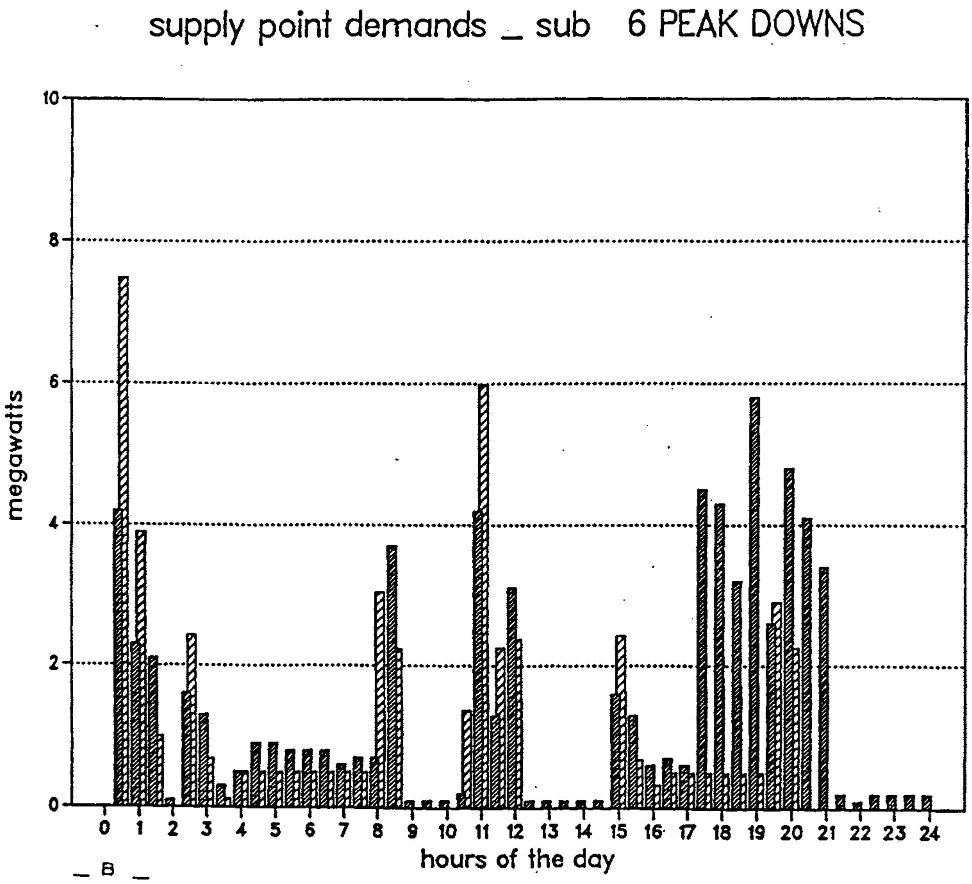


SIMULATION RESULTS :
maximum demand = 12.99 MW
occurred between 1.5 2.0 hours
minimum demand = 0.00 MW
occurred between 0.0 0.5 hours
average demand = 3.76 MW
standard deviation = 3.63
total consumption = 90.25 MWh
DAILY LOAD FACTOR = 28.95 %

simulation performed :
on 06/09/89 at 16:25:4
with 7 consists
output processed :
on 06/09/89 at 17:12:57

simgr.pascal/TT/TRG/BU/

_ A _



SIMULATION RESULTS :
maximum demand = 7.48 MW
occurred between 0.0 0.5 hours
minimum demand = 0.00 MW
occurred between 1.5 2.0 hours
average demand = 1.01 MW
standard deviation = 1.57
total consumption = 24.21 MWh
DAILY LOAD FACTOR = 13.49 %

simulation performed :
on 06/09/89 at 16:25:4
with 7 consists
output processed :
on 06/09/89 at 17:19:33

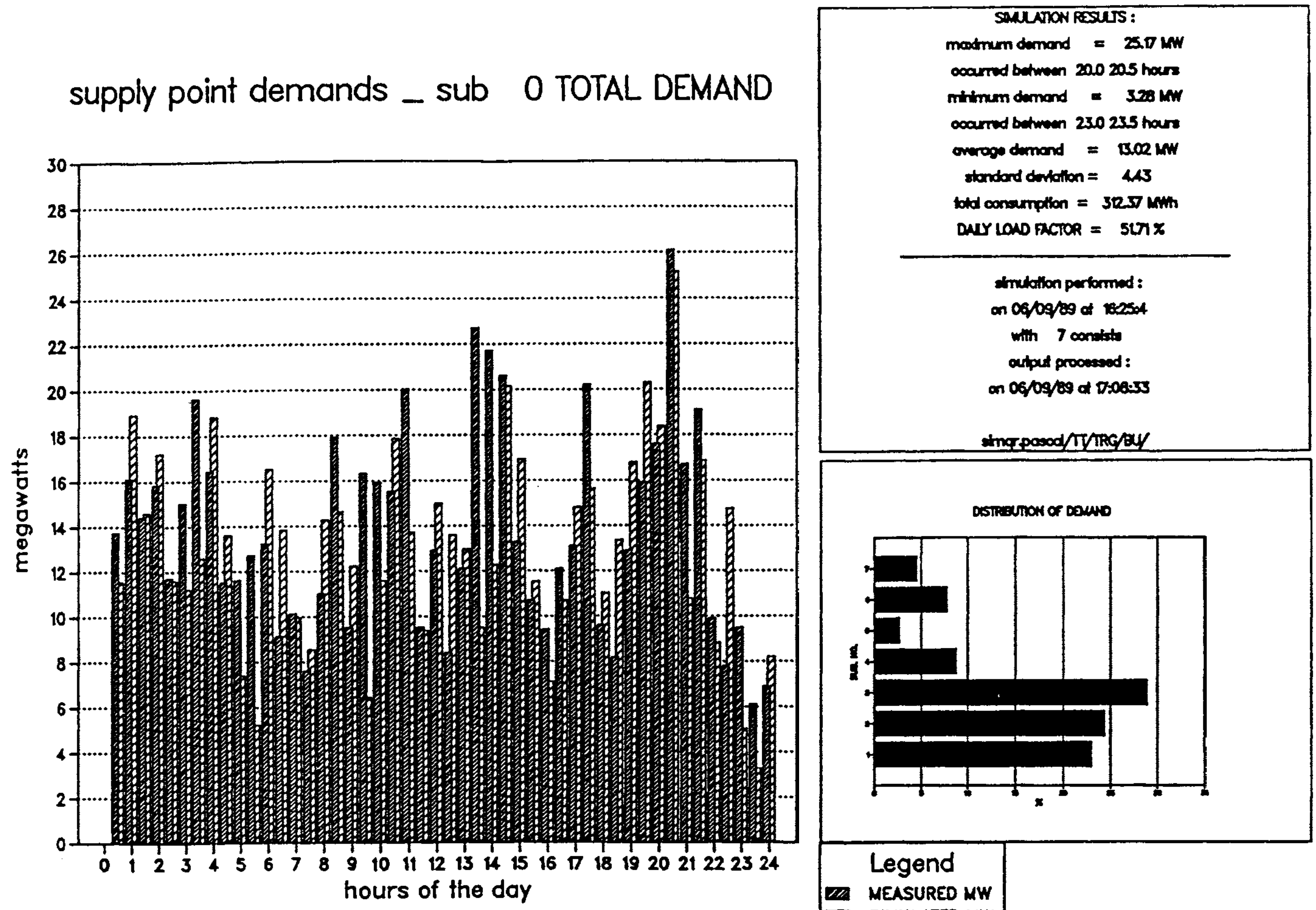
simgr.pascal/TT/TRG/BU/

_ B _

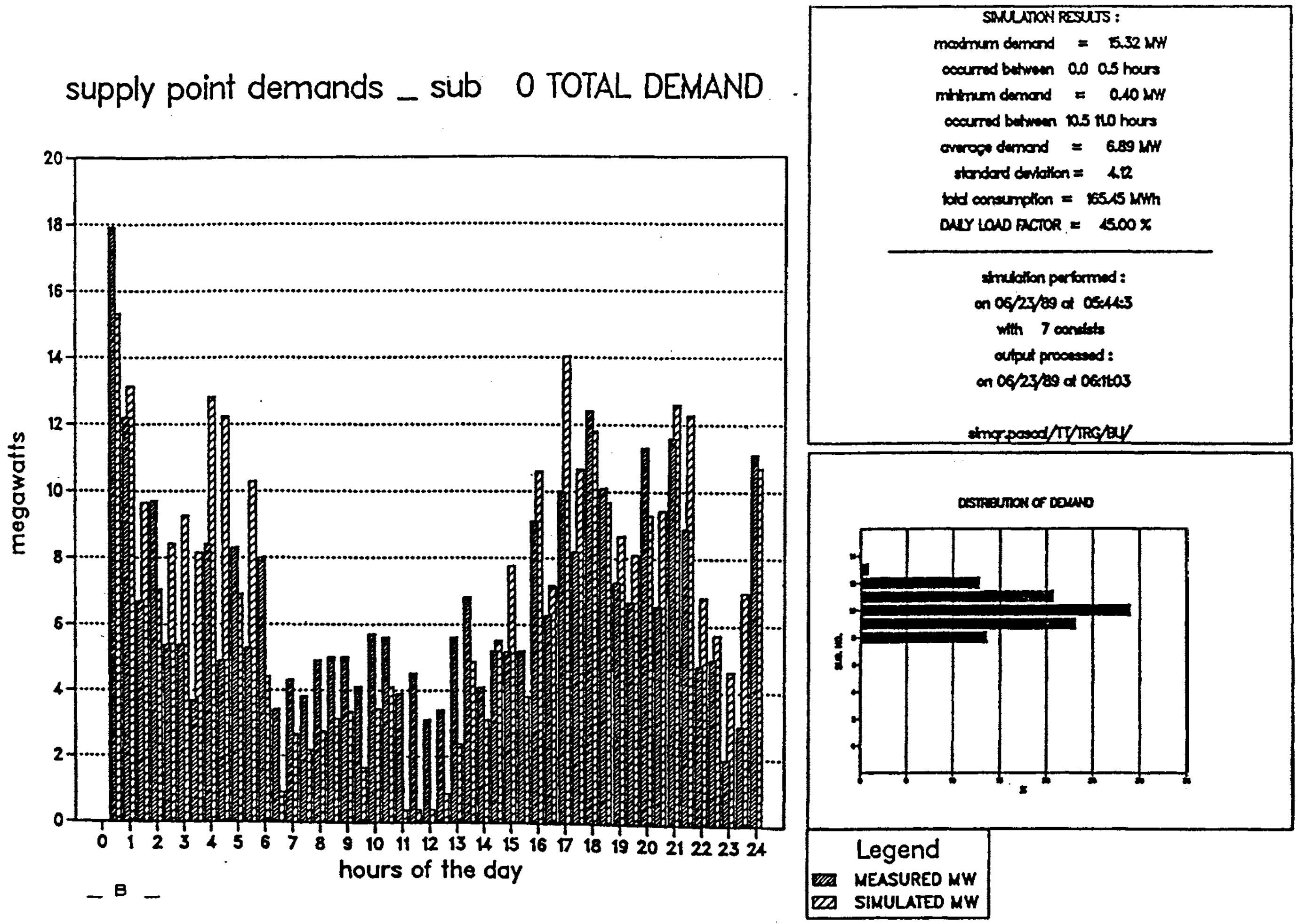
Legend
MEASURED MW
SIMULATED MW

FIGURE 8.4 _ EFFECT OF SUBSTATION SWITCHING

A _ COPPABELLA SUBSTATION B _ PEAKS DOWN SUBSTATION


supply point demands _ sub 0 TOTAL DEMAND
megawatts
hours of the day
SIMULATION RESULTS :
maximum demand = 25.17 MW
occurred between 20.0 20.5 hours
minimum demand = 3.28 MW
occurred between 23.0 23.5 hours
average demand = 13.02 MW
standard deviation = 4.43
total consumption = 312.37 MWh
DAILY LOAD FACTOR = 51.71 %
simulation performed :
on 06/09/89 at 16:25:4
with 7 consists
output processed :
on 06/09/89 at 17:08:33
simqr.pasod/TT/TRG/BU/
DISTRIBUTION OF DEMAND
Legend
MEASURED MW
SIMULATED MW

— A —


supply point demands _ sub 0 TOTAL DEMAND
megawatts
hours of the day
SIMULATION RESULTS :
maximum demand = 15.32 MW
occurred between 0.0 0.5 hours
minimum demand = 0.40 MW
occurred between 10.5 11.0 hours
average demand = 6.89 MW
standard deviation = 4.12
total consumption = 165.45 MWh
DAILY LOAD FACTOR = 45.00 %
simulation performed :
on 06/23/89 at 05:44:3
with 7 consists
output processed :
on 06/23/89 at 06:11:03
simqr.pasod/TT/TRG/BU/
DISTRIBUTION OF DEMAND
Legend
MEASURED MW
SIMULATED MW

— B —

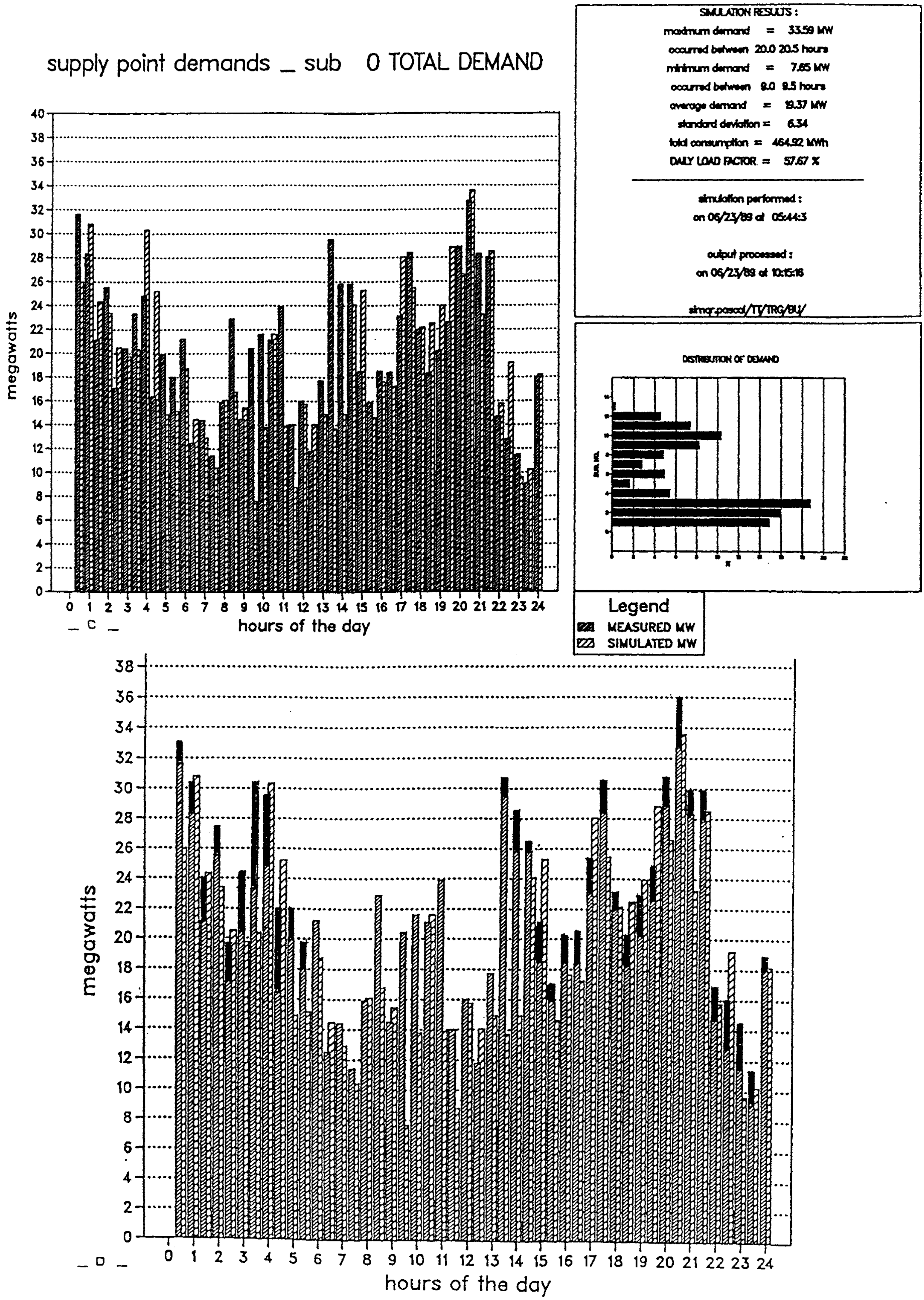


FIGURE 8.5 _ COMPARISON OF MEASURED AND SIMULATED HALF-HOUR DEMANDS

A _ STAGE 2 ON 24/2/1988. B _ STAGE 1 ON 24/2/1988
C _ STAGE 1+2 ON 24/2/1988 D _ STAGE 1+2 MANUALLY CORRECTED

8.6 PROJECTED 1990 SERVICES

8.6.1 1990 Timetable Derivation

The validation tests described in Section 8.5 were based on the actual timetable as run on that particular run. This involves approximately half of the coal haulage being electrically hauled, the remainder being diesel hauled. In the circumstances expected to prevail when the maximum demand control system might be operational, the fleet should be all electrically hauled. Consequently, a hypothetical timetable is created to represent this level of operation. This is done regarding all trains running in 1988 as electrically hauled, as this stage will be reached by the end of 1990. Expected train timings are available from the given timing diagrams.

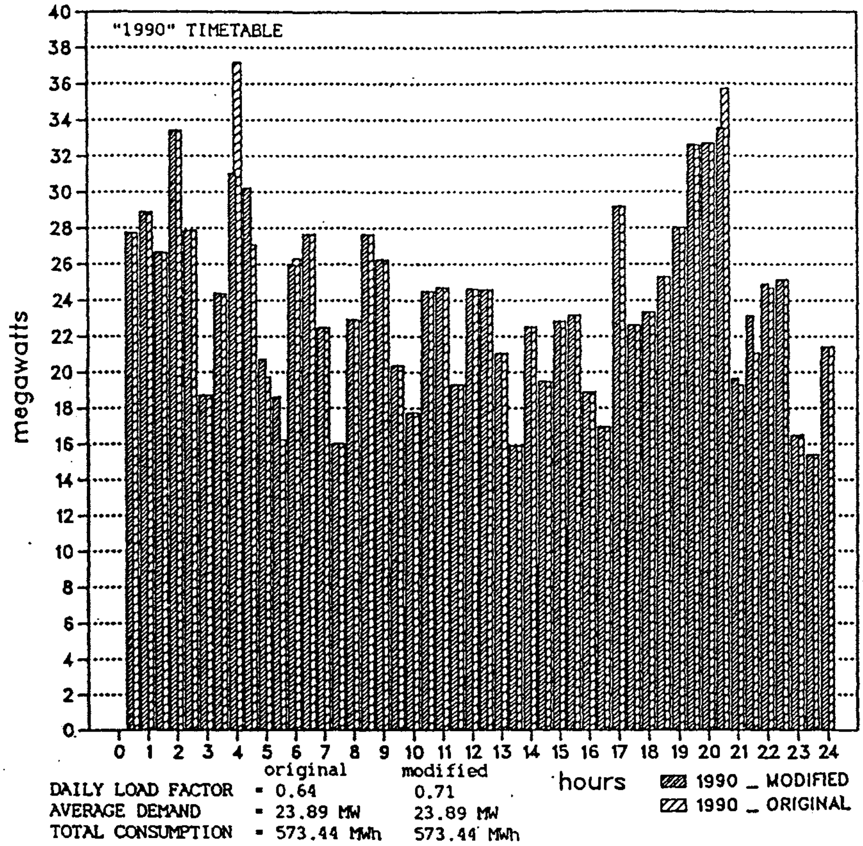
8.6.2 Results of 1990 Simulations

Stage 1 and Stage 2 are simulated independent of each other since there is no interaction between them through train operations control or the power supply system. The load histograms for this case are presented in Figure 8.6a for Stage 2, Figure 8.6b for Stage 1, Figure 8.6c for Stage 1+2. Here the general trend whereby the substations on the duplicated sections to/from the unloaders have more steady loads than those on the single branches to/from the loaders can be observed clearly. The load factors for the former are typically around 0.4 whereas the latter have load factors varying between 0.1 and 0.3.

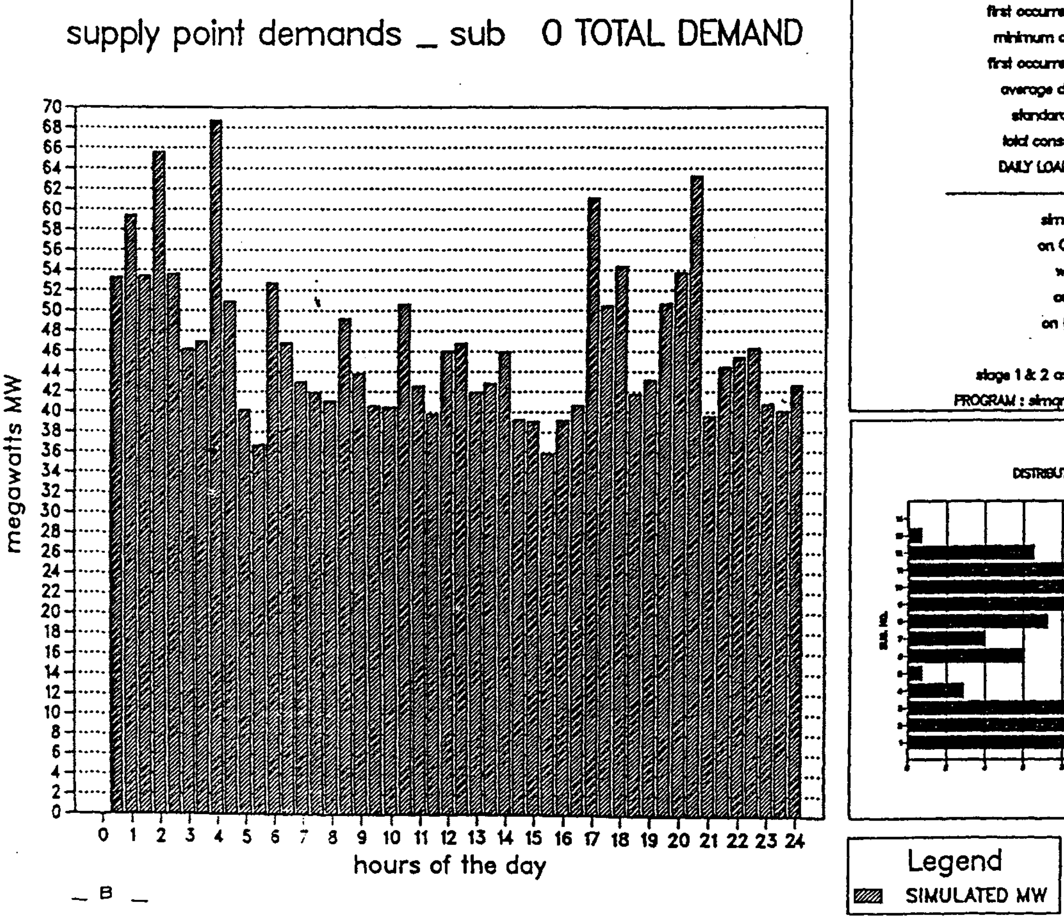
The combined load factor for Stage 2 from the total load plot in Figure 8.6a shows a value of 0.64, which may be regarded as typical of a day's running with this level of traffic. As this is a typical, rather than minimal, day for the projected series it is probable that individual days over a full month may well be noticeably worse than this figure. It is likely that load factors around 0.50 may appear when odd trains are cancelled or added, or special circumstances limit running severely for a period of a few hours on a particular day.

Figure 8.6b shows the total demand pattern for Stage 1 1990 timetable. The combined load factor is 0.71 which is better than the 0.64 of Stage 2. The combined load factor of Stage 1+2 is 0.68. Contrary to initial expectations,the simulation results show that the Stage 1+2 runs has given a worse load factor than Stage 1 alone for the particular timetable simulated. Evidently, the more peaky nature of Stage 2 and the coincidence of the maximum demands is affecting the overall load factor.

These results demonstrate that greater diversity of traffic does not necessarily improve the load factor. This is due to the random nature of the unplanned train operations and the lack of any load management between two systems and within each independent system of QR. Nevertheless, as will be discussed in Subsection 8.6.3 the situation can easily be improved by rescheduling the trains contributing to the demand peaks. There is more flexibility for that kind of load management if two stages are controlled together.



_ A _



SUMMARY OF THE SIMULATION RESULTS :

maximum demand = 68.66 MW

first occurred between 3.5 4.0 hours

minimum demand = 35.85 MW

first occurred between 15.0 15.5 hours

average demand = 46.71 MW

standard deviation = 7.64

total consumption = 1121.03 MWh

DAILY LOAD FACTOR = 68.03 %

---

simulation performed :

on 07/09/89 at 21:09:17

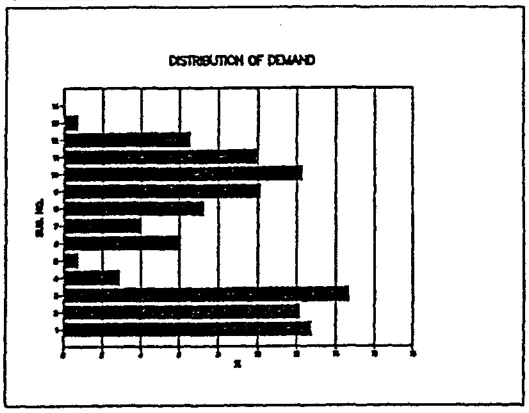
with 62 consists

output processed :

on 07/10/89 at 11:27:14

stage 1 & 2 as original

PROGRAM : simqr.pascal/Tamer Taskin/TRG/BU/



_ B _

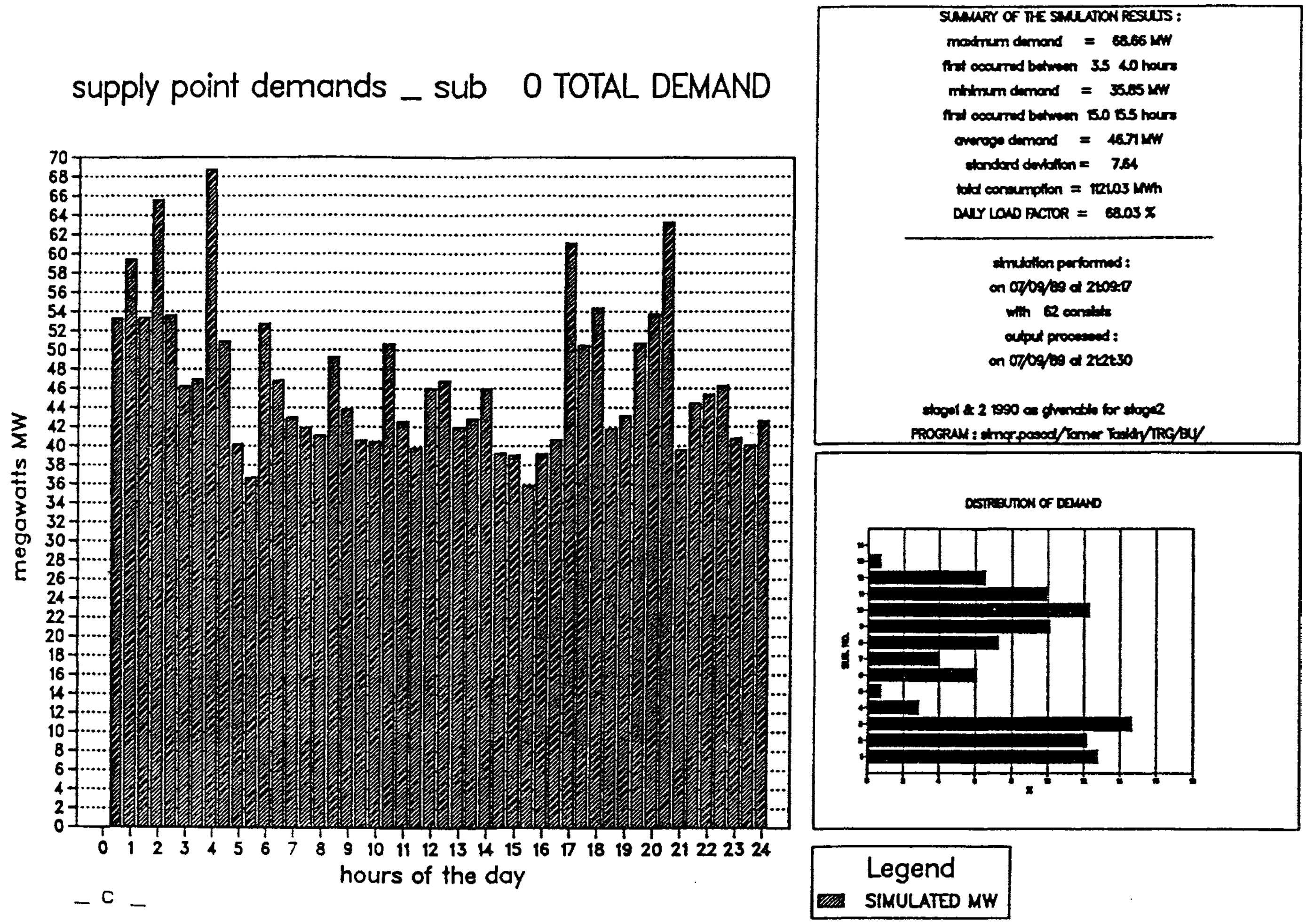


FIGURE 8.6 _ SIMULATED DEMAND FOR PROJECTED 1990 TIMETABLE

A _ STAGE 2 B _ STAGE 1 C _ STAGE 1+2

8.6.3 Experiments with Load Shifting

8.6.3.1 Constraints on Load Shifting

The aim of the maximum demand control is to reduce an excess demand by rescheduling the trains contributing to this demand. This process is called load shifting. On the real system there are many constraints on what is possible when considering the rescheduling of a train to avoid it drawing current in a critical half-hour when a maximum demand is predicted :

Crew shift time : Rostered shift times are limited to eight hours with some overtime due to unplanned disruption achievable. Trains cannot run faster than they are running at present due to speed restrictions. If they are instructed to run slower during the peak demand period, this delay must be recovered by the end of the shift time. The delay strategy can be used when the delay does not extend beyond the normal shifts and the time losses can be recovered by changing the times spent at other stopping positions.

Fleet Utilisation : As trains are delayed to minimise electricity costs, a balancing effect must be considered in relation to their turnaround times at the loaders and unloaders because the throughput of the system must be maximised as well through the best utilization of the fleet.

Meal breaks : Train crews are entitled to meal breaks within certain defined periods of their shifts. These meal breaks require the train to be stationary and this can have an impact on train rescheduling. Some flexibility exists for meal breaks which needs to be explored.

Train sizes : It is obvious that a better distribution of load can be established through tight scheduling. If shorter and lighter trains can be used and the cost of doing so can be justified, the natural diversity of the system will increase. Constraints exist due to the cost of extra crew and a probable decrease in the maximum system capacity if the signalling system is not improved.

8.6.3.2 Approach to Demand Reduction

Peak demands are quantified by the following steps :

1. From the total energy supply reports or histograms (Stage 1, Stage 2 or Stage 1+2) peak half hour demands are selected for investigation.

2. From the individual supply point (i.e. substation) demand reports or histograms the distribution of the selected peak half hour demands among the supply points can be investigated.

3. From the individual train demand plots it is possible to determine the involved trains and their individual contribution to the energy demand peak.

4. From the train timing diagrams it is possible to determine what each train involved is doing before and after the peak demand periods.

After the demand is quantified, the timetables are studied to alter the running patterns of the contributing trains without any detrimental effect on the coal haulage.

8.6.3.3 Examples of Load Shifting

Some possible manipulations, which do not violate the constraints, are examined below. These manipulations illustrate some of the techniques that can evolve into a coordinated approach to demand reduction.

Actions 1 and 2 : A close examination of the total Stage 2 demand for the 1990 timetable (Figure 8.6a) shows that the two highest demands occur for the half-hour 3:30 to 4:00 at 37.2 MW and for the half-hour 20:00 to 20:30 at 35.8 MW. The examination of the train timing diagrams reveals this to be principally due to 3 loaded trains proceeding simultaneously towards the unloaders. The most suitable of these (loaded train EV73) waits at a crossing for 35 minutes due to a conflict as shown in Figure 8.7.

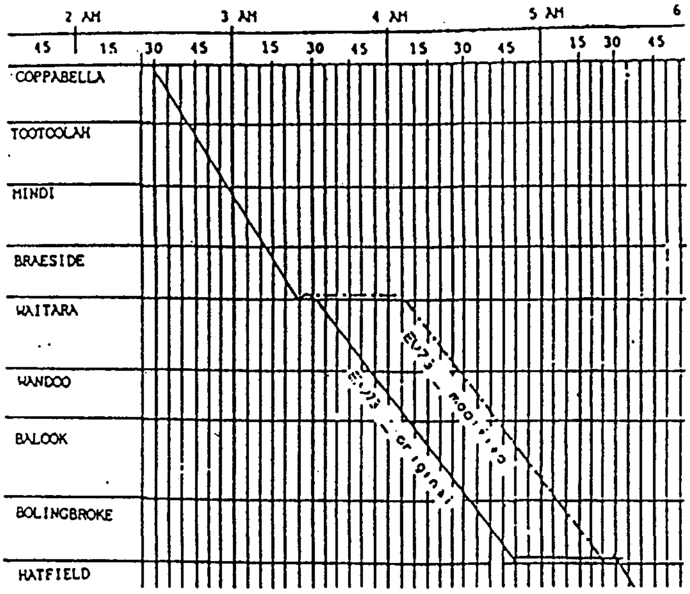


FIGURE 8.7 _ A FRAGMENT OF 1990 TRAIN TIMING DIAGRAMS

If this could be predicted in advance in the real system, it would be possible to halt this train at an earlier crossing instead without changing its overall run time. This action has been tried and reduced this peak to 31 MW by shifting the load to subsequent periods where it does not cause a peak. This action moves the peak demand on Stage 2 to the half-hour 20:00 to 20:30.

To reduce the later peak, empty train 9582 is delayed at Dysart before moving up into German Creek mine such that it only just starts to move again as the period 20:00 to 20:30 is ending. Together, these two simple load shifting actions improve the load factor from 0.64 to 0.72 for Stage 2 by reducing the peak from around 37 MW to 31 MW. These two shifts are detailed in Table 8.2. The overall effect of these two changes on Stage 2 is shown on the superposed histograms in Figure 8.8a.

	ORIGINAL		MODIFIED	
Vertex	Arrive	Dwell	Arrive	Dwell
GRACEMERE	01 : 28	00 : 15	01 : 28	00 : 30
KABRA	01 : 51	–	02 : 06	–
STANWELL	02 : 05	–	02 : 20	–
WYCARBAH	02 : 22	–	02 : 37	–
WESTWOOD	02 : 40	–	02 : 55	–
WINDAH	02 : 53	00 : 15	03 : 08	00 : 00

MODIFICATION 3/STAGE 1/1990 TIMETABLE/ empty train 9N30-9N29

	ORIGINAL		MODIFIED	
Vertex	Arrive	Dwell	Arrive	Dwell
S. GLADSTONE	00 : 48	00 : 05	00 : 48	00 : 00
CALLEMONDAH	01 : 07	–	01 : 02	–
MT. MILLER	01 : 14	–	01 : 09	–
YARWUN	01 : 20	–	01 : 15	–
ALOOGA	01 : 28	–	01 : 23	–
MT. LARCOM	01 : 38	–	01 : 33	–
AMBROSE	01 : 45	00 : 05	01 : 40	00 : 18
EPALA	01 : 57	–	02 : 05	–
RAGLAN	02 : 09	–	02 : 18	–
MARMOR	02 : 20	–	02 : 28	–
BAJOOL	02 : 30	–	02 : 38	–
ARCHER	02 : 57	00 : 08	03 : 05	00 : 00

MODIFICATION 4/STAGE 1/1990 TIMETABLE/ empty train 9131
TABLE 8.2 _ DETAILS OF SHIFTS IN TRAIN TIMINGS ON STAGE 1.

An examination of the results for Stage 2 (Figure 8.6a) and Stage 1+2 (Figure 8.6c) shows that two highest peaks on Stage 2 alone coincide with the first and third highest peaks on Stage 1+2 . Therefore, the shifts already used for Stage 2 only can be used to clip two of the three highest peaks (i.e. greater than 62 MW) in the combined system. Figure 8.8b shows the effect of the same shifts on Stage 1 and Stage 2 (Stage 1+2) combined. The shifts improve the load factor from 0.68 to 0.71 for Stage 1+2 by reducing the original peaks of 68.7 MW at 03:30-04:00 and 63.4 MW at 20:00-20:30 to 62.1 MW and 61.0 MW respectively.

Actions 3 and 4 : Reviewing Figure 8.6c and Figure 8.8b show that these shifts have no effect on the second highest peak of Stage 1+2 (65.6 MW at 01:30-02:00). Naturally, some action is necessary to reduce this peak. For that peak, it was apparent that no simple actions were available on Stage 2 and the shifts detailed in Table 8.3 were proposed for two empty trains 9N30-9N29 and 9131 on Stage 1.

	ORIGINAL		MODIFIED	
Vertex	Arrive	Dwell	Arrive	Dwell
WAITARA	03 : 25	00 : 05	03 : 25	00 : 40
WANDOO	03 : 50	–	04 : 25	–
BALOOK	04 : 05	–	04 : 40	–
BOLINBROKE	04 : 32	–	05 : 07	–
HATFIELD	04 : 50	00 : 40	05 : 25	00 : 05

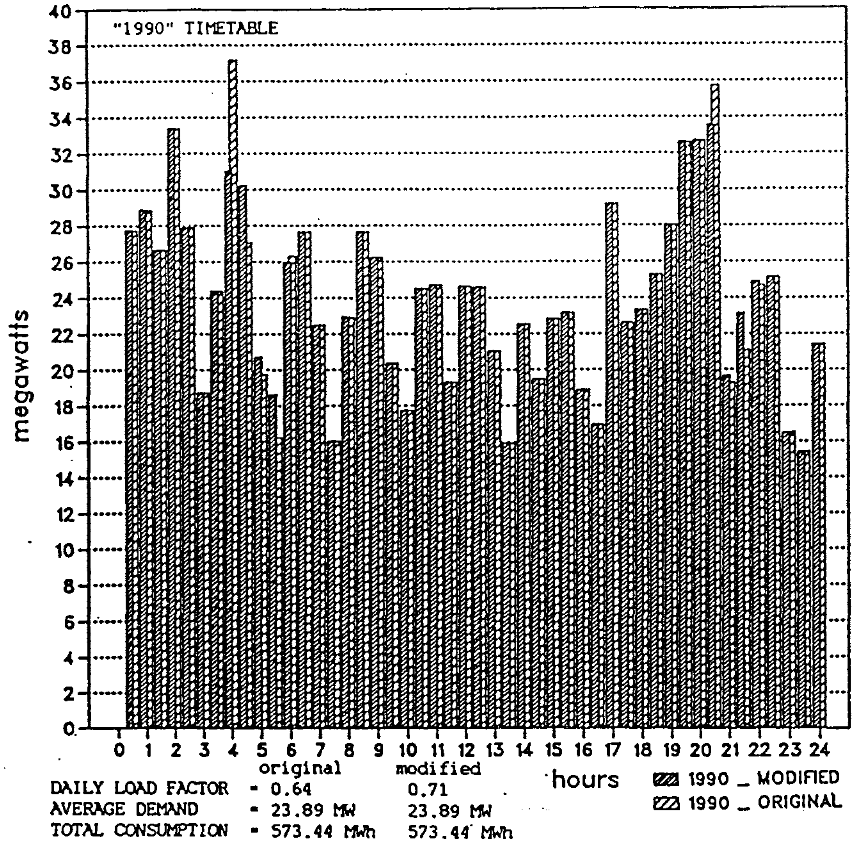
MODIFICATION 1/STAGE 2/1990 TIMETABLE/ loaded train EV73

	ORIGINAL		MODIFIED	
Vertex	Arrive	Dwell	Arrive	Dwell
DYSART	19 : 58	00 : 12	19 : 58	00 : 42
NORWICH PARK	20 : 33	–	21 : 03	–
BUNDOORA	20 : 50	–	21 : 20	–
GERMAN CREEK	21 : 00	–	21 : 30	–

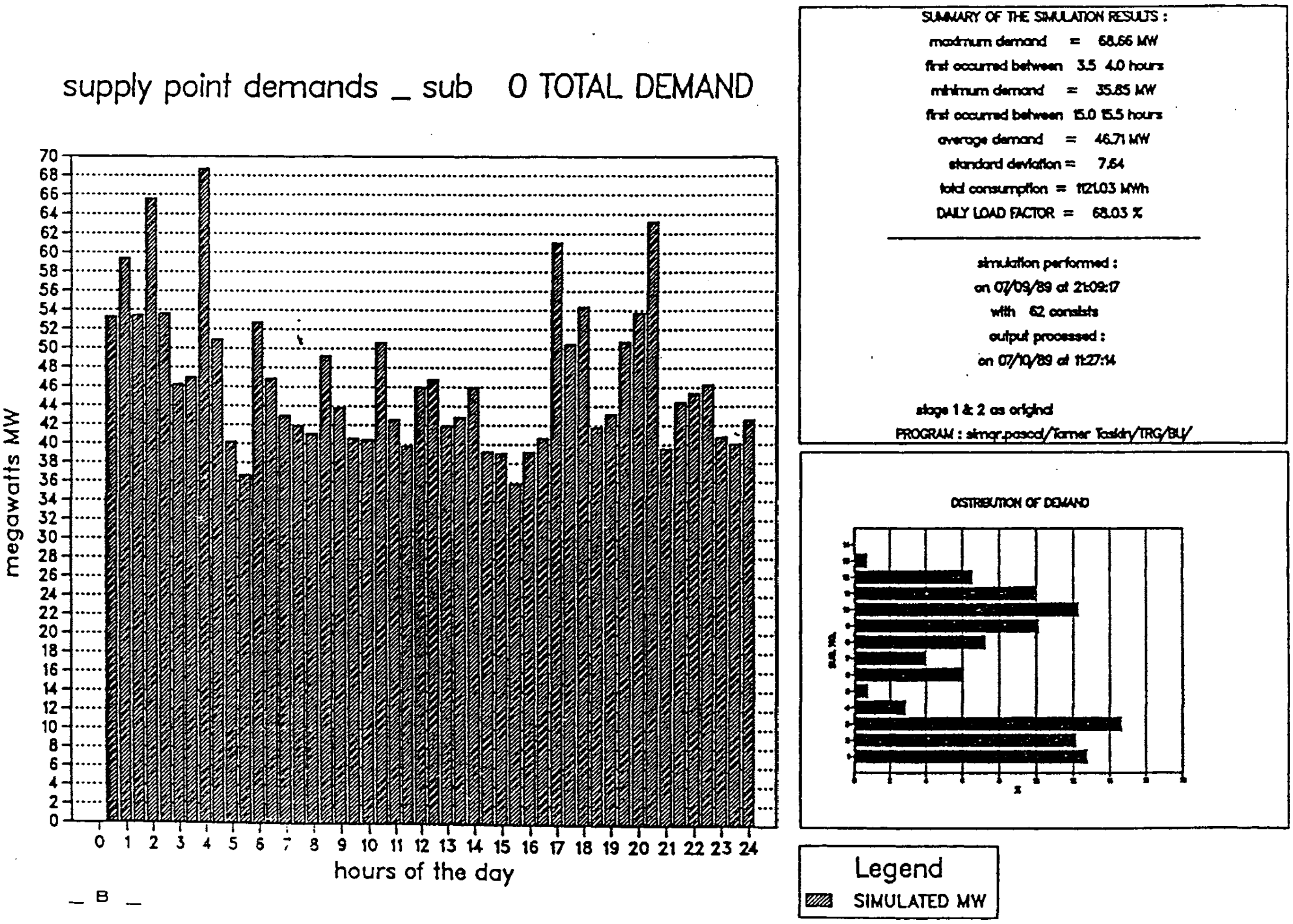
MODIFICATION 2/STAGE 2/1990 TIMETABLE/ empty train 9582

TABLE 8.3 _ SUMMARY OF SHIFTS IN TRAIN TIMINGS ON STAGE 1.

In this case, two trains were caused to pause within the relevant period without changing their runtimes or disturbing the traffic flow in the system. These actions on Stage 1 trains reduce the corresponding half-hour load and improve the load factor to 0.73 on Stage 1 and to 0.74 on Stage 1+2. The histogram in Figure 8.8c shows the combined effect of all four load shifting actions. No obvious other actions are available, partly due to tightness of 'timetabling'. These results are summarized in Table 8.4.

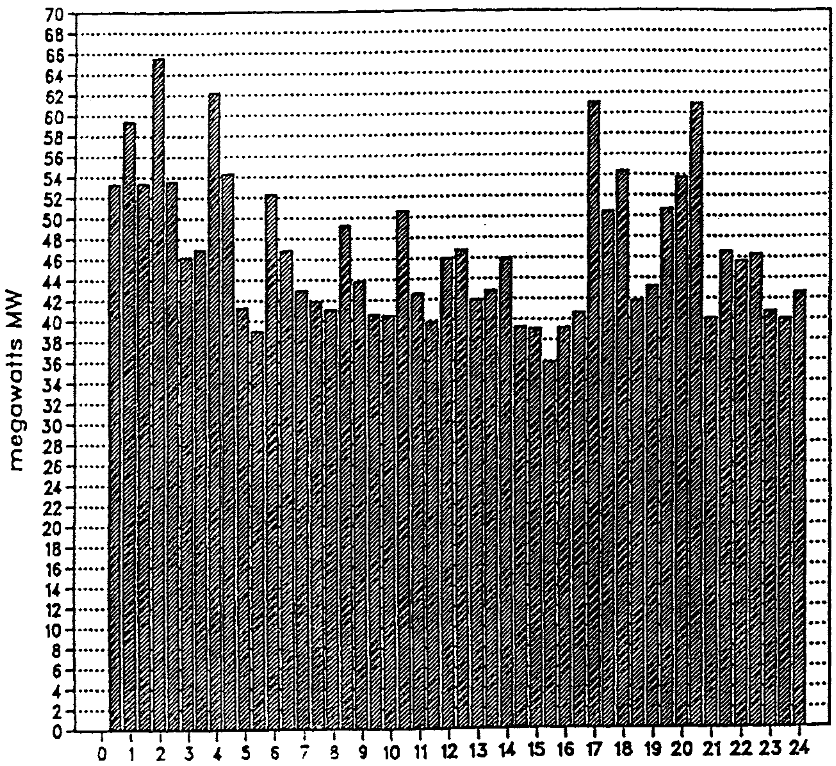

"1990" TIMETABLE
megawatts
hours
original modified
DAILY LOAD FACTOR = 0.64 0.71
AVERAGE DEMAND = 23.89 MW 23.89 MW
TOTAL CONSUMPTION = 573.44 MWh 573.44 MWh
1990 _ MODIFIED
1990 _ ORIGINAL

— A —


supply point demands _ sub 0 TOTAL DEMAND
megawatts MW
hours of the day
SUMMARY OF THE SIMULATION RESULTS :
maximum demand = 68.66 MW
first occurred between 3.5 4.0 hours
minimum demand = 35.85 MW
first occurred between 15.0 15.5 hours
average demand = 46.71 MW
standard deviation = 7.64
total consumption = 1121.03 MWh
DAILY LOAD FACTOR = 68.03 %
simulation performed :
on 07/09/89 at 21:09:17
with 62 consists
output processed :
on 07/10/89 at 11:27:14
stage 1 & 2 as original
PROGRAM : simqr.pascal/Tamer Taskin/TRG/BU/
DISTRIBUTION OF DEMAND
Legend
SIMULATED MW

— B —

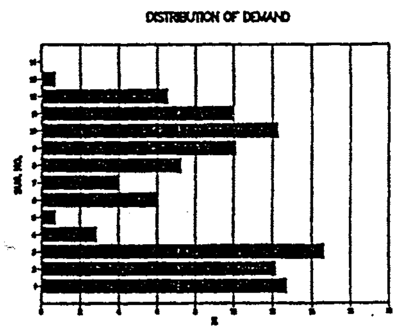
supply point demands _ sub 0 TOTAL DEMAND



SUMMARY OF THE SIMULATION RESULTS :
maximum demand = 65.52 MW
first occurred between 1.5 2.0 hours
minimum demand = 35.85 MW
first occurred between 15.0 15.5 hours
average demand = 46.72 MW
standard deviation = 7.14
total consumption = 1121.28 MWh
DAILY LOAD FACTOR = 71.31 %

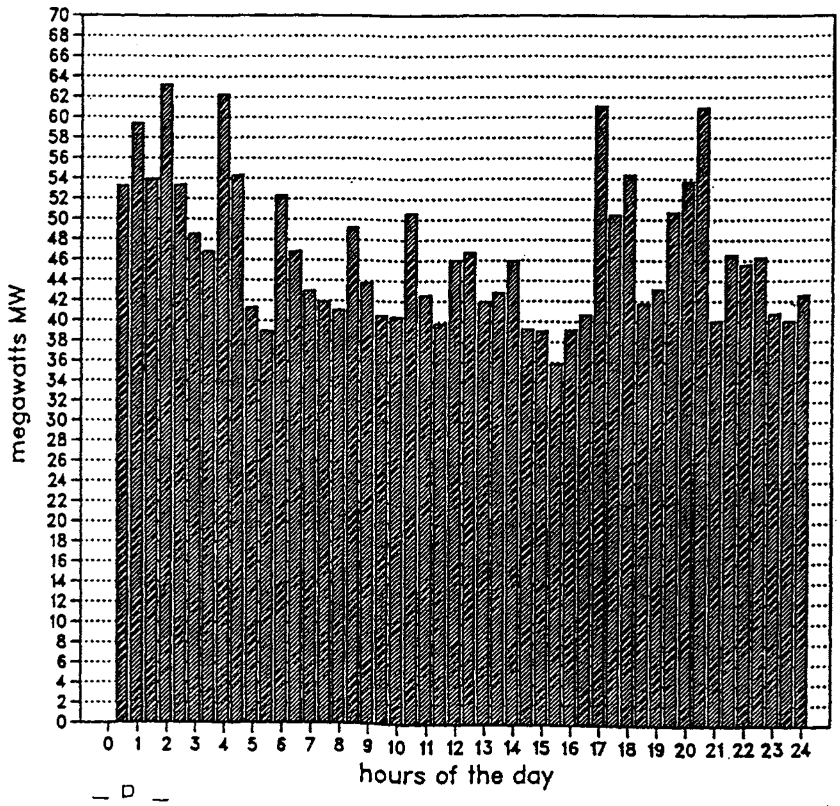
simulation performed :
on 07/09/89 at 18:26:47
with 62 consists
output processed :
on 07/10/89 at 11:38:38

stage 1 & 2 1990 stage 2 modified
PROGRAM : simqr.pascal/Tamer Taskiry/TRG/BU/



_ C _

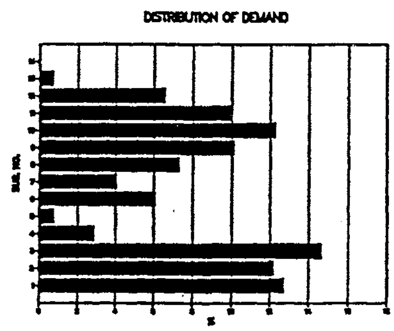
supply point demands _ sub 0 TOTAL DEMAND



SUMMARY OF THE SIMULATION RESULTS :
maximum demand = 63.15 MW
first occurred between 1.5 2.0 hours
minimum demand = 35.85 MW
first occurred between 15.0 15.5 hours
average demand = 46.72 MW
standard deviation = 7.03
total consumption = 1121.32 MWh
DAILY LOAD FACTOR = 73.99 %

simulation performed :
on 07/09/89 at 18:26:47
with 62 consists
output processed :
on 09/12/89 at 19:28:31

stg 1&2-90-2+2 mods
PROGRAM : simqr.pascal/Tamer Taskiry/TRG/3U/



_ D _

Legend
SIMULATED MW

FIGURE 8.8 _ EFFECT OF LOAD SHIFTING ON ENERGY DEMAND

A _ STAGE 2. TWO ACTIONS - COMPARED WITH ORIGINAL
B _ STAGE 1+2. ORIGINAL
C _ STAGE 1+2. TWO ACTIONS ON STAGE 2
D _ STAGE 1+2. TWO ACTIONS ON STAGE 2 AND TWO ACTIONS ON STAGE 1

	STAGE 2 Load Factor	STAGE 1 Load Factor	STAGE 1+2 Load Factor
no action	0.64	0.71	0.68
actions 1, 2	0.72	n/c	0.71
actions 1, 2, 3, 4	n/c	0.73	0.74

n/c : not changed

TABLE 8.4 _ EFFECT OF LOAD SHIFTING ACTIONS ON LOAD FACTOR

8.6.3.4 Effect of Extended Averaging Periods

The traditional maximum demand tariff structures are based on loads averaged over half-hour periods and all the results presented so far have been based on this assumption. If, however, a longer averaging period is used for each demand calculation then the effects of short term peaks will diminish.

In order to establish the gain from extending the averaging period some experiments have been made to assess the effect of using different averaging periods. Taking the Stage 1, 1990 timetable is as an example and using four-hours averaging period has improved the load factor 0.72 to 0.82. This load factor has further improved to 0.92 when averaged over eight-hour period. The distribution of load in these cases are shown in Figure 8.9. This experiment also establishes a measure on the distribution of train movements over twenty four hours.

8.6.3.5 Conclusions Regarding Load Shifting and Averaging Period

These results clearly demonstrate that even relatively simple train rescheduling, provided it fits within the operational constraints, can make

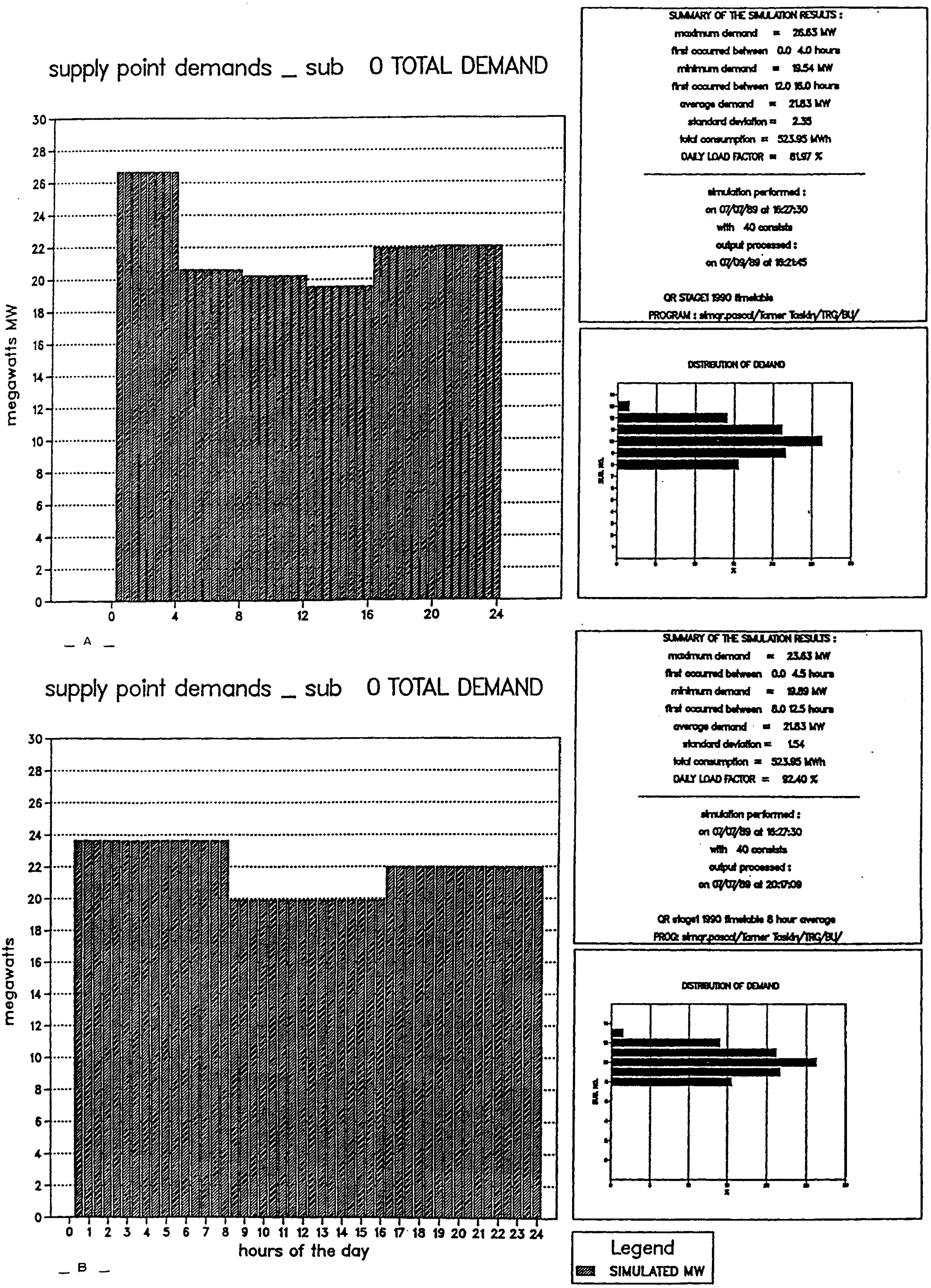


FIGURE 8.9 _ EFFECT OF EXTENDED AVERAGING PERIOD ON LOAD FACTOR

A _ FOUR-HOUR DEMANDS B _ EIGHT-HOUR DEMANDS a noticeable shift in the load factor and readily reduce the actual peak demands. The following conclusions can be drawn :

a. There is limited flexibility available to the maximum demand control system in the Stage 1 area where coal traffic is mixed with other priority freight and passenger trains. For example, it has not been possible to manipulate the loaded trains which are the major contributors to the peak demand. Instead, two empty trains had to be shifted.

b. There is enough flexibility available in the Stage 2 area if the service is kept at 1990 timetable level. This flexibility is explored by rescheduling two trains as explained in Subsection 8.6.4. The result demonstrates that use of a real time maximum demand control system may offer economic returns when considering that the simulations suggest a load factor of 0.71 is attainable. It would have been ideal if the simulation program could have been run with more timetables and more corrective actions could have been tried. This would have entailed the creation of new data bases according to each timetable which is a very laborious process at the moment. For a scheme of this nature to be successful in practice an automated method is necessary to input train timing diagrams.

c. Even at the 1990 timetable traffic level the control of one or two loaded trains which may be adding individually high maximum demands offers significant improvement to the total half hour demand.

d. The Stage 1+2 load shifting examples have shown that, in the typical situation, there is greater scope for demand control if two stages are combined together rather than controlled independently. The results quantifies that the Stage 1+2 load factor can be improved significantly by the control actions taken on Stage 2 only. The case for aggregation of demand for tariff purposes is made abundantly obvious by these results.

e. Predicting train conflicts before they occur will decrease the energy consumption if the load shifting actions can also resolve some of these conflicts and therefore, reduce the frequency of stops and restarts.

If the service can be planned taking maximum energy demand into account in advance with the help of the simulation model then any realtime control system (i.e. control computer) will have to cater only for the unplanned delays and unscheduled operations which will inevitably occur. If the system is to be operated according to the current practice, that is under the given constraints and resolving the conflicts when they occur, implementation of a realtime energy demand control system is more crucial to control this unplanned mode of operation with train scheduling and realtime energy optimization facilities.

8.7 PROJECTED 2000 SERVICES

8.7.1 2000 Timetable Derivation

With a typical 1990 timetable operating, the natural diversity of the system improves and the daily load factor becomes 0.64 instead of 0.53. To further examine this trend, a further extrapolation of the 1990 scenario has been made and a hypothetical traffic pattern has been created. This involves adding approximately 100% more train movements than the 1990 scenario to operate each mine at a capacity approaching its maximum.

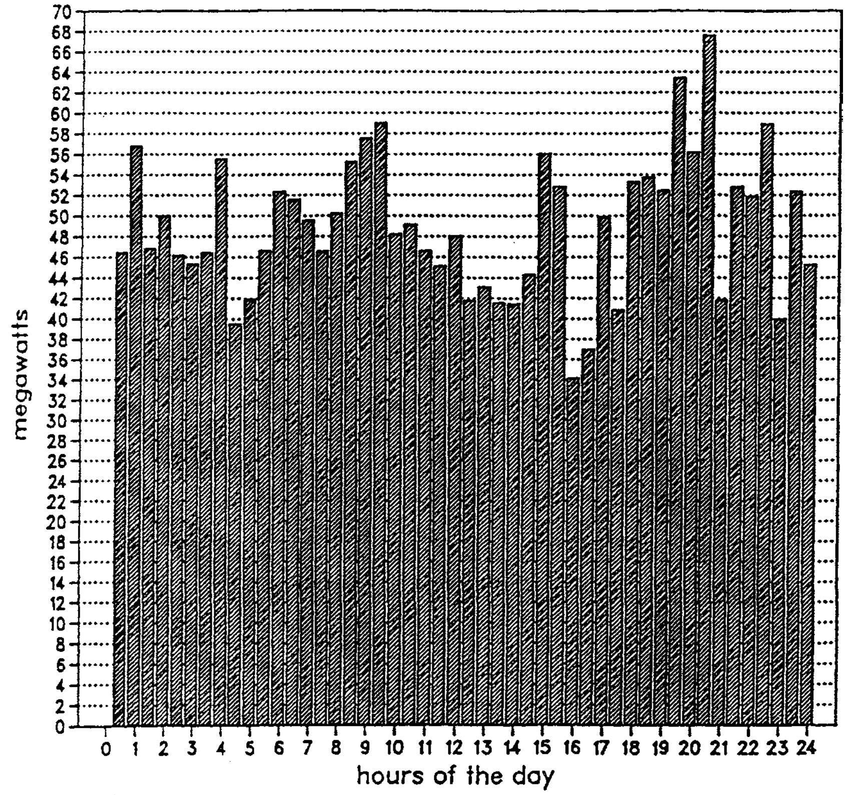
8.7.2 Results of 2000 Simulations

The substation loadings resulting from running the 2000 timetable are shown in Figure 8.10a for Stage 2, Figure 8.10b for Stage 1 and Figure 8.10c and 8.10d for Stage 1+2. From these histograms it can be seen that the increased traffic does indeed result in smoother loadings. With the 2000 timetables, where the individual stages both have quite good load factors of 0.72, the effect of combination is a significant improvement to 0.80. This is distinctly different to 1990 case where the combined load factor was a little worse than Stage 1 alone. Evidently, where the loads are sufficiently high to be fairly smooth the combination does exploit the greater natural diversity. Otherwise, the result is quite random. For ease of comparison, Table 8.5 summarises the results for 1988, 1990 and 2000 timetables.

	STAGE 2 Load Factor	STAGE 1 Load Factor	STAGE 1+2 Load Factor
1988 Timetable	0.52	0.45	0.58
1990 Timetable	0.64	0.71	0.68
2000 Timetable	0.72	0.72	0.80

TABLE 8.5 _ LOAD FACTORS FOR 1988, 1990 AND 2000 TIMETABLES

supply point demands _ sub 0 TOTAL DEMAND



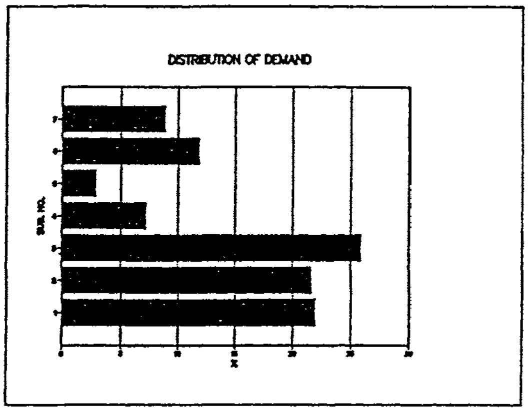
— A —

SIMULATION RESULTS :

maximum demand = 67.61 MW
occurred between 20.0 20.5 hours
minimum demand = 34.15 MW
occurred between 15.5 16.0 hours
average demand = 49.01 MW
standard deviation = 6.86
total consumption = 1176.35 MWh
DAILY LOAD FACTOR = 72.50 %

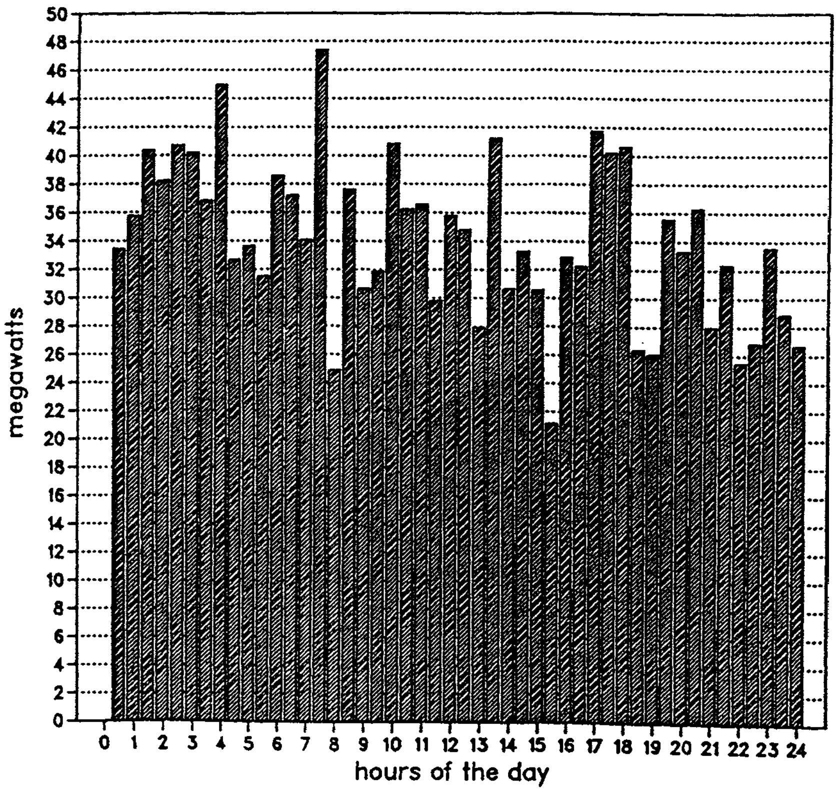
simulation performed :
on 04/16/89 at 20:13:5
with 44 consists
output processed :
on 06/02/89 at 11:22:16

simqr.pascal/TT/TRG/BU/



Legend
SIMULATED MW

supply point demands _ sub 0 TOTAL DEMAND



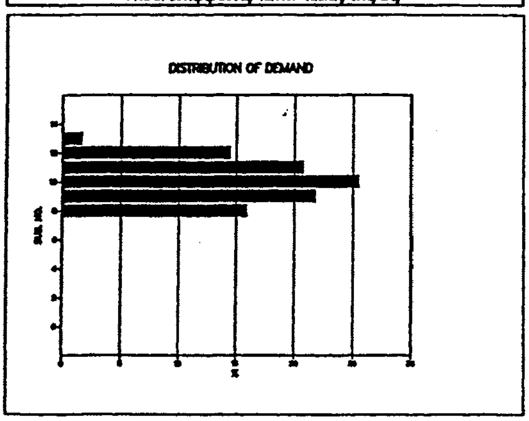
— B —

SUMMARY OF THE SIMULATION RESULTS :

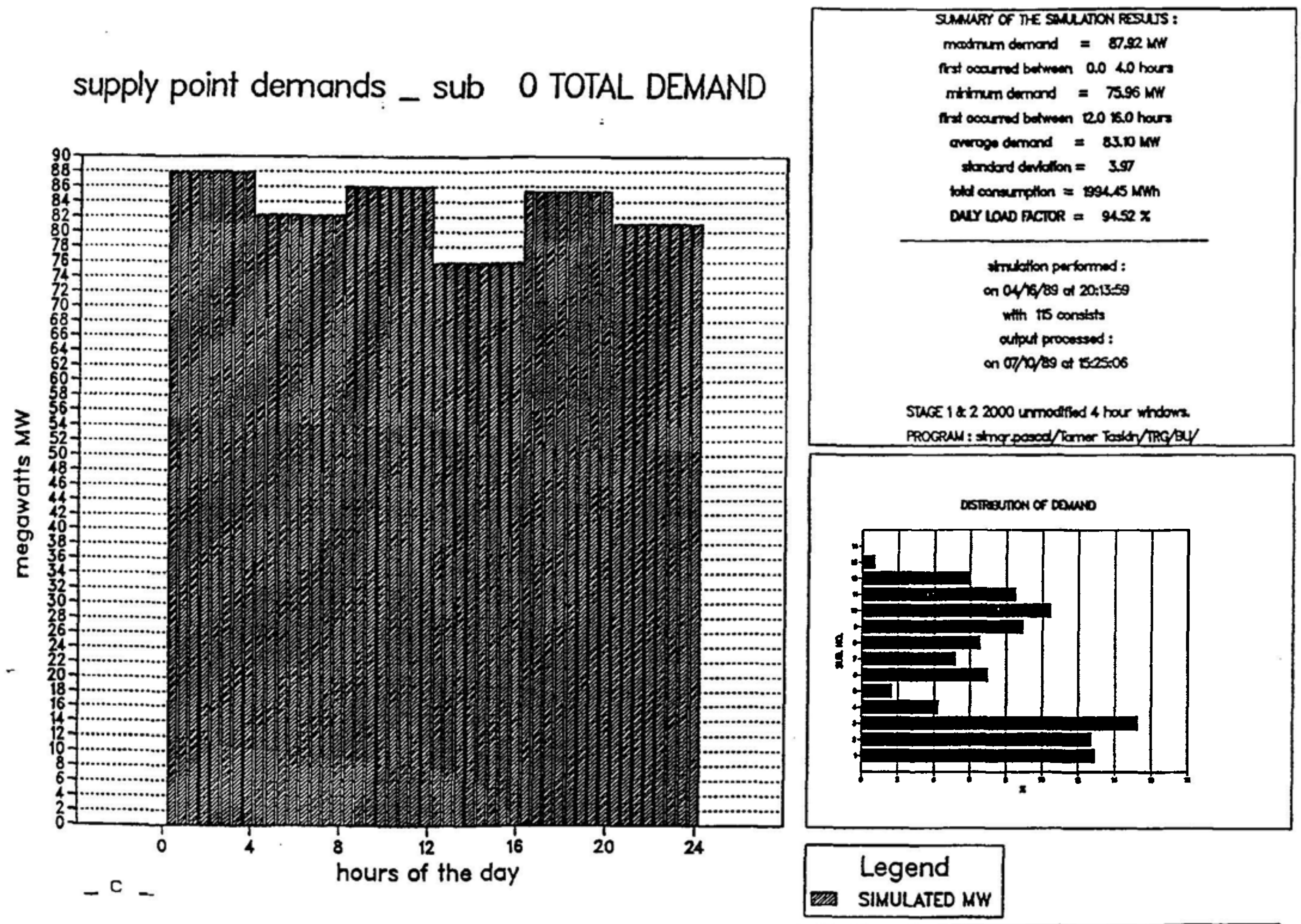
maximum demand = 47.36 MW
first occurred between 7.0 7.5 hours
minimum demand = 21.17 MW
first occurred between 15.0 15.5 hours
average demand = 34.09 MW
standard deviation = 5.60
total consumption = 818.10 MWh
DAILY LOAD FACTOR = 71.98 %

simulation performed :
on 07/07/89 at 01:35:4
with 71 consists
output processed :
on 07/07/89 at 11:58:56

QR STAGE1 2000 timetable
PROG: simqr.pascal/Tamer Taskin/TRG/BU/



Legend
SIMULATED MW



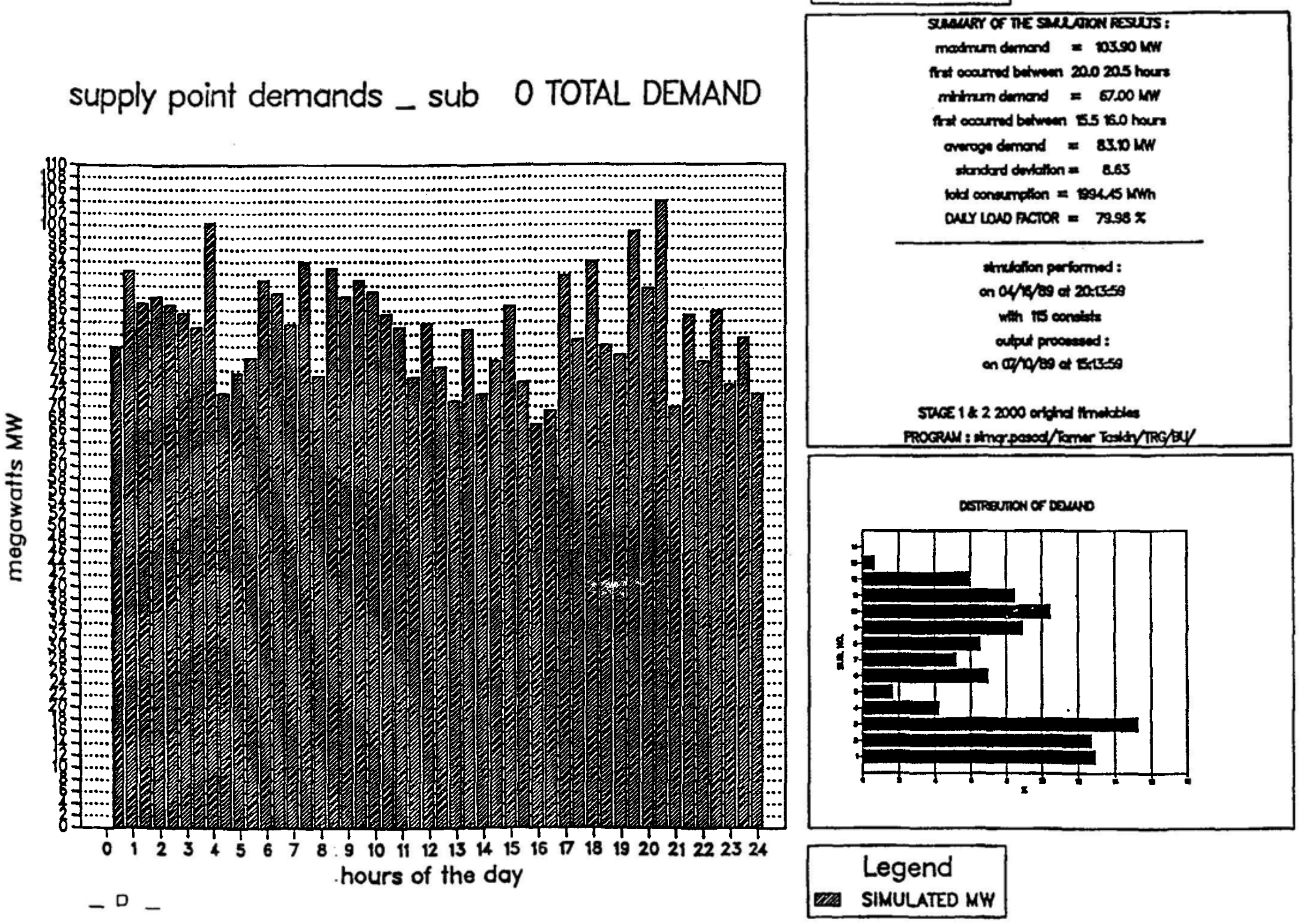


FIGURE 8.10 _ SIMULATED DEMAND FOR PROJECTED 2000 TIMETABLE

A _ STAGE 2 B _ STAGE 1
C _ STAGE 1+2, 4-HOUR PERIOD D _ STAGE 1+2

When results for Stage 1 and Stage 2 are examined individually, it is apparent that the load factor improves through tight scheduling but the natural diversity improvement with total load is a law of diminishing returns. Any further improvement can only result from load management whereby realtime control is exercised to shift loads between time periods. Paradoxically, the less flexibility is available for load shifting when the system approaches to the saturation point for traffic flow like in 2000 scenario.

8.8 CONCLUSIONS AND POSSIBLE APPLICATIONS

8.8.1 General Conclusions of the Simulation Study

a. The Central Queensland rail network has required 235 vertices and 334 line sections in its representation. This large scale network running on it, has been represented without any major modification in the software which was used for the traffic regulation experiments in Chapter 7. The simulation study described in this chapter has demonstrated that the software is capable of modelling a large scale rail transit system with an adequate level of detail.

b. A new tractive effort module which also calculates electrical power inputs of the locomotives and models the expected driver behaviour has been interfaced to the model. A set of additional methods, which calculate the electrical quantities and allocate them to particular substations, have been added to the existing simulation model. This new version of the simulation model has been fully validated, thus it has been demonstrated that the model is appropriate for this study.

c. Running the simulation model for three different timetables has given some quantitative estimates for the load factors resulting from the uncontrolled train operations. Table 8.5 above summarises the results over the two stages and the three timetables. For Stage 2 alone the simulated daily load factors are 0.52, 0.64 and 0.72 for the 1988, 1990 and 2000 timetables, respectively. This shows the tendency to follow a law of diminishing returns, as each step represents an approximate doubling of the coal haulage but a significantly smaller improvement between 1990 and 2000 than between 1988 and 1990. This point is even clearer from the Stage 1 only results, giving 0.45,0.72,0.72 respectively. The energy consumption increased proportionally to the number of trains operating, while the load factor stayed unchanged for 1990 and 2000 timetables.

d. Stage 1 results also demonstrate the uneven nature of peak energy demand. When train operations are not controlled the probability is great that there will be a random occurrence of a situation in which a number of trains, while operating normally, draw large currents at the same time causing the half-hour period to have an unusually high demand.

e. For Stage 1+2, the 1990 case gives a figure (0.68) between that for the Stages separately whereas the 2000 case sees a further improvement to 0.80 again emphasising the uneven nature of the peak demand when the demand on the two Stages is aggregated but the train operations are not controlled in coordination. It must be emphasised that these results are for daily load factors of three train timing diagrams as it was only feasible to run the simulation model for a limited number of times (the limitation is mostly data preparation time rather than computer run time). Whatever the actual figures, there is clear evidence, despite the law of diminishing returns, that there is advantage in aggregating the demand over as much as the rail network as possible.

f. A number of simulation experiments with typical 1988, 1990 and 2000 timetables have led to the conclusion that simple load shifting techniques, whereby the trains are rescheduled on-line, can give useful reductions in peak demand but operational constraints limit the actions that can be taken. Nevertheless, the use realtime demand control may offer economic returns when considering that two simple actions on Stage 2 can improve the load factor from 0.64 to 0.72 on Stage 2 and from 0.68 to 0.71 on Stage 1+2 when the demand is aggregated over the two Stages. This is clearly a useful improvement.

g. In line with progress in processing speeds of industry standard microcomputers and workstations, one can now consider a realtime demand control system which includes a fast predictive simulation feature. This system would follow realtime operation of the rail transit system and simulate ahead the possible effect of the current situation so that corrective actions can be taken. The simulation study has also shown that it is possible to model QR system with an adequate acceleration with respect to real time. The simulation of a typical Stage 2 1990 timetable with 1 second update time for a 24 hours window with 22 train consists takes about 2600 seconds CPU time on a Multics main-frame computer, including network setup, precalculations and file input and output processes which can largely be avoided in a realtime type application. That is around 36 times faster than real time. Equivalent CPU time is achievable on a fully configured (i.e. 16 Mb dynamic memory,floating point processor) 32 bit 25/33 MHz personal computer or workstation. Further improvement is possible in a realtime implementation by increasing the update time, improving the integration methods used for train displacement calculations and making full use of event-oriented techniques.

8.8.2 Maximum Demand Control System

The results presented earlier in this chapter have shown that there is scope for the improvement of daily load factors by rescheduling the trains in real time so that energy demand peaks are reduced. In order to achieve this load shifting in the real system three major system components would be necessary :

An on-line version of the simulation model for demand prediction : It has been shown that fast predictive simulation of the QR system is possible. The simulations can be further accelerated by making better use of its event-based features and by parallel calculations of non-interacting train movements. Since the interactions between Stage 1 and Stage 2 are not significant, the two simulations can be run independently.

A knowledge-based program to recommend corrective actions : Once demand peaks are predicted as being in excess of some limit, decisions are required for altering the train running in order to reduce the excess demands. The knowledge-base will consist of the rules of load shifting for possible train combinations that conform to the operational constraints. An inference mechanism will also be needed to choose the corrective actions. This program should be an open-ended design which will improve as further experience is gained on the energy demand patterns of the system.

An automated train controller's diagram (telemetry) : This subsystem will provide the updated route and timetable information and current train positions, speeds and modes directly to the control computer (i.e. the simulation model and the knowledge-based optimal rescheduling program) to enable it to perform predictive calculations and to recommend the corrective actions. This equipment is commercially available.

The block diagram of the proposed system is given in Figure 8.11. In detail, these components would function together as follows :

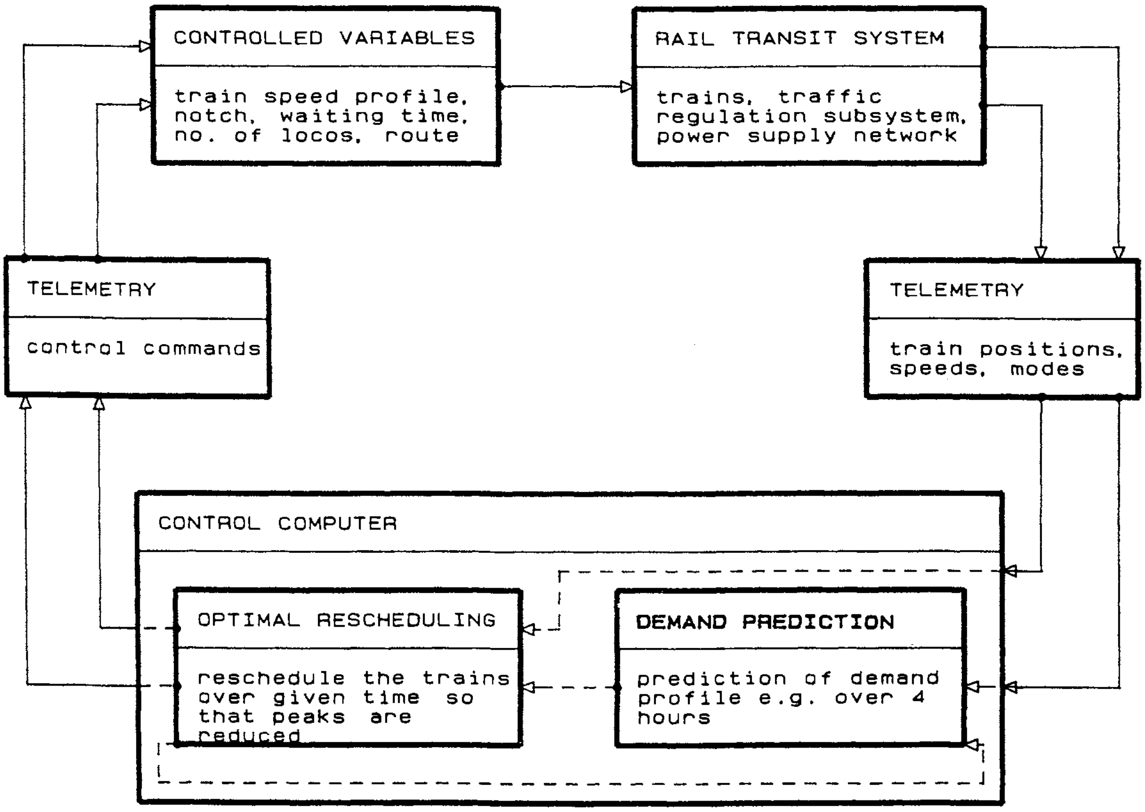


FIGURE 8.11 _ STRUCTURE OF MAXIMUM DEMAND CONTROL SYSTEM

1. At the start of each 'update' period of real time, the simulation model would take route and timetable information from the automated train timing diagram. This information must also include current positions, speeds and modes of the trains.

2. Using this information, the simulation model is used to run the planned service in accelerated time and predict the half hour patterns for the next 'controlled' period e.g. over 4 hours. If the service is not already planned or is disturbed, the model must also resolve the conflicts imitating the signalling interlocking subsystem.

3. The results from the simulation run are transferred to the knowledge-based program which now looks for half hour demands in excess of a preset level and the individual trains and substations contributing to these demands.

4. If such an excess demand exists, the knowledge-based program will examine the route and timetable information to see if it can find suitable trains to reschedule. Many options are available :

a. Reduce the speed or stop completely the progress of particular trains.

b. Instead of using a 'first come first served' strategy at passing loops and junctions, resolve the predicted conflicts in such a way that some of the load will be shifted.

c. Reduce the power of locomotives (i.e. notch down), taking into account the traction characteristics and the track geometry so that loss of runtime is acceptable.

d. Feed parts of the system from storage batteries or add a diesel locomotive to the consist which will be operated to clip the peak off.

If the knowledge-based program cannot find a suitable solution, a considerable likelihood since the available actions are limited, it will simply report the impending overload and contributing trains and leave it to the train control clerk to try and find a means of shifting load. If a solution can be found, it will be added to the knowledge-base.

5. On receiving the recommended actions the train control clerk will review the projected running pattern for the next 'controlled' period and restart the simulation to access the new traffic plan and rerun the prediction. This will check whether the proposed action removes the excess peak demands. The proposed actions will then be communicated to the relevant trains by radio and/or through lineside signals.

The elements of the energy demand control system outlined in this section are individually available and feasible. The realisation of the system requires an economic decision which should be reached by comparing the estimated returns against the cost of designing, implementing and maintaining such a system.

8.8.3 Probabilistic Estimation of Load Factor

The approach adopted in this study can be classified as deterministic since the calculation of the daily load patterns was linked to typical but fixed timetables. The approach was appropriate for this study for it was mainly aimed at demonstrating the capability of the model in simulating a large scale rail network accurately. The approach still remains appropriate if the services are planned in advance and if the timetable input can be automated e.g. by digitizing the train timing diagrams.

This deterministic approach is not appropriate if a statistical measure of load factor variations at a fixed level of traffic is required for a continuously operating system, with no fixed timetables like the Central Division of the QR system. In current practice, daily operation patterns of the system are subject to random variations. They are determined by the signalling interlocking subsystem which keeps a safe distance between the trains and resolves the conflicts when they occur and the operational constraints discussed in Subsection 8.6.3.

The half-hour average energy demand of the system is being monitored continuously by the supply authority. The 1988 data suggests that the daily load patterns may vary drastically for a specific number of trains whereas the total demand over 24 hours is almost fixed. Therefore, a probabilistic approach must be considered to evaluate the distribution function of the daily load factor. To have a measure like this is important while negotiating a tariff structure for the electrical supply. Two alternative approaches can be considered :

a. In the conventional Monte-Carlo type approach the initial train positions will be generated randomly. Except loaders and unloader, the probability of being anywhere on its route which has not already been occupied is the same for each train. The trains that have been placed on a particular route will constrain the placement of the next train on the same route since two trains cannot be closer than the distance determined by the signalling interlocking subsystem.

b. Alternatively, a simulation run starting with a typical timetable and covering several days of operation under the signalling interlocking subsystem control and under the given operational constraints could be made. This approach is easier to implement than the Monte-Carlo type simulation since it does not involve the initialization of trains for daily runs. Repetitive daily operation patterns are unlikely since several mines and three unloaders are involved. Only the loading/unloading times etc. should be derived from a service time distribution function.

The apparent drawback of both alternatives is their very high CPU time requirements. The simulation model must be adapted to this type of application :

a. Instead of integrating the movement equations, each class of train will be assigned a runtime and the corresponding energy consumption (with a distribution function for both if required) for each signal block-to-block run and for each signal aspect combination. These figures can be calculated and held in the signal block nodes by running the simulation in its pure time-oriented mode. Then it is possible to run the simulation in the event-oriented mode without any movement calculations. The energy demand would be accumulated in the usual way.

b. Since the train movements would not be updated by point to point timings from a fixed timetable, the signalling and interlocking subsystem and the operational constraints of the system must be fully modelled. Single track sections would be controlled in the conventional way. Automatic signalling setting logic for the double track sections can be easily modelled since a 3-aspect fixed-block signalling scheme has been adopted. In cases of conflict the loaded coal train has the priority otherwise a 'first come first served' strategy would be used. The fixed timetable operation of other Stage 1 trains (i.e. intercity, suburban, freight) must also be simulated.

CHAPTER 9

FURTHER APPLICATIONS AND CONCLUSIONS

9.1 SUGGESTIONS FOR FURTHER APPLICATIONS

9.1.1 Further Deterministic Applications

This section describes some further applications the simulation model can support in addition to the ones that have already been described in Chapter 7 and Chapter 8 :

Train timing runs : In a timing run the trains are moved without any traffic regulation. This means if a fast train is following a slower one, it will 'pass through'. A timing run gives results which are a useful comparison with the actual and expected point-to-point timings. This enables the delays due to interactions of the trains to be predicted.

Signal layout tests : As has been demonstrated, different multi-aspect signalling schemes can be modelled with only minor modifications to software. Signal/track circuit layout data can be changed independently of the other track data which eases the task of experimenting with different signalling arrangements. Interlocking logic can also be tested by creating interdependencies between track circuits similar to the real systems.

Timetable and route assignment tests : The model runs the trains to given timetables and route data. It records the actual arrival and departure times. It also reports the conflicts between the trains and the delays due to these conflicts. Proposed timetables and alternative routes can easily be tested and propagation of delays can be examined should conflicts occur.

System capacity studies : The simulator can also be used for predicting the effects of different operation practices on the capacity of a rail transit system. It may be desirable to know if a certain level of traffic can be handled by an existing or proposed system, or find the capacity of a mixed traffic system under a given set of timetable constraints.

Train control and traction equipment simulation : The train speed control methods are coded within the tractive effort models. The characteristics of different traction equipments and train driving and control techniques including the allowances for jerk limiting etc. can be modelled. The modular structure of the software ensures that such local changes will have only local consequences in tractive effort modules. The effects of different running patterns e.g., under a different set of speed restrictions or coasting points, on energy consumption, runtimes etc. can also be easily examined.

System control techniques simulation : Although very different in technical details, all existing ATO/ATP/ATS systems are based on similar operational principles. The design of the data structures and processing methods of this simulation model are based on this generalization. Therefore, operation of the modern and more conventional systems should be simulated with no or minor modifications to the model.

Small area detailed simulation : The hyperdigraph structure of the rail network representation provides the facility to model a rail network down to every single diamond crossing, point and track circuit if required. By creating interdependencies between track circuits the operation of conflict areas e.g. yards, terminals, junctions etc. can be simulated in detail.

Power supply network solution : It is possible to interface the simulation model to one of the AC or DC power supply network models provided that a synchronized pure time-oriented mode of the simulation model is used. The recent interest in regenerative operation of trains on AC fed rail networks and the increase in the numbers of DC fed light rail transit and suburban rail networks should lead to an increasing interest in the power supply network modelling of these systems. Simplified calculations or models without proper power network representations are not reliable or useful to calculate complex interactions between the trains through the power supply system.

9.1.2 Optimization Applications

Having the simulation capability on which to proceed, it should be the aim of further research to explore new application areas in addition to conventional 'what-if' analysis and optimization is one of them.

In an analytic model, the optimization problem can be expressed in terms of explicit mathematical function. The optimization problem is then solved to yield the values that optimize the model's objective function. Unlike analytic models, simulation models cannot be constructed in the framework of an optimization process. The implementation of an optimization process in a simulation model can be achieved by systematically changing the input data according to previous output by making proper simulation runs. If the simulation process involves only one variable e.g., runtime, energy consumption, a systematic search technique can be used. The convergence of these techniques depends on the properties of the functions that measure the output of the model. For multivariable objective functions, the optimization process becomes unreliable, particularly in that the mathematical properties of the measure of output (i.e. response surface) are usually unknown.

For optimization applications, it is recommended that the simulation model should be driven by an 'optimization' module without impairing the integrity of the model. Some optimization applications can also be carried out as interactive sessions of 'what-if' studies to find 'feasible' or 'acceptable' solutions when optimization module is not available or when finding the 'optimum' is not essential.

Signal layout : The simulation model is especially suitable to signal layout exercises since the signal layout data can easily be modified. The objective in a signal layout optimization application should be to place signalling features on a track so that trains can run with a specified headway time without conflicts. The model should generate time versus distance profiles, then place the signalling features at the locations calculated by the optimization module and pass the corresponding headway times to the optimization module for corrections until sufficient results have been obtained.

Train scheduling : These applications usually have two objectives; to maximize network capacity with a given number of trains or to maintain a specified capacity with a minimum number of trains. Other objectives can be to minimize energy consumptions, point-to-point runtimes, number of train conflicts etc.. In practice a combination of these objectives can be used simultaneously. These objectives can be achieved by rescheduling trains and assigning new routes where possible under timetable constraints. In order to be able to use simulation in such applications successfully, a systematic method must be used instead of exhaustive enumeration.

9.1.3 Probabilistic Applications

The deterministic nature of the studies proposed above is not appropriate if statistical measures of the *simulation model* output under uncertain input conditions is required. An application of this kind has already been suggested in Chapter 8 to calculate a probability density function for the daily energy demand of a large scale rail network. In that example uncertainty can be defined as 'a lack of knowledge about the daily timetables' in a system where the number of trains is fixed.

There are some more common cases where the probability density functions e.g., passenger flow, station dwell times, train loads, runtimes etc., are known in advance. In some other cases, the probability density function of a variable e.g., station-to-station runtime, may not be known but the decision maker may possess the information that it is equal to one of the predetermined values and for example, a total run time cannot be exceeded.

For each of these cases a statistical measure can be obtained provided that the simulation runs can be repeated a sufficiently large number of times. Like optimization applications, this type of application of the simulation model requires a driver module which will systematically change the input data and collect the output. In such applications event-based features of the model should be enhanced in order to reduce computer processing times.

9.1.4 Realtime Applications

In recent years, there has been a parallel growth in software engineering techniques and in processing speeds and capabilities of inexpensive computers. In line with this, one can consider the possibility of developing a realtime control system which includes a fast and accurate predictive simulation feature. This predictive simulation feature would follow current realtime operation of a rail transit system and simulate ahead the possible effects of different control strategies. The results of these simulation runs would enable the supervisor (or the supervisory program) controlling the transit system to both solve current problems as they arise and optimize the operation according to any given criteria. A maximum energy demand control system of this kind has already been suggested in Chapter 8.

A second type of system which could be developed is an on-board version of the simulation model for each train as a part of a decentralized control system. The model could, for example, optimize the energy consumption while minimizing the runtime, based on current measurements and interfacing with the other trains through a central computer.

9.2 SUGGESTIONS FOR FURTHER SOFTWARE IMPROVEMENTS

9.2.1 Visual Output Design

There are a number of methods for 'visualizing' the running simulation. During the validation runs some trace statements have been included in the software, so that the values of relevant parameters are written after every simulation cycle. This type of tabular output is very difficult to follow. Once a valid model has been built, the simulation has been regarded as a 'black box' and the output has been processed after the simulation run. However, there are many situations where it is useful to view the simulation as it proceeds in time :

a. To validate the model - it is helpful to look at parts of the model in considerable detail, in order to check that the logic is correct.

b. To see how various elements interact and to identify the causes of the problems.

c. To interest users and help them interpret the simulation.

Train diagrams and histograms can be displayed as the simulation proceeds. Whilst displays such as these are very useful they do not provide a comprehensive insight into the detailed logic of train movements. Some of the modern transit systems employ 'dynamic iconic' displays to monitor the movement of trains. System elements such as lineside signals, trains, are represented by icons (i.e. symbolic representations) on a static background which represent the track layouts, stations etc. These icons change position or colour as the systems operates. A similar display with additional windows to display changing quantities (e.g. energy consumption histograms, number of active trains etc.) during the simulation run should be designed.

9.2.2 Data Input Automation

One of the major drawbacks of the simulation model is the amount of effort required to create new track and signal databases and to input and modify train route and timetables. A system that will read in these data from civil engineering drawings and train timing diagrams and a preprocessing software with a user friendly screen interface to transform these data into the format required by the simulation model is crucial for future large scale applications.

9.2.3 Knowledge-based Decision Rules

One approach to modelling complex decision-making mechanisms in simulation is to use situation-action rules, where chunks of knowledge are expressed in the form :

IF $\{s_1, s_2, s_3, \ldots, s_j\}$ THEN $\{c_1, c_2, \ldots, c_k\}$

where $s_1, \ldots, s_j$ are facts, or conclusions from other rules, and can be combined with logical operators AND, OR, and NOT. If the result of the logical operation is TRUE, it can be concluded that $c_1, \ldots c_k$ are true. This approach has been used to implement two basic conflict area control strategies in the model. More complex decision mechanisms should be expressed and implemented as a set of rules to enable the modelling of complex interlocking procedures and conflict area control strategies.

9.3 CONCLUDING REMARKS

The work presented in this thesis has mainly been concerned with the methodology of rail transit system modelling and the design and implementation of a general-purpose simulation model. A unified approach to seemingly different features of diverse rail transit systems, the utilization of modern software engineering techniques and the advances in the hardware technology have made this versatile, complex and fast simulation model possible with a consequent increase in the application areas. The model offers a novel solution to the rail transit system modelling and analysis problems faced by many operators and manufacturers. The validity of this solution has been demonstrated by various applications. A framework of methods, tools and guidelines has also been provided to support further research in this area. The main features of the model can be summarized as below :

a. The model described in this thesis is structurally suitable for the detailed simulation of mixed traffic situations on large scale complex rail networks. It can also be used for the simulation of mass rail transit and light rail transit systems. The simulation capability offered by this new model has been demonstrated by three diverse applications. In these applications, four different rail network configurations have been modelled and the train operations on them have been simulated without any major modification to software. The simulation model has been succesfully used as an analysis tool for predicting the effect of changes to operating patterns and as a design tool for predicting the energy demands of a set of timetables.

b. Unlike existing simulation models, which are either strictly time-oriented (continuous) or event-oriented (discrete), the model is designed with expandable event-oriented facilities depending on the type of application and the number and frequency of the interactions to be considered. These facilities will reduce the computational load running the simulation model in optimization, realtime and statistical simulation applications.

c. The model is different from the others in being a modern data-structure oriented design. The rail transit system components have been represented by using linked-list data structures which support an explicit, one-to-one correspondence with these components and their relationships. In parallel with this process, a set of train movement and traffic regulation methods have been coded which make the best use of these structures. This approach has not only afforded a more economical method of storage and a flexible model but also enabled train movements to be performed in a natural manner.

The different types of system it can simulate and the large domain of applications it can support should justify the high development cost of this simulation model.

APPENDIX 1

EXISTING SIMULATION MODELS AND THEIR APPLICATIONS

Location	Reference	Summary
Toronto	[109]	Digital continuous deterministic single train simulation in Fortran. Simulation is used to evaluate a proposed regenerative flywheel system.
Taiwan	[110]	Digital discrete stochastic entire system simulation in Simscript. Operation of a grossly underloaded system operating under strict priority rules and suffering from enormous accumulated delays is studied. The first results of the proposed policy are shown.
Disneyland	[111]	Digital discrete entire system simulation in a GPSS dialect (GESIMTEL). A dispatch policy is studied to optimize the system design. The results achieved in the simulation study were verified by operating the system at the derived optimum policy.
Hamburg	[112]	Hybrid simulation of a single train. The geometry of the track is optimized by calculating travel times, energy consumptions and braking distances as functions of track alignment alternatives.
U.S.A. North	[113]	Digital discrete simulation with some stochastic variables, written in Fortran. A demand activated single car intercity trip model is studied. Trips are generated according to an origin/destination demand matrix which is periodically updated.
British Rail	[114]	Digital discrete deterministic system simulation written in a dialect of Fortran. 4 aspect signalling used by BR is shown to cause instability when disturbances occur in the system. Interesting paper but the same conclusions could have been achieved by calculation of minimum headway time and showing their capacities.

NCTA	[115]	Digital continuous deterministic system simulation written in Fortran. A description of the model is given. The program was never verified.
San Francisco	[116]	Digital discrete interactive system simulation written for eventual on-line application on BART (Bay Area Rapid Transit System). The features of the simulator are described but the structure of the model is not described at all.
British Rail	[117]	Digital continuous system simulation (GATTS) written in Fortran. This version contains an optimization logic and is applied to new service planning, disturbance analysis, track capacity maximization and junction optimization problems. Unfortunately, the papers written on GATTS only give a minimum of information about one of the most used simulation models in the world.
Swiss Federal	[118]	Digital Discrete simulation stochastic simulation of two or more trains written in SIMULA to study track layout and signalling at junctions and small terminals. A superficial description of the simulation is given. It has been applied to problems in Zurich and Berne but no actual results are presented.
Paris	[119]	Digital discrete stochastic system simulation written in Simscript. Development of a headway time control and reduction method is described.
New York	[120]	Digital discrete simulation of an entire system written in Fortran. The report presents a short description of the programs. Examples of selected output are given. The descriptions are short and of a commercial nature.
London	[121]	Digital discrete stochastic simulation of an entire system written in SIMULA. The paper shows an example of the use of simulation in direct economic calculation of a proposed change in the system.
Rotterdam	[122]	Digital discrete stochastic simulation of a single line written in PL1. Probability distributions for runtimes and station waiting times are developed.
Montreal	[123]	Digital continous deterministic simulation of a single line. The study aims to reduce energy consumption through trajectory optimization for a metro line.

APPENDIX 1A

DERIVATION OF MONTREAL METRO SIGNAL BLOCK LENGTH CONSTRAINT

From the definitions given in Chapter 2, it has been seen that a train travelling at u_{int} (i.e. u_1) must be able to brake to stop within any given block in a 4-aspect signalling system. This gives rise to a constraint on block length :

$$z_j > d_j\ (u_{int},\ 0) \qquad \text{(A1.1)}$$

Consider a train travelling at maximum line speed u_{max} which is sent a yellow aspect at point x_{j-1} and a red aspect at point x_j. The three possible speed versus distance profiles which may arise are illustrated in the figure below. Note that only one of these profiles would represent the true situation at a given point x_{j-1}.

Case 1 : The train begins its braking action and reduces speed from u_{max} to u_{int} (i.e. u_1) within block j-1. It continues at u_{int} until reaching point x_j where it begins braking to eventually stop at point x_1 a distance d_j $(u_1,\ 0)$ from x_j.

Case 2 : The train begins its braking action but is unable to reduce its speed to u_{int} within block j-1. Braking continues until the train is eventually brought to a stop at the point $x_2 < x_1$.

Case 3 : This case is identical to Case 2 except that the train stops at the point $x_3 > x_2$. Reaction time is normally independent of train speed. Thus during the reaction time the distance travelled by a train whose speed was u_{max} would be greater than that travelled by a train whose speed was u_{int}. It can thus be seen that for certain values of reaction time and track gradients Case 3 could arise.

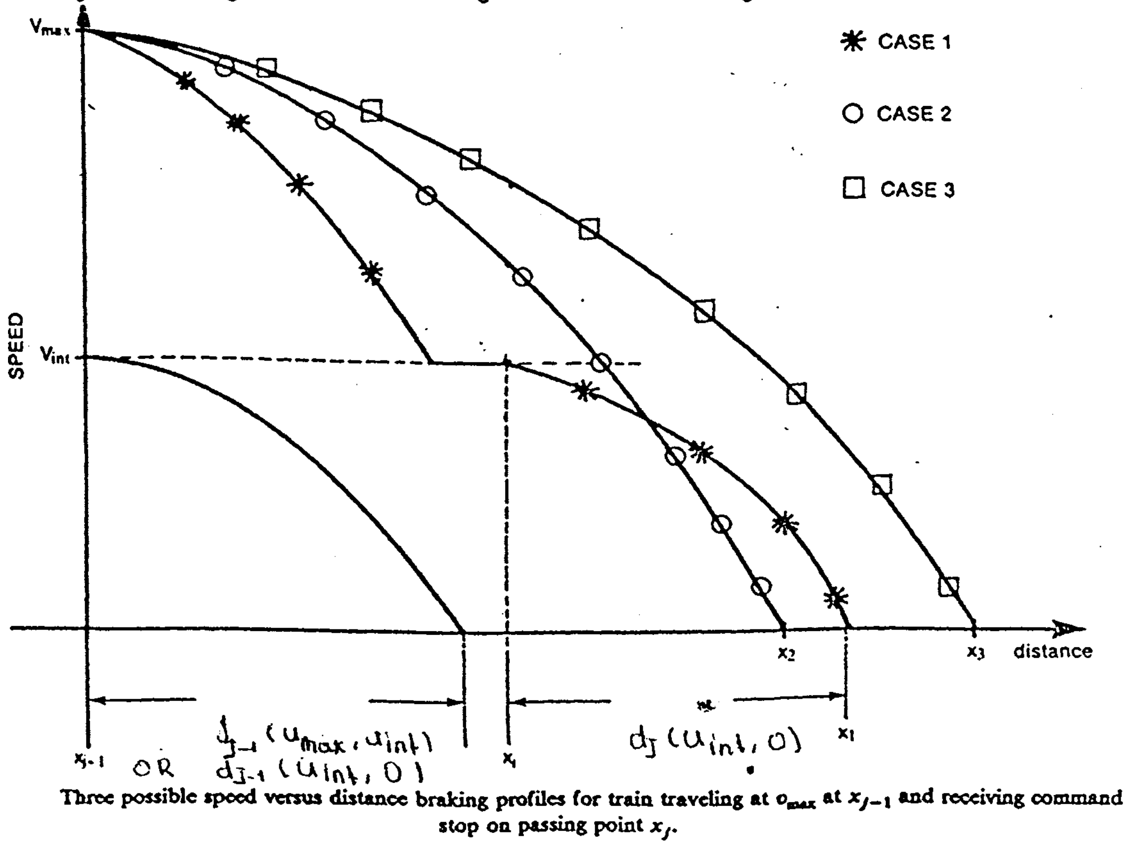
If either Case 1 or Case 2 arises at a given x_{j-1} the constraint on block length given in Equation A1.1 is sufficient to assure safe operation. But Case 3 gives rise to another constraint on block length :

$$d_{j-1}(u_{max}, 0) > z_{j-1} + d_j(u_{int}, 0) \text{ or}$$

$$z_j > d_{j-1}(u_{max}, 0) - z_{j-1} \qquad \text{(A1.2)}$$

From Equations A1.1 and A1.2, the overall constraint on block length becomes :

$$z_j = \max\left(d_j(u_{int}, 0), [d_{j-1}(u_{max}, 0) - z_{j-1}]\right) \qquad \text{(A1.3)}$$



Three possible speed versus distance braking profiles for train traveling at u_{max} at x_{j-1} and receiving command to stop on passing point x_j.

APPENDIX 2

PASCAL DECLARATIONS

Line section node (i.e. signal block/track circuit, gradient block, curvature block, civil engineering speed limit block) and vertex node declaration :

```
tracklink = ^datablocks
datablocks = RECORD
  id_number : ARRAY [1..4] OF integer;
  train_existence : boolean;
  CASE vertex : boolean OF
    true : (vertex_name : PACKED ARRAY [1..12] OF char;
            vertex_link : ARRAY [1..28] OF tracklink;
            CASE main : boolean OF
              true : (vertex_logic : ARRAY [1..4,1..4] OF integer;
                      train_order : ARRAY [1..4,1..2] OF integer;
                      thru_time : ARRAY [1..4,1..4] OF integer;
                      thru_route : ARRAY [1..4,1..4] OF integer);
              false: (length_shift : real));
    false : (section_link : ARRAY [1..5] OF tracklink;
             same_circuit : ARRAY [1..4] OF integer;
             block_location : ARRAY [1..2] OF real;
             more_circuits : ARRAY [1..4] OF real;
             block_length, block_value : real);
   END;
```

Timetable and route list structure node declaration :

```
timelink = ^timeroutetable;
timeroutetable = RECORD
  down, right : timelink;
  CASE head : boolean OF
    true : (next : timelink);
    false: (up,left : timelink;
            type_number : integer;
            row, col : integer;
            scheduled_time : integer;
            simulated_time : integer);
  END;
```

Specific and general train node declarations :

a. specific

```
trainlink = ^subgroup;
subgroup = RECORD;
  train_number : integer;
  train_string : ARRAY [1..12] OF char;
  current_time : integer;
  signal_time  : ARRAY [1..12] OF real;
  rst_spd, run_done : boolean;
  strain_link : train_link;
END;
```

b. general

```
grouplink = ^maingroup
maingroup = RECORD
  class_indent : ARRAY [1..4] OF integer;
  train_exit : boolean;
  class_size, train_model : integer;
  train_char : ARRAY [1..12] OF real;
  signal_speed, train_resist : ARRAY [1..4] OF real;
  network_links : ARRAY [1..4,1..12] OF datablocks;
  table_links : ARRAY [1..4] OF timetable;
  mtrain_link : subgroup;
END;
```

Node declaration for run profile structures :

```
runlink = ^runtimelist;
runtimelist = RECORD;
  rnlink1,rnlink2 : runtimelist;
  run_time : integer;
  run_dist : real;
  CASE head : boolean OF
    true : (cnlink1, cnlink2 : runtimelist;
            marklink : runtimelist;
            run_route : ARRAY [1..2] OF integer);
    false : (run_speed : real);
  END;
```

APPENDIX 3

DERIVATION OF

DC MOTOR MODEL

A3.1 DERIVATION OF TRACTIVE EFFORT IN MOTORING AND BRAKING

A3.1.1 Control Strategy

The control of each motor passes through 4 stages as the speed is increased :

Region 1A ($0 < \omega < \omega_1$): The armature and field currents are kept constant. The motor voltage is varied by controlling the mark/period ratio of the choppers. This ratio is increased as the machine speed is increased. Tractive effort remains relatively constant in this region.

Region 1B ($\omega_1 < \omega < \omega_2$) : The mark/period ratio still increases with the speed. The field current is still constant while the armature current is decreased with a slope s_1.

Region 2A ($\omega_1 < \omega < \omega_2$) : The mark/period ratio is equal to 1. The armature and field currents decrease as the speed increases.

Region 2B ($\omega > \omega_2$) : Similar to Region 2A, except that the slope of armature current is s_2.

A3.1.2 Calculation of Armature Current

It is assumed that armature current I_A is piece-wise continuous in three different regions of speed. In these regions it varies according to the given ω vs I_A (train speed vs. armature current) characteristics. In the actual traction equipment, a microprocessor based controller has made the implementation of this control strategy possible. This variation of I_A can be defined as a function of train speed ω and line voltage V_L as below for all regions of control :

$$I_A = \begin{cases} I_{Amax} & 0 < \omega < \omega_1\ (VL) \\ I_{Amax} - \dfrac{I_{Amax} - 325}{\omega_2 - \omega_1(V_L)} (\omega - \omega_1(V_L)) & \omega_1\ (V_L) < \omega < \omega_2 \\ 325 - 4.5\ (\omega - \omega_2) & \omega > \omega_2 \end{cases} \qquad (A3.1)$$

where V_L : line voltage [450...900 V, 750 V nominal]

$$I_{Amax}\ (V_L) = \begin{cases} 460\ [A] & 700 < V_L < 900 \\ 325 + 0.30\ (V_L - 450) & 450 < V_L < 700 \end{cases} \qquad (A3.2)$$

and breakpoints ω_1 and ω_2 defined as :

$$\omega_1\ (V_L) = \begin{cases} 35\ [km/h] & I_{Amax} > 460 \\ 35 + \dfrac{50 - 35}{460 - 325}(IAmax - 325) & \text{otherwise} \end{cases} \qquad (A3.3)$$

$$\omega_2 = 50\ [km/h]\ \text{constant} \qquad (A3.4)$$

A3.1.3 Calculation of Mark/period Ratio

The energy balance for each motor can be written as :

$$I_L V_L = I_L{}^2 R_L + 2R_T I_A{}^2 + 2R_T I_A{}^2 + 2EI_A + 2EI_A$$
$$+ 2I_A V_t + 2(1-\alpha)V_D I_A \qquad \text{(A3.5)}$$

where I_A : armature current, I_L : line current,

α : conduction ratio of chopper (mark/period ratio) and $IL = \alpha IA$

V_L : line voltage, R_L : filter choke resistance (line resistance)

and $R_T I_A = (R_A + R_F) I_A + V_B$

where R_A : armature resistance and R_F : field resistance

V_t, V_D, V_B : voltage drops in choppers, diodes and brushes

Replacing I_L by αI_A and neglecting $(1 - \alpha)V_D I_A$ which is very small Equation A3.5 can be rewritten as :

$$\alpha^2(I_A(R_L + R)) + \alpha(V_T - V_L) + (E + V_b) = 0 \qquad \text{(A3.6)}$$

This leads to a practical formula for the mark/period ratio of the choppers in regions 1A and 1B to be used in the model :

$$\alpha = \frac{(V_L - V_T) + \sqrt{(V_L - V_T)^2 - 4I_A(R_L + R_T)(E + V_b)}}{2(R_L + R_T)\ I_A} \qquad \text{(A3.7)}$$

where $I_A = I_L/\alpha$ (A3.8)

A3.1.4 Calculation of Flux

Field current I_f, like armature current I_A, is evaluated from the characteristics supplied by the manufacturer. In order to calculate the flux ϕ and therefore the induced voltage in Region 1A and Region 1B the following method is used.

$$I_f = \begin{cases} 22\ [A] & V_L > 600 \\ 0.1158\ VL - 47.47 & V_L < 600 \end{cases} \qquad (A3.9)$$

I_A is calculated using the equations given in Subsection A3.1.2.

The flux ϕ is then extracted as a function of I_f, I_A and V_L from the curves supplied by the manufacturer. Once the flux is known, the induced voltage E is easily calculated by using the basic equation of DC machines :

$$E = kn\phi \qquad (A3.10)$$

where k : DC motor constant, n : motor speed [rpm]

Outside the chopper control region (i.e. for the two field weakening regions 2A and 2B) the flux is directly calculated using the same basic motor equation as :

$$\phi = \frac{E}{kn} \qquad (A3.11)$$

where E is calculated as $E = \frac{1}{2} (V_L - I_A(R_A + R_L) - V_B - V_T)$ from the simplified circuit diagram of a logical motor (i.e. equivalent of 4 single motors)

A3.1.5 Calculation of Losses

The losses that are taken into account are of four kind. All are calculated using the equations supplied by the manufacturer.

Iron losses :

$$P_{fe} = 1.82\ (\phi / 1.85)^2\ (n/n_0)\ ((n + 3000)/(n_0 + 3000)) \quad (A3.12)$$

where $n_0 = 2200$

Friction loses :

$$P_{fr} = 0.8\ (n/n_0) + 0.005(n/n_0)^3 \quad (A3.13)$$

Eddy current loses :

$$P_t = 2.0\ (n/n_0)^{1.5}\ (I_A/I_{A0})^2 \quad (A3.14)$$

where $I_{A0} = 260$ A

Gear box losses :

$$P_{vx} = 1.5\ (n/n_0) \quad (A3.15)$$

Total loses for a single motor are therefore :

$$Pfsum = Pfe + Pfr + Pt + Pvx \quad [kW] \quad (A3.15)$$

A3.1.6 Calculation of Available Gross Tractive Effort

Air gap power of a single motor is :

$$P_{del} = EI_A/1000\ [kW] \quad (A3.16)$$

Power at the wheels for motoring is then calculated as :

$$P_{hjul} = P_{del} - P_{fsum} \quad (A3.17)$$

and similarly the tractive effort for braking is :

$$P_{hjul} = P_{del} + P_{fsum} \quad (A3.18)$$

Therefore, available gross tractive effort output from a logical unit consists of 4 single motors is :

$$Fehjul = 3.6 \frac{Pehjul}{\omega} \quad [kN] \qquad (A3.19)$$

A3.2 ORGANISATION OF MODULE

1. Calculate armature current I_A
2. If the motor is in chopper control region (i.e. regions 1A and 1B) then
   a. Calculate mark/period ratio α
   b. Calculate field current I_f and flux ϕ
   c. Calculate induced voltage E

   else
   a. Calculate induced voltage E
   b. Calculate flux ϕ
3. Calculate loses for a single motor
4. Calculate tractive effort

APPENDIX 4

STRUCTURE OF SIMULATION MODEL

MODULE 1 _ TRAIN

Method 1.1 TRAIN_STRUCTURES

* Reads in the general and specific train data.
* Creates circular lists for train classes and for individual trains of each class.
* Sorts the trains according to their entry times

Method 1.2 CONTROL_COMMANDS

* Reads in notch and active locomotive assignments
* Reads in specific speed restriction values and regions for each individual train.
* Reads train dependent signalling and interlocking data

Method 1.3 T_DIAGNOSIS

* Writes the train structures to a file (optional)

MODULE 2 _ NETWORK

Method 2.1 VERTEX_INITIALIZE

* Creates vertex structures according to the data read from the network construction file.

Method 2.2 NETWORK_SETUP

* Constructs the network frame by linking vertices with unweighted line sections.

Method 2.3 LINE_INITIALIZE

* Reads track geometry and speed restrictions from track data base to line sections, calculates the block positions.

* Checks the network structure and data base for consistency.

Method 2.4 N_DIAGNOSIS

* Writes the network structure to a file (optional).

MODULE 3_ ROUTE AND TIMETABLE

Method 3.1 CREATE_RTTABLE

* Reads timing and route data of individual trains.

* Creates a route/time table structure.

Method 3.2 RELEATE_RTTABLE

* Organizes the route/timetable structure.

* Links the train structures to the table and vice versa.

Method 3.3 MODEL_CHECK

* Performs a global consistency check over network, train, and route/time table structures

Method 3.4 R_DIAGNOSIS

* Writes the route/time table structure to a file (optional).

MODULE 4 _ SIGNAL

Method 4.1 SIGNAL_BLOCK_ON

* Reads in the signal block data for existing train routes.

* Creates and links signal block lists to network structure.

Method 4.2 SIGNAL_BLOCK_OFF

* Creates dummy signal blocks lists and links them to network structure.

Method 4.3 S_DIAGNOSIS

* Writes signal block lists to a file (optional).

MODULE 5 _ EFFECTIVE GRADIENT

Method 5.1 VERTEX_MODIFY

* Creates subvertices to accommodate the new effective track geometry lists.

Method 5.2 EFFECTIVE_GEOMETRY

* Calculates effective gradients.

* Calculates effective curvatures.

* Sorts the lists and links to the structure.

Method 5.3 G_DIAGNOSIS

* Writes the results of the calculations to a file (optional).

MODULE 6 _ PROFILE

Method 6.1 and Method 6.2 Calculate the braking profiles for the trains braking for track-based speed restrictions and scheduled stops.

MODULE 7 _ MOVEMENT

Method 7.1 CONFLICT_CONTROL

* At a predetermined point from the entrance of the conflict area gets the next vertex number from the time route table.

* Activates the chosen strategy. This usually involves checking all conflicting routes and trains.

* Connects the trains to the new line sections on their route.

* Releases the route completely or partially.

Method 7.2 SIGNAL_SET

* Checks the appropriate signal blocks ahead of trains and sets the signal aspect and signal speed limit accordingly.

Method 7.3 MOVE_TRAIN

* Chooses the target speed, tractive equipment model, tractive mode and acceleration controller regions.

* Calculates the available nett acceleration by deducing the effects of track geometry and train resistance from the gross tractive effort. Calculates the controlled nett acceleration according to the strategy chosen.

* Calculates the train displacements and final speeds.

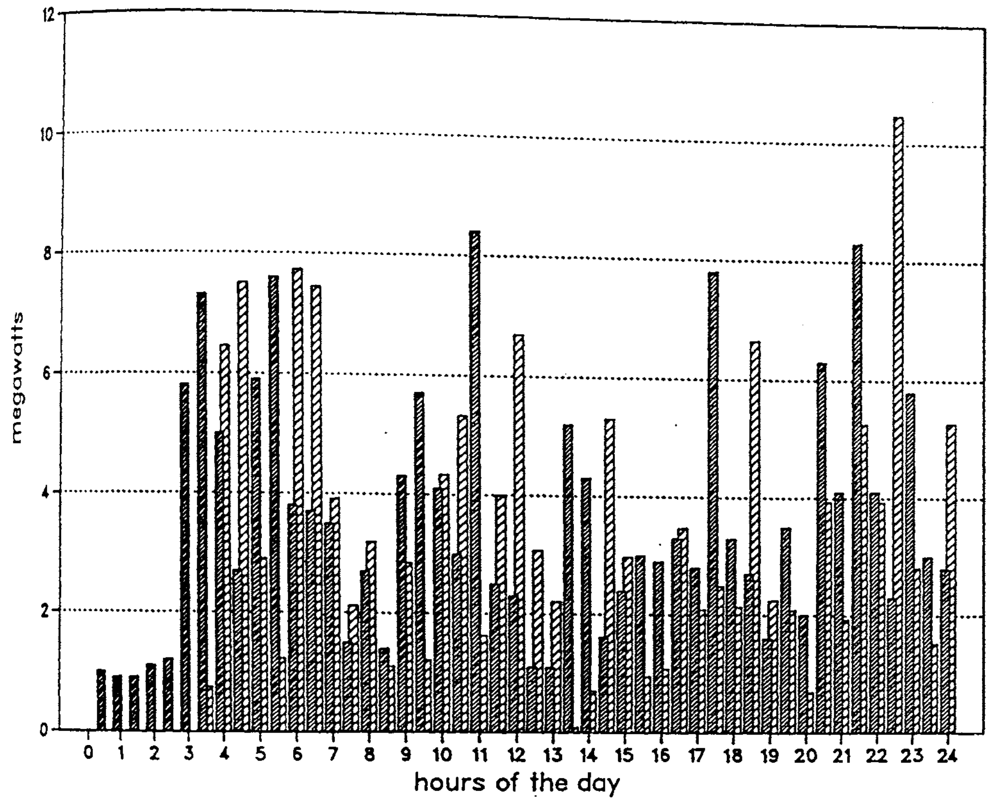
Method 7.3 TRAIN_SEQUENCE

* Enters and removes the trains from the rail network. Updates train structures.

APPENDIX 5

COMPARISONS OF SIMULATED AND MEASURED SUBSTATION ENERGY DEMANDS FOR 1988 RUN

supply point demands _ sub 1 OONOOIE



Legend
MEASURED MW
SIMULATED MW

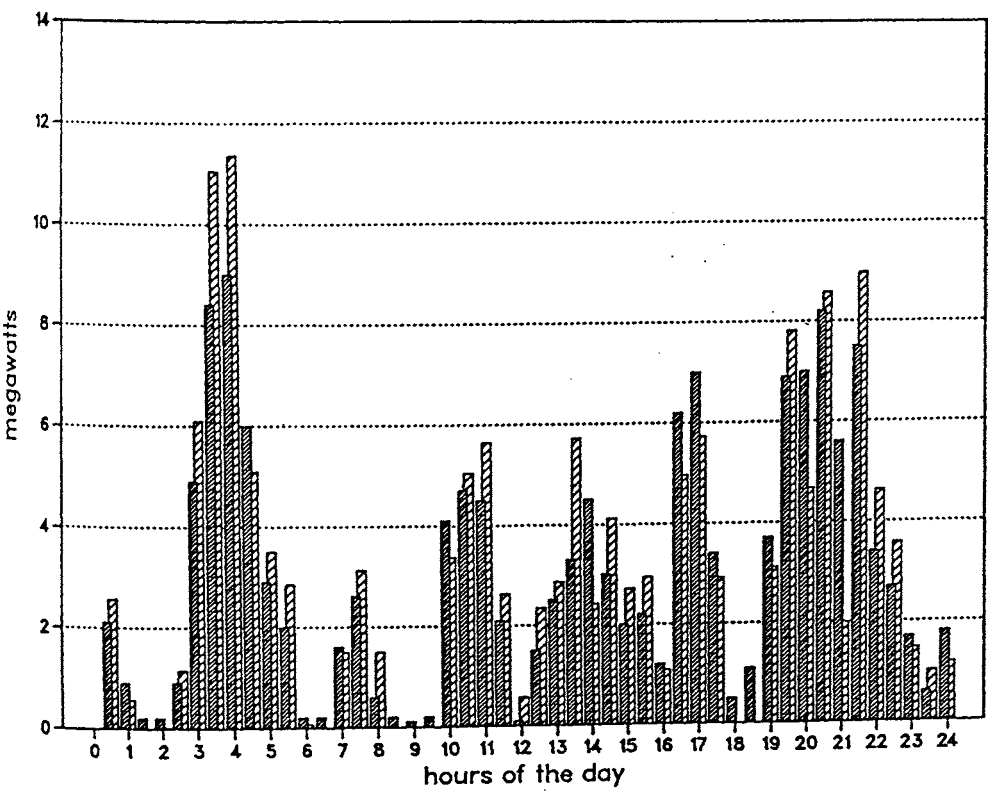
SIMULATION RESULTS :

maximum demand = 10.48 MW
occurred between 22.0 22.5 hours
minimum demand = 0.00 MW
occurred between 0.0 0.5 hours
average demand = 3.00 MW
standard deviation = 2.48
total consumption = 71.94 MWh
DAILY LOAD FACTOR = 28.60 %

simulation performed :
on 06/09/89 at 16:25:4
with 7 consists
output processed :
on 06/09/89 at 17:05:52

simqr.pascal/TT/TRG/BU/

supply point demands _ sub 2 WANDOO



Legend
MEASURED MW
SIMULATED MW

SIMULATION RESULTS :

maximum demand = 11.36 MW
occurred between 3.5 4.0 hours
minimum demand = 0.00 MW
occurred between 1.0 1.5 hours
average demand = 3.18 MW
standard deviation = 2.88
total consumption = 76.25 MWh
DAILY LOAD FACTOR = 27.97 %

simulation performed :
on 06/09/89 at 16:25:4
with 7 consists
output processed :
on 06/09/89 at 17:09:34

simqr.pascal/TT/TRG/BU/

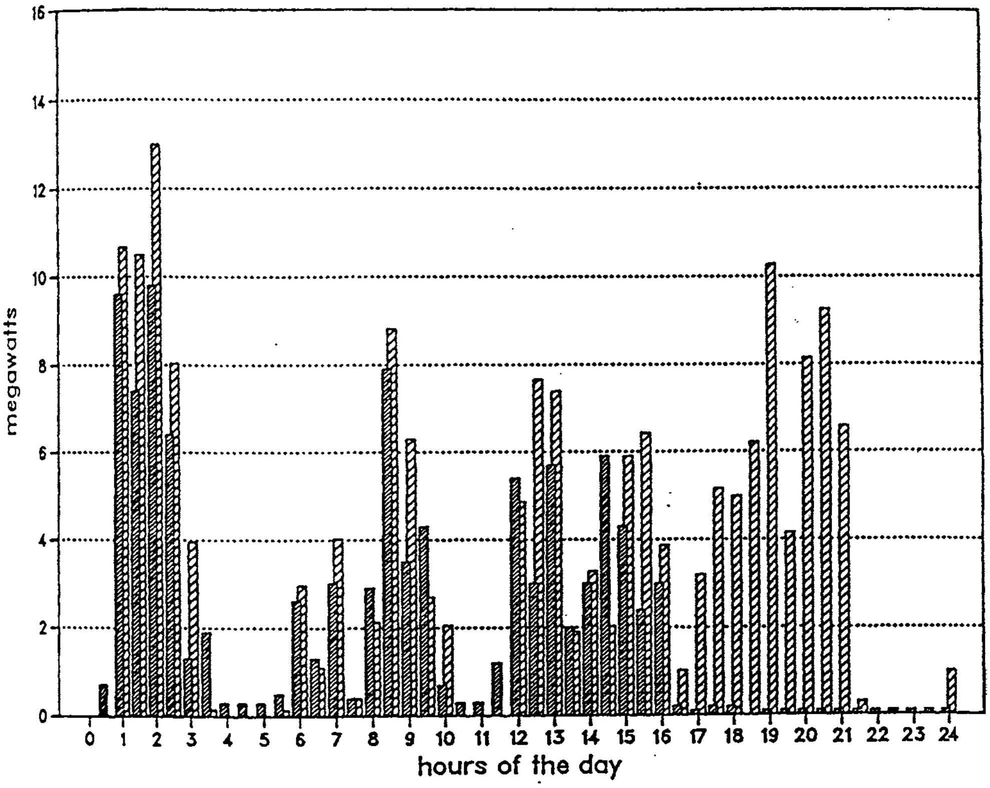
SIMULATION RESULTS :

maximum demand = 12.99 MW
occurred between 1.5 2.0 hours
minimum demand = 0.00 MW
occurred between 0.0 0.5 hours
average demand = 3.76 MW
standard deviation = 3.63
total consumption = 90.25 MWh
DAILY LOAD FACTOR = 28.95 %

simulation performed :
on 06/09/89 at 16:25:4
with 7 consists
output processed :
on 06/09/89 at 17:12:57

simqr.pascd/TT/TRG/BU/

supply point demands _ sub 3 COPPABELLA



Legend
MEASURED MW
SIMULATED MW

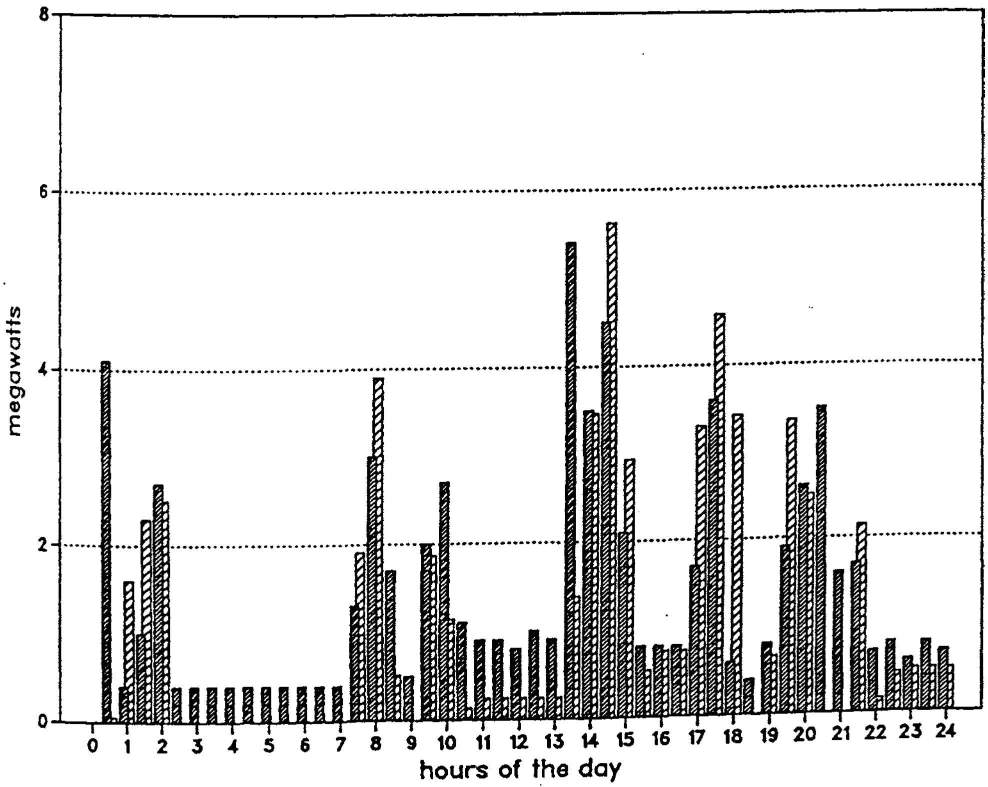
SIMULATION RESULTS :

maximum demand = 5.62 MW
occurred between 14.0 14.5 hours
minimum demand = 0.00 MW
occurred between 2.0 2.5 hours
average demand = 1.14 MW
standard deviation = 1.45
total consumption = 27.34 MWh
DAILY LOAD FACTOR = 20.27 %

simulation performed :
on 06/09/89 at 16:25:4
with 7 consists
output processed :
on 06/09/89 at 17:14:24

simqr.pascd/TT/TRG/BU/

supply point demands _ sub 4 MORANBA



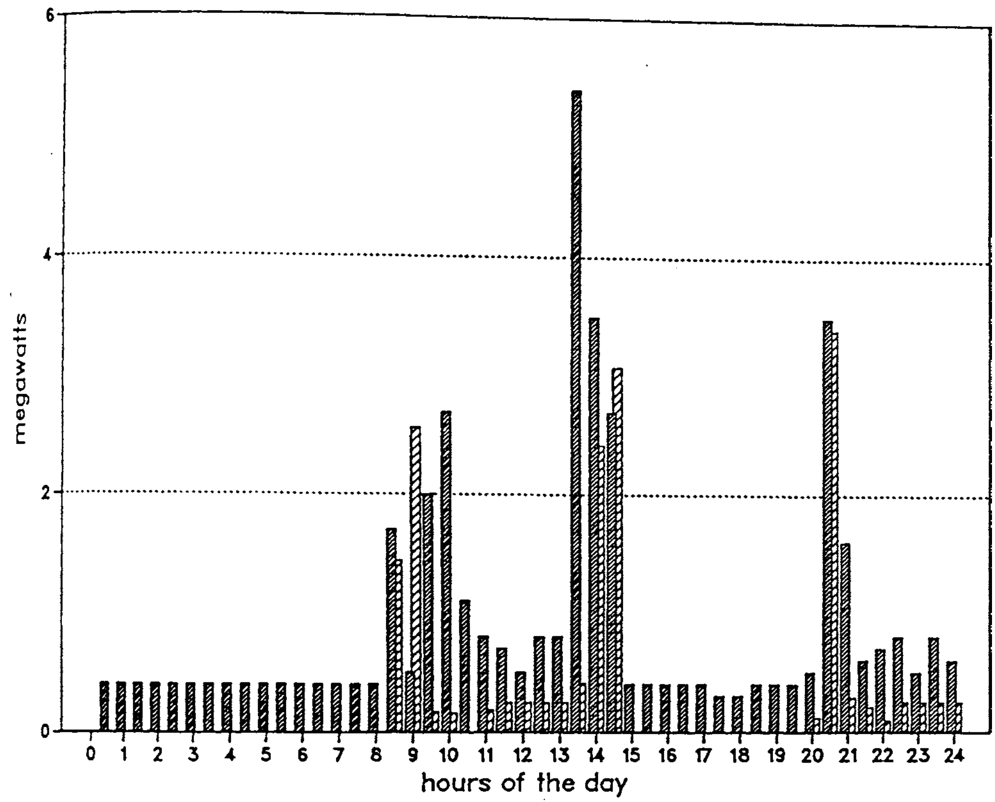
Legend
MEASURED MW
SIMULATED MW

supply point demands _ sub 5 MT. MCLAREN

SIMULATION RESULTS :
maximum demand = 3.40 MW
occurred between 20.0 20.5 hours
minimum demand = 0.00 MW
occurred between 0.0 0.5 hours
average demand = 0.34 MW
standard deviation = 0.81
total consumption = 8.28 MWh
DAILY LOAD FACTOR = 10.15 %

simulation performed :
on 06/09/89 at 16:25:4
with 7 consists
output processed :
on 06/09/89 at 17:18:52

simgr.pascal/TT/TRG/BU/

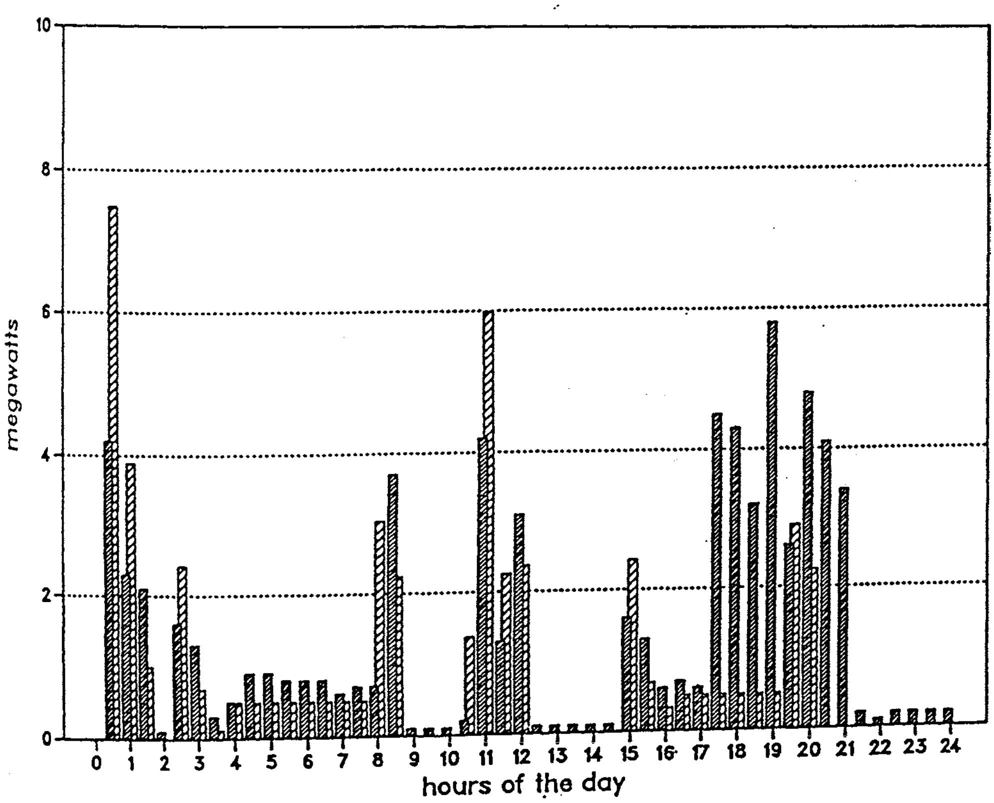


supply point demands _ sub 6 PEAK DOWNS

SIMULATION RESULTS :
maximum demand = 7.48 MW
occurred between 0.0 0.5 hours
minimum demand = 0.00 MW
occurred between 1.5 2.0 hours
average demand = 1.01 MW
standard deviation = 1.57
total consumption = 24.21 MWh
DAILY LOAD FACTOR = 13.49 %

simulation performed :
on 06/09/89 at 16:25:4
with 7 consists
output processed :
on 06/09/89 at 17:19:33

simgr.pascal/TT/TRG/BU/

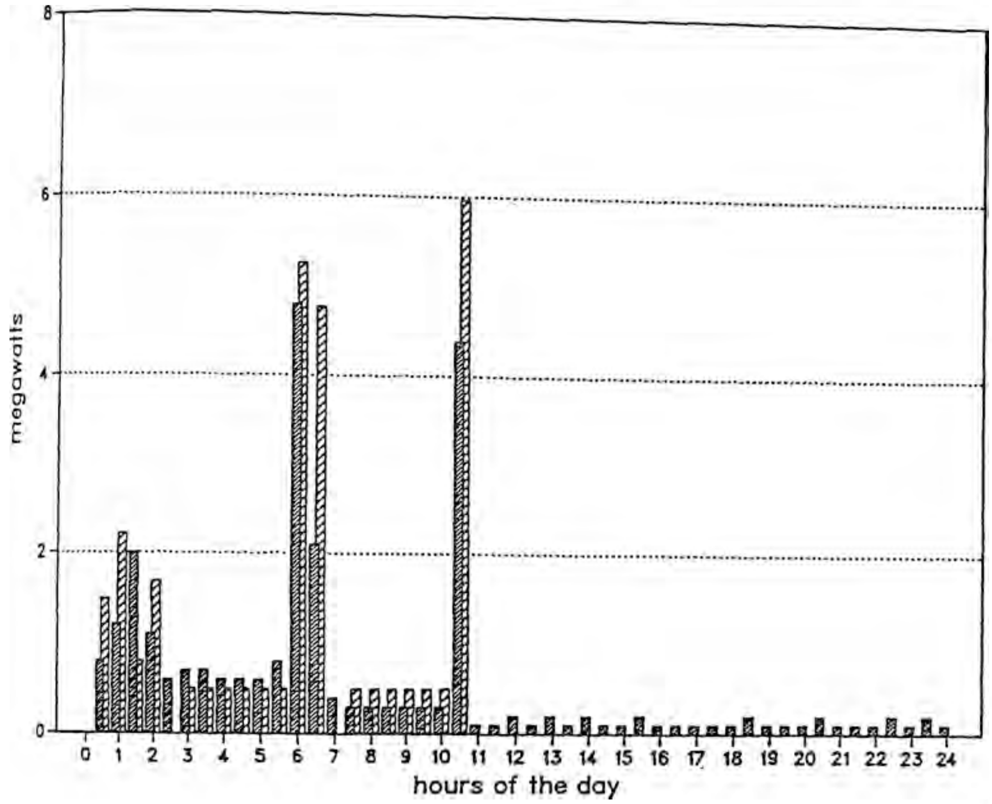


SIMULATION RESULTS :
maximum demand = 5.97 MW
occurred between 10.0 10.5 hours
minimum demand = 0.00 MW
occurred between 2.0 2.5 hours
average demand = 0.59 MW
standard deviation = 1.33
total consumption = 14.08 MWh
DAILY LOAD FACTOR = 9.83 %

simulation performed :
on 06/09/89 at 16:25:4
with 7 consists
output processed :
on 06/09/89 at 17:20:10

simqr.pascal/TT/TRG/BU/

supply point demands _ sub 7 NORWICH



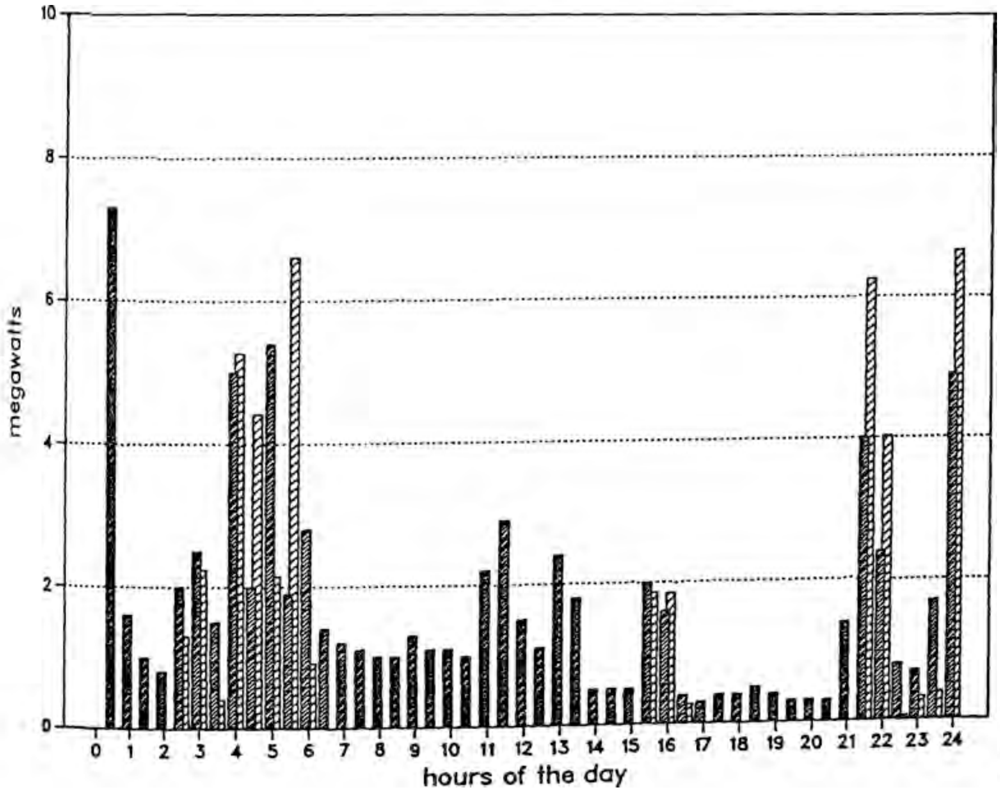
Legend
MEASURED MW
SIMULATED MW

SIMULATION RESULTS :
maximum demand = 6.65 MW
occurred between 23.5 24.0 hours
minimum demand = 0.00 MW
occurred between 0.0 0.5 hours
average demand = 0.94 MW
standard deviation = 1.89
total consumption = 22.51 MWh
DAILY LOAD FACTOR = 14.11 %

simulation performed :
on 06/23/89 at 05:44:3
with 7 consists
output processed :
on 06/23/89 at 06:31:15

simqr.pascal/TT/TRG/BU/

supply point demands _ sub 8 CALLEMONDAH



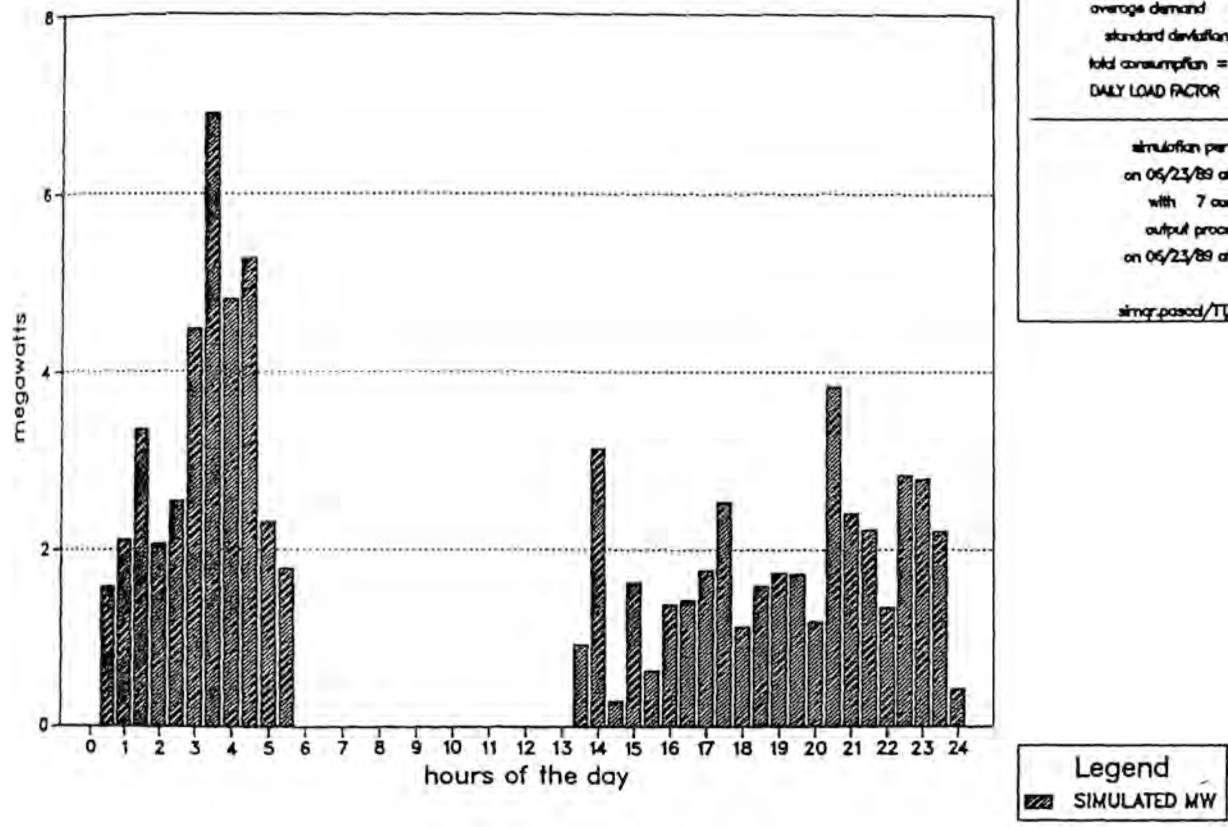
Legend
MEASURED MW
SIMULATED MW

SIMULATION RESULTS :
maximum demand = 6.90 MW
occurred between 3.0 3.5 hours
minimum demand = 0.00 MW
occurred between 5.5 6.0 hours
average demand = 1.59 MW
standard deviation = 1.61
total consumption = 38.25 MWh
DAILY LOAD FACTOR = 23.10 %

simulation performed :
on 06/23/89 at 05:44:3
with 7 consists
output processed :
on 06/23/89 at 06:35:47

simgr.pascal/TT/TRG/BU/

supply point demands _ sub 9 ROCKLANDS

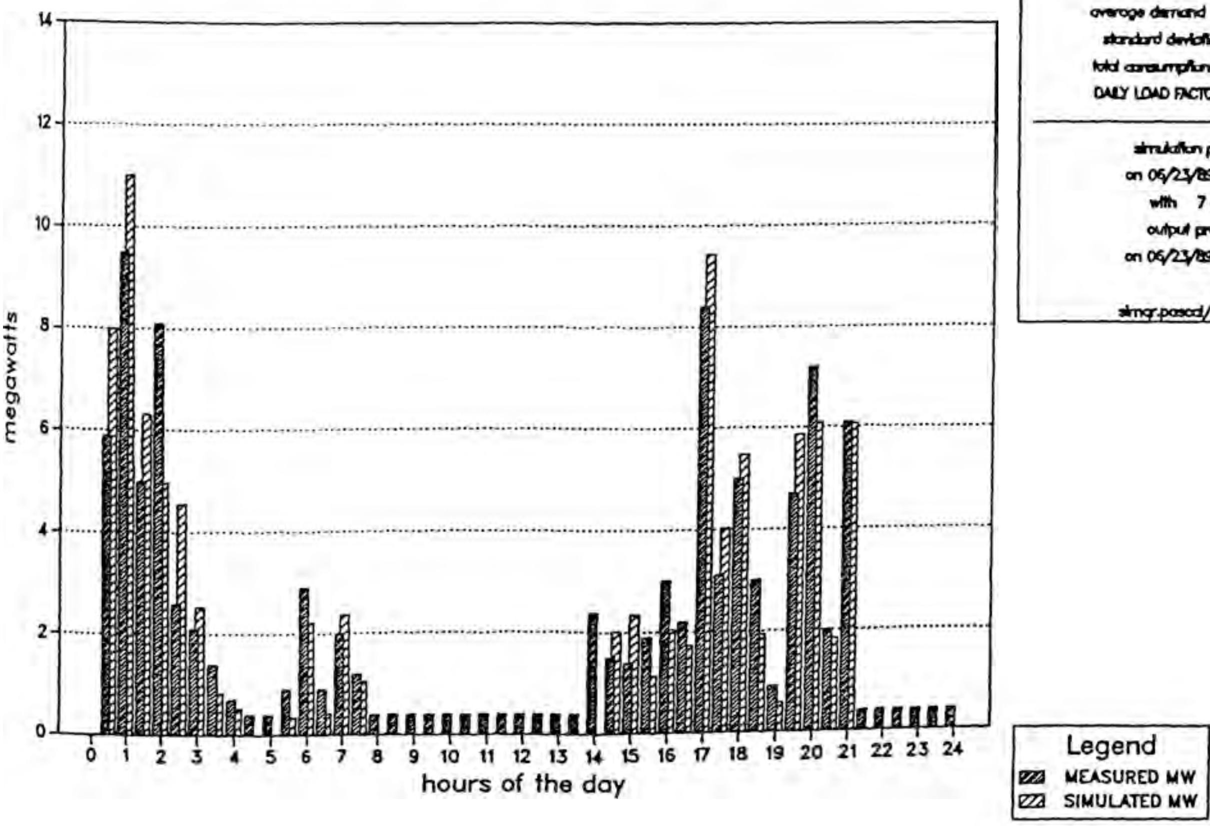


SIMULATION RESULTS :
maximum demand = 11.02 MW
occurred between 0.5 1.0 hours
minimum demand = 0.00 MW
occurred between 4.0 4.5 hours
average demand = 2.00 MW
standard deviation = 2.80
total consumption = 47.92 MWh
DAILY LOAD FACTOR = 18.12 %

simulation performed :
on 06/23/89 at 05:44:3
with 7 consists
output processed :
on 06/23/89 at 06:37:29

simgr.pascal/TT/TRG/BU/

supply point demands _ sub 10 GRANTLEIGH

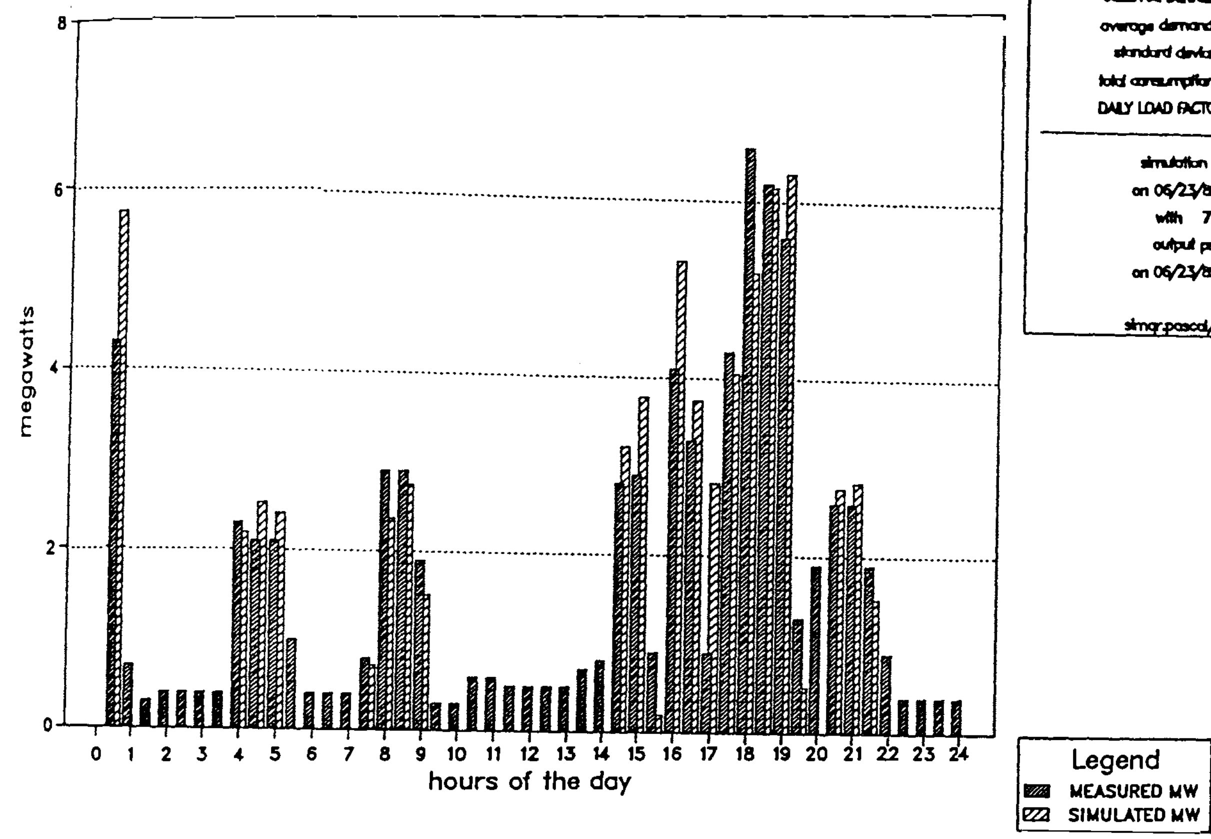


SIMULATION RESULTS :
maximum demand = 6.32 MW
occurred between 18.5 19.0 hours
minimum demand = 0.00 MW
occurred between 0.5 1.0 hours
average demand = 1.43 MW
standard deviation = 1.97
total consumption = 34.35 MWh
DAILY LOAD FACTOR = 22.65 %

simulation performed :
on 06/23/89 at 05:44:3
with 7 consists
output processed :
on 06/23/89 at 06:40:12

simgr.pascal/TT/TRG/BU/

supply point demands _ sub 11 DINGO

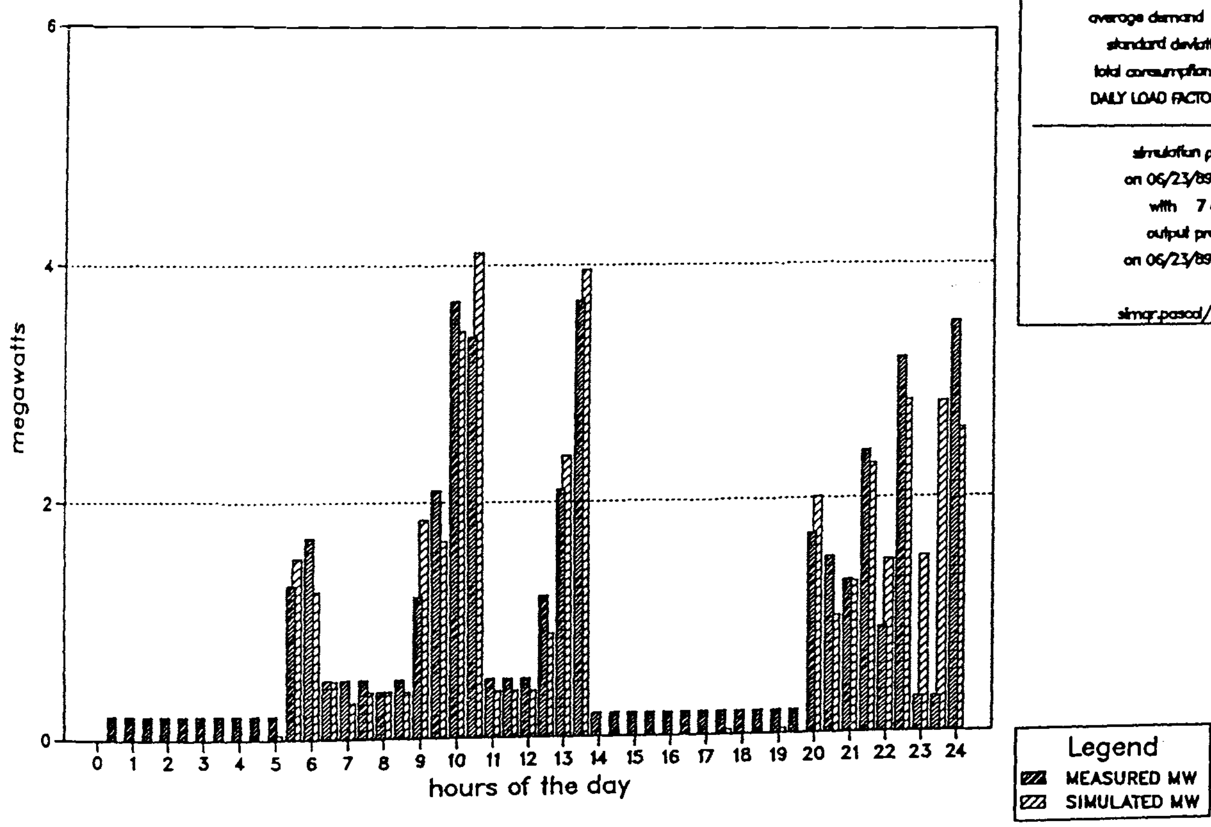


SIMULATION RESULTS :
maximum demand = 4.11 MW
occurred between 10.0 10.5 hours
minimum demand = 0.00 MW
occurred between 0.0 0.5 hours
average demand = 0.88 MW
standard deviation = 1.17
total consumption = 21.10 MWh
DAILY LOAD FACTOR = 21.40 %

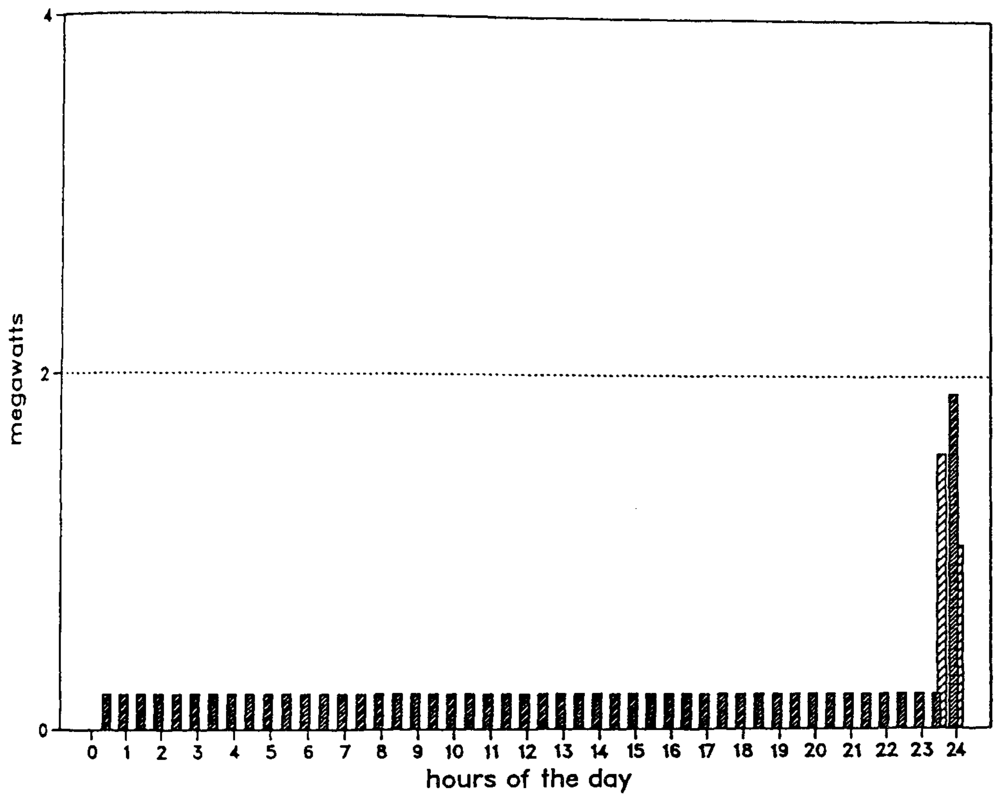
simulation performed :
on 06/23/89 at 05:44:3
with 7 consists
output processed :
on 06/23/89 at 06:42:52

simgr.pascal/TT/TRG/BU/

supply point demands _ sub 12 RANGAL



supply point demands _ sub 13 GREGORY



Legend
MEASURED MW
SIMULATED MW

SIMULATION RESULTS :
maximum demand = 1.56 MW
occurred between 23.0 23.5 hours
minimum demand = 0.00 MW
occurred between 0.0 0.5 hours
average demand = 0.05 MW
standard deviation = 0.27
total consumption = 1.30 MWh
DAILY LOAD FACTOR = 3.47 %

simulation performed :
on 06/23/89 at 05:44:3
with 7 consists
output processed :
on 06/23/89 at 06:45:25

simgr.pascal/TT/TRG/BU/

APPENDIX 6

DATA PREPARATION AND INPUT FILE FORMATS

INTRODUCTION

Two source data files for each section of the network were supplied by Queensland Railways. The first of these files (*.TRK) contains vertical and horizontal track profile data and speed restrictions (i.e. gradient, curvature and civil engineering speed restriction data) while the second file (*.FET) contains data relating to track configuration such as junction, terminal, point and signal block locations and types. Naturally, the structure of these files is not compatible with the ones required by the simulation model, so a suite of preprocessing programs were written. The first part of this appendix describes the data preparation process. In the second part, the main input files of the simulation model are described with examples.

a) Program: METRICTRK. FORTRAN
Input File: *. TRK
Output File: *. MOD
Function: Detects the sections of the data given in imperial units and replaces them with the metric equivalents. The original structure is not modified.

b) Program: REFSHIFT. FORTRAN
Input File: *. MOD
Output File: *. REF
Function: Deals with the reference shifts. The original file structure is not modified except the distances are incremental from zero to maximum section length. Also useful to join *. MOD files.

c) Programs: GRDCON. FORTRAN,
SPDCON. FORTRAN,
CRVCON. FORTRAN
Input File: *. REF
Output File: *. GRD,
*. SPD,
*. CRV
Function: Separates the single track data file into three files (i.e. gradients, curvatures and civil speed restrictions). In the input file one line of data is required for the start and end of every gradient, curvature, and speed restriction (i.e. location at which it changes). The data is compressed and all comments are omitted.
Format:
length [m] value [1 in x meters for gradient]
[km/h for speed restrictions]
[radius in metres for curvature]

d) Program: LENGTHCHK. FORTRAN

Input File: *. GRD,
*. SPD,
*. CRV,
*. REF

Function: Compares the total section lengths in the data files. Prints error messages if the totals are not consistent.

e) Program: CHOP. FORTRAN

Input File: *. GRD,
*. SPD,
*. CRV
*. POS

Output File: GRDSPDCRV. DAT

Function: Creates a file which is compatible with the format required by the simulator to set up the rail network. Files *. POS contain the positions of the vertices in ascending order. The program can cope automatically with standard passing and ballon loops and duplicated tracks but the other structures require manual manipulation of the output file. The file from different track sections then combine to form the GRDSPDCRV. DAT whose format will be defined in a following section.

3.8.2 Format Of The Network Configuration File

File Name: NETWORKCON. DAT

Definition: This file defines the configuration of the rail network including the identifiers of the vertices and their interconnections. The file consists of two parts. The first part contains the names and type identifiers of the vertices. A number which is simply the order of the vertex in the file is also assigned. The Stage 2 of QR network consists of 77 vertices and 112 interconnections (i.e. line sections, zero length connections). The vertex types are defined as below:

Format Of The Track Data File

File name: GRDSPDCRV .DAT

Definition: The file starts with the first vertex and progresses in ascending order until all the track data is exhausted. Each vertex section of the file contains the gradients, speed restrictions and curvatures between the vertex and the vertices it is connected to for both directions. The order of adjacent vertices must be the same in section 2 of the network configuration file. Duplication of the data is allowed.

Format: For each vertex, first line of data; the numbers of the vertices involved second line of data; total number of break points, total length of the line section. These are followed by the line section track data in *. GRD, *. SPD or *. CRV format. Repeated for each vertex and for gradient, speed restriction and curvature data; length [m] and value.

Format Of The Signal Block Data File

File name: SIGNALBLK. DAT

Definition: The file contains the positions of the signal blocks and overlaps in both direction of travel. Its format is the same as the track data file.

Keeping this file independent of the track data file has two advantages. The simulator was originally developed to experiment with the signal layout and signalling strategies so it is important to be able to change signal positions without changing the track data file. Alternatively, if no signalling is required the simulator can run without this file.

Format: Two lines of data, the number of the vertices involved, number of break points and line section length followed by signal block data;
length of signal block [m]
length of overlap [m]

Format Of The Traction Data File

File names: QRROLSTK1. DAT,
QRROLSTK2,.DAT

Definition: This file contains the train speed controller parameters and the rolling stock data for the movement and electrical input calculations. The simulation of train/locomotive systems using this data has been discussed earlier in this report. The file consists of three parts. The first part contains the parameters required for the speed controller emulation and maximum notch setting for empty and loaded trains.

The second part contains the coefficients of the 10 ASEA tractive effort curves TK6103-860 (notches 1-10 at 25 kV, full bridge).

The third part contains data relating to train consists, weights, lengths, electrical efficiency, auxiliary load, adhesion factor, train resistance etc.

Format: See the file given

Format Of The Speed Restriction, Notch And Locomotive Assignment File

File name: CTCONTROL. DAT

Definition: This file has two main parts; notch and loco assignment and speed limit assignment.

Part 1: This part contains data on the notch and active loco assignments for the particular section of the network. This data is derived from J. Wecker's notes (received 9/9/88), R.J. Galvin's letter (received 26/1/89), and our own experience with the network.

Part 2: This part contains data on dynamic speed restriction assignments. This allows speed changes to particular trains over a particular section of the network within a given time interval. The data in this part serves for two purposes.

Firstly changing the speed restrictions dynamically is a strategy to be exploited to increase the load factor of the system. Secondly, it has been observed from the timing diagrams that the same type of trains can travel at different average speeds on the same sections of the network.

This is especially true between Yukan and Jilalan.

Format:

Part 1: One line new notch and active locomotive assignments for loaded trains and one line new notch and active locomotive assignments for empty trains (if 0 no new assignment) followed by a set of vertices.

Part 2: One line of flags (1 0 loaded, 0 1 empty, 1 1 both, 0 0 none). One line train type and train numbers set. One line time interval start and end. One line of set of vertices.

An example of the file is given

Format Of The Time/Route Table File

File name: TIMEROUTE. DAT

Definition: This file contains all relevant data on the timetables and routes of the train. For every train there exists a block of data which includes the vertices the train passes through (route), waiting and arrival times if available, main/loop, loaded/empty flags, entry and re-entry times.

Format: For each train four lines of train identifier and heading. For each vertex on the route one line of data, containing vertex number; arrival time (hours, minutes, seconds) if given, otherwise 999. Waiting time if train stops, otherwise -1; main/loop flag; loaded/empty flag. For each entry or re-entry one line of data containing entry time; re-entry time; -240000 to end the block.

3.8.8 Format Of The Electrical Section File

File name: ELECSEC. DAT

Definition: This file contains the data to divide the rail network into the electrical feeding sections. For every electrical section there exists a block of data which contains the positions of the neutral sections limits and the set of vertices contained within the electrical section.

Format: One line of data for each neutral section and each track. Each line consists of two uproad vertex numbers; the distance of the N/S from the second vertex, two downroad vertex numbers; the distance of the N/S from the second vertex. One line of data which is the set of vertices in the electrical feeding section.

Note that two consecutive electrical feeding sections define a substation area.

The file used for Stage 2 is given

Format Of The Simulation Configuration File

File name: CONFIG.DAT

Definition: This file keeps the simulator configuration data. The file can be written or modified using either a purpose written program or an editor. The file contains data lines on simulation type (time-based/ combined), simulator time increment (0.1 to 4 seconds), simulation window (start and end time) and several switches to control signal file input and signalling, diagnostic files, graphical files, energy calculation and harmonic calculations.

type 1 : 1_branch vertex
    subtype 1: line ends, end of ballon loops and Jilalan Yard.

type 2 : 2_branch vertex
    subtype 1: intermediate simple station
    subtype 2: balloon loop entry/exit points

type 3 : 3_branch vertex
    subtype 1: single line passing loop
    subtype 2: single line junction
    subtype 3: duplicated track crossover
    subtype 4: duplicated unidirectional crossover

type 4 : 4_branch vertex
    subtype 1: crossover + passing loop
    subtype 2: centre passing loop
    subtype 3: balloon loop + passing loop
    subtype 4: Jilalan Yard

The vertex interconnections are defined in the second part of the file.

Format:

Part 1: Two lines of data contain type, subtype identifiers and name, number of a vertex.

Part 2: Two lines of data contain the number of a vertex and the numbers of the vertices to which it is connected. The number of connections is limited to 4.
The network construction file of Stage 2 is given in Appendix 3.2.

```
******************************************************************** *
*                                                ************        *
*  RAW TRACK DATA - COPPABELLA TO GOONYELLA  *    * *****  SEPT '86  *
*                   MLE STAGE 2                ******** *            *
*                   DATA UPDATE SEPTEMBER '86                        *
*                                                                    *
 ******************************************************************* *
```

ADD GOONDNLD ACETRACK

reference shift	metric	gradient	curvature	speed limit			information	
4	145.432	77		0.0	0	0	99899	T/O SARAJI
4	91-41.0	77		0.0	0	0	99899	T/O SARAJI
0	91-69.6	63		0.0	0	0	99899	146 KP
0	92- 2.0	85	+.0650	0.0	0	0	0	
0	92-39.7	85		0.0	0	0	99899	147 KP
0	93- 8.9	85		0.0	0	0	99899	148 KP
0	93-22.7	85		-40.0	0	0	0	
0	93-33.0	77	-.0400	-40.0	0	0	0	
0	93-51.2	77		0.0	0	0	0	
0	93-58.8	77		0.0	0	0	99899	149 KP
0	93-60.7	77		+25.0	0	0	0	
0	imperial	-100	+.0840	+25.0	0	0	0	
0	94- 0.4	-100		0.0	0	0	0	
0	94- 5.7	-100		-25.0	0	0	0	
0	94- 7.0	-116	-.0450	-25.0	0	0	0	
0	94-13.0	-100	-.0450	-25.0	0	0	0	
0	94-13.9	-100		0.0	0	0	0	
0	94-28.7	-100		0.0	0	0	99899	150 KP
0	94-61.1	-100		+30.0	0	0	0	
0	94-62.0	-114	-.0400	+30.0	0	0	0	
0	94-79.0	-114		+30.0	0	0	99899	151 KP
0	95-03.0	-100	+.0400	+30.0	0	0	0	
4	95- 3.4	-100		0.0	0	0	0	
4	95- 3.9	-100		0.0	0	0	0	
0	95-09.0	-100		+25.0	0	0	0	
0	95-10.0	-116	-.0450	+25.0	0	0	0	
0	95-27.0	-106	+.0250	+25.0	0	0	0	
0	95-27.7	-106	.	0.0	0	0	0	
0	95-47.5	-106		0.0	0	0	99899	OCC. X'ING
0	95-48.4	-106		0.0	0	0	99899	152 KP
0	95-64.0	-100	+.0200	0.0	0	0	0	
0	96-18.1	-100		0.0	0	0	99899	153 KP
0	96-31.9	-100		-40.0	0	0	0	
0	96-33.0	-110	-.0300	-40.0	0	0	0	
0	96-45.5	-110		0.0	0	0	0	
0	96-51.5	-110		0.0	0	0	99899	SLAB CREEK
0	96-52.0	0	-.0429	0.0	0	0	0	
0	96-61.9	0		-40.0	0	0	0	
0	96-67.8	0		-40.0	0	0	99899	154 KP
0	96-78.8	0		0.0	0	0	0	
0	97-24.0	-132	+.0830	0.0	0	0	0	
0	97-27.7	-132		+40.0	0	0	0	
0	97-36.5	-132		0.0	0	0	0	
0	97-37.7	-132		0.0	0	0	99899	155 KP
0	97-42.0	688	-.0496	0.0	0	0	0	
0	97-50.0	688		0.0	0	0	99899	NORTH CREEK

RAW TRACK DATA SUPPLIED BY QUEENSLAND RAILWAYS

QUEENSLAND RAILWAYS STAGE 1
NETWORK CONSTRUCTION FILE "networkfi" INPUT APRIL 1989 / TT

225 total number of line sections
158 total number of vertices
158 number of the referred vertices

1234567890123456789012345678901234567890123456789012345678912345678 90

V. 1	1 : 1	IVERAGH	C. 2			
V. 2	3 : 1	IVERAGH	C. 1	3	3	
V. 3	3 : 1	IVERAGH	C. 2	2	4	
V. 4	3 : 1	RODD'S BAY	C. 3	5	5	
V. 5	3 : 1	RODD'S BAY	C. 4	4	6	
V. 6	3 : 1	BENARABY	C. 5	7	7	
V. 7	3 : 1	BENARABY	C. 6	6	8	
V. 8	3 : 1	PARANA	C. 7	9	9	
V. 9	4 : 1	PARANA	C. 8	8	10	131
V. 10	4 : 2	CALLEMONDAH	C. 9	11	120	136
V. 11	4 : 2	CALLEMONDAH	C. 10	12	138	139
V. 12	3 : 1	MOUNT MILLER	C. 11	13	13	
V. 13	3 : 1	MOUNT MILLER	C. 12	12	14	
V. 14	3 : 2	YARWUN	C. 13	15	140	
V. 15	4 : 2	YARWUN	C. 14	16	140	140
V. 16	3 : 1	ALDOGA	C. 15	17	17	
V. 17	4 : 1	ALDOGA	C. 16	16	18	141
V. 18	4 : 1	MOUNT LARCOM	C. 17	19	19	141
V. 19	4 : 1	MOUNT LARCOM	C. 18	18	20	142
V. 20	4 : 1	AMBROSE	C. 19	21	21	142
V. 21	3 : 1	AMBROSE	C. 20	20	22	
V. 22	3 : 1	EPALA	C. 21	23	23	
V. 23	3 : 1	EPALA	C. 22	22	24	
V. 24	4 : 1	RAGLAN	C. 23	25	25	143
V. 25	4 : 1	RAGLAN	C. 24	24	26	144
V. 26	4 : 2	MARMOR	C. 25	27	145	
V. 27	3 : 2	MARMOR	C. 26	28	145	
V. 28	3 : 1	BAJOOL	C. 27	29	29	
V. 29	3 : 1	BAJOOL	C. 28	28	30	
V. 30	3 : 1	ARCHER	C. 29	31	31	
V. 31	3 : 1	ARCHER	C. 30	30	32	
V. 32	3 : 1	MIDGEE	C. 31	33	33	
V. 33	3 : 1	MIDGEE	C. 32	32	34	
V. 34	4 : 1	ROCKLANDS	C. 33	35	35	134
V. 35	4 : 1	ROCKLANDS	C. 34	34	36	39
V. 36	2 : 1	YEPPEN	C. 35	37		
V. 37	2 : 1	ROCKHAMPTON	C. 36	38		
V. 38	1 : 1	ROCKHAMPTON	C. 37			
V. 39	4 : 1	ROCKLANDS	C. 35	40	40	134
V. 40	4 : 1	ROCKLANDS	C. 39	39	41	134
V. 41	3 : 1	GRACEMERE	C. 40	42	42	
V. 42	4 : 3	GRACEMERE	C. 41	41	43	43
V. 43	3 : 1	GRACEMERE	C. 42	42	44	
V. 44	3 : 1	KABRA	C. 43	45	45	
V. 45	3 : 1	KABRA	C. 44	44	46	
V. 46	3 : 1	STANWELL	C. 45	47	47	
V. 47	3 : 1	STANWELL	C. 46	46	48	
V. 48	3 : 1	WYCARBAH	C. 47	49	49	
V. 49	3 : 1	WYCARBAH	C. 48	48	50	
V. 50	4 : 1	WESTWOOD	C. 49	51	51	146
V. 51	4 : 1	WESTWOOD	C. 50	50	52	147
V. 52	4 : 3	WINDAH	C. 51	53	53	147

definition information connexions

V. 53	3 : 1	WINDAH	C. 52	52	54	
V. 54	3 : 1	GOGANGO	C. 53	55	55	
V. 55	3 : 1	GOGANGO	C. 54	54	56	
V. 56	3 : 1	GRANTLEIGH	C. 55	57	57	
V. 57	3 : 1	GRANTLEIGH	C. 56	56	58	
V. 58	3 : 2	TUNNEL	C. 57	59	148	
V. 59	3 : 3	TUNNEL	C. 58	60	148	
V. 60	3 : 3	EDUNGALBA	C. 59	61	149	
V. 61	3 : 1	EDUNGALBA	C. 60	62	149	
V. 62	3 : 1	AROONA	C. 61	63	63	
V. 63	3 : 1	AROONA	C. 62	62	64	
V. 64	3 : 3	DUARINGAH	C. 63	65	150	
V. 65	4 : 1	DUARINGAH	C. 64	66	151	152
V. 66	3 : 1	WALLARRO	C. 65	67	152	
V. 67	3 : 2	WALLARRO	C. 66	68	152	
V. 68	3 : 1	TRYPHINIA	C. 67	69	69	
V. 69	3 : 1	TRYPHINIA	C. 68	68	70	
V. 70	3 : 1	DINGO	C. 69	71	71	
V. 71	3 : 1	DINGO	C. 70	70	72	
V. 72	3 : 1	UMOLO	C. 71	73	73	
V. 73	3 : 1	UMOLO	C. 72	72	74	
V. 74	3 : 1	PARNABAL	C. 73	75	75	
V. 75	3 : 1	PARNABAL	C. 74	74	76	
V. 76	3 : 1	WALTON	C. 75	77	77	
V. 77	3 : 1	WALTON	C. 76	76	78	
V. 78	4 : 4	BLUFF	C. 77	79	153	154
V. 79	4 : 4	BLUFF	C. 78	80	155	156
V. 80	4 : 1	BOONAL	C. 79	81	81	157
V. 81	3 : 1	BOONAL	C. 80	80	82	
V. 82	4 : 4	BLACKWATER	C. 81	83	83	112
V. 83	4 : 4	BLACKWATER	C. 82	82	84	158
V. 84	3 : 2	SAGITTARIUS	C. 83	85	132	
V. 85	4 : 2	BURNGROVE	C. 84	86	91	105
V. 86	2 : 1	TOLMIES	C. 85	87		
V. 87	2 : 1	COMET	C. 86	88		
V. 88	2 : 1	YAMALA	C. 87	89		
V. 89	2 : 1	EMERALD	C. 88	90		
V. 90	1 : 1	EMERALD	C. 89			
V. 91	3 : 1	CREW	C. 85	92	92	
V. 92	3 : 1	CREW	C. 91	91	93	
V. 93	3 : 1	FAIRHILL	C. 92	94	94	
V. 94	3 : 1	FAIRHILL	C. 93	93	95	
V. 95	3 : 2	YAN YAN	C. 94	96	98	
V. 96	2 : 1	YAN YAN	C. 95	97		
V. 97	1 : 1	YAN YAN	C. 96			
V. 98	3 : 2	GREGORY	C. 95	99	101	
V. 99	3 : 2	OAKY CREEK	C. 98	100	102	
V. 100	2 : 1	GERMAN CREEK [72]	C. 99	103		
V. 101	1 : 1	GREGORY	C. 98			
V. 102	1 : 1	OAKY CREEK	C. 99			
V. 103	2 : 1	GERMAN CREEK [73]	C. 100	104		
V. 104	1 : 1	GERMAN CREEK [74]	C. 103			
V. 105	3 : 1	TIKARDI	C. 85	106	106	
V. 106	3 : 1	TIKARDI	C. 105	105	107	
V. 107	3 : 2	BOORGOON	C. 106	108	111	
V. 108	2 : 1	BOORGOON	C. 107	109		
V. 109	2 : 1	KINROLA	C. 108	110		
V. 110	1 : 1	KINROLA	C. 109			

V. 111	1 : 1	BOORGOON	C. 107			
V. 112	3 : 1	BLACKWATER	C. 82	113	158	
V. 113	3 : 2	KOORILGAH	C. 112	114	117	
V. 114	2 : 1	LALEHAM	C. 113	115		
V. 115	2 : 1	LALEHAM	C. 114	116		
V. 116	1 : 1	LALEHAM	C. 115			
V. 117	2 : 1	KOORILGAH	C. 113	118		
V. 118	2 : 1	KOORILGAH	C. 117	119		
V. 119	1 : 1	KOORILGAH	C. 118			
V. 120	4 : 1	GLADSTONE	C. 10	121	127	127
V. 121	4 : 1	GLADSTONE	C. 120	122	125	125
V. 122	4 : 1	GLADSTONE	C. 121	123	128	128
V. 123	2 : 1	GLADSTONE	C. 122	124		
V. 124	1 : 1	GLADSTONE	C. 123			
V. 125	3 : 1	AUKLAND POINT	C. 121	121	126	
V. 126	1 : 1	AUKLAND POINT	C. 125			
V. 127	3 : 1	BARNEY POINT	C. 120	120	129	
V. 128	3 : 1	BARNEY POINT	C. 122	122	129	
V. 129	4 : 1	BARNEY POINT	C. 127	128	130	130
V. 130	4 : 1	BARNEY POINT	C. 129	129	131	131
V. 131	3 : 1	PARANA	C. 9	130	130	
V. 132	2 : 1	CURRAGH	C. 84	133		
V. 133	1 : 1	CURRAGH	C. 132			
V. 134	3 : 2	ROCKLANDS	C. 34	39	40	
V. 135	1 : 1	GOLDING	C. 136			
V. 136	3 : 2	POWERHOUSE	C. 10	135	138	
V. 137	1 : 1	GOLDING	C. 138			
V. 138	3 : 2	POWERHOUSE	C. 11	136	137	
V. 139	1 : 1	CALLEMONDAH	C. 11			
V. 140	3 : 1	YARWUN	C. 14	15	15	
V. 141	4 : 1	MOUNT LARCOM	C. 17	18	142	142
V. 142	4 : 1	MOUNT LARCOM	C. 19	20	141	141
V. 143	2 : 1	RAGLAN	C. 24	144		
V. 144	3 : 2	RAGLAN	C. 25	143	145	
V. 145	3 : 3	MARMOR	C. 26	27	144	
V. 146	2 : 1	WESTWOOD	C. 50	147		
V. 147	3 : 2	WESTWOOD	C. 51	52	146	
V. 148	3 : 3	TUNNEL	C. 58	59	149	
V. 149	3 : 3	EDUNGALBA	C. 60	61	148	
V. 150	3 : 1	DUARINGAH	C. 64	151	151	
V. 151	3 : 1	DUARINGAH	C. 65	150	150	
V. 152	3 : 3	WALLARRO	C. 65	66	67	
V. 153	3 : 1	BLUFF	C. 78	155	155	
V. 154	3 : 1	BLUFF	C. 78	156	156	
V. 155	3 : 1	BLUFF	C. 79	153	153	
V. 156	3 : 1	BLUFF	C. 79	154	154	
V. 157	1 : 1	BOONAL	C. 80			
V. 158	2 : 1	BLACKWATER	C. 83	112		

NETWORK CONFIGURATION FILE FOR STAGE 1

1
0
==
1 OUTBOUND TRACK
2 datum point is 1
24 number of gradient sections
5647.0 section length [m]

296.0	0.0
241.0	-264.0
362.0	-99.0
222.0	0.0
160.0	66.0
242.0	0.0
201.0	-83.0
101.0	0.0
161.0	132.0
181.0	0.0
301.0	-198.0
403.0	0.0
161.0	99.0
40.0	0.0
241.0	-66.0
403.0	-83.0
287.0	0.0
336.0	264.0
402.0	330.0
322.0	88.0
202.0	220.0
60.0	0.0
201.0	-110.0
121.0	0.0

2 INBOUND TRACK
1 datum point is 1
24 number of gradient sections
5647.0 section length [m]

296.0	0.0
241.0	264.0
362.0	99.0
222.0	0.0
160.0	-66.0
242.0	0.0
201.0	83.0
101.0	0.0
161.0	-132.0
181.0	0.0
301.0	198.0
403.0	0.0
161.0	-99.0
40.0	0.0
241.0	66.0
403.0	83.0
287.0	0.0
336.0	-264.0
402.0	-330.0
322.0	-88.0
202.0	-220.0
60.0	0.0
201.0	110.0
121.0	0.0

1 OUTBOUND TRACK
2 datum point is 1
5 number of speed restrictions

```
5647.0     section length [m]
              505.0                    0.0
              849.0                    0.0
             1529.0                    0.0
             2530.0                    0.0
              234.0                    0.0
2  INBOUND TRACK
1 datum point is 1
4         number of speed restrictions
5647.0     section length [m]
              505.0                    0.0
             4273.0                    0.0
              849.0                    0.0
               20.0                    0.0
1 OUTBOUND TRACK
2  datum point is 1
9         number of curves
5647.0     section length [m]
              217.0                    0.0
              280.0                  392.0
              897.0                    0.0
              837.0                -3206.0
             2010.0                    0.0
              350.0                 1539.0
              187.0                    0.0
              344.0                 -798.0
              525.0                    0.0
2  INBOUND TRACK
1 datum point is 1
9         number of curves
5647.0     section length [m]
              217.0                    0.0
              280.0                 -392.0
              897.0                    0.0
              837.0                 3206.0
             2010.0                    0.0
              350.0                -1539.0
              187.0                    0.0
              344.0                  798.0
              525.0                    0.0
 -------NORMAL-LINE-SECTION-ABOVE-------------
2 OUTBOUND TRACK
3  datum point is 2
4         number of gradient  sections
1095.0     section length [m]
               40.0                    0.0
              422.0                  528.0
              624.0                  176.0
                9.0                    0.0
3  INBOUND TRACK
2 datum point is 2
4         number of gradient  sections
1095.0     section length [m]
               40.0                    0.0
              422.0                 -528.0
              624.0                 -176.0
                9.0                    0.0
2 OUTBOUND TRACK
3  datum point is 2
```

STRUCTURE OF TRACK DATA FILE (DATA BASE)

```
STATIC TRAIN CONTROL DATA
changes the standard notches and the number of active locos
4              TOTAL NUMBER OF NONSTANDARD ASSIGNMENTS
===========================================================
0    0  ACTIVE NOTCH AND LOCOS FOR LOADED TRAINS
6    2                        FOR EMPTY TRAINS
1 2 3 21 22
-----------------------------------------------------------
0    0
2    2
3 4 5 22 23 24
-----------------------------------------------------------
0    0
6    4
5 6 7 8 9 10  24 25 26 27 28
-----------------------------------------------------------
10    4
8    2
13 14 32 33
-----------------------------------------------------------
* DYNAMIC CONTROL DATA.
-----------------------------------------------------------------
0    0                  G TRAIN 0  train identifiers
0    0
speed control applied between
000000 240000           [hhmmss]
speed control applied between vertices
5 6 7 8 9 10 24 25 26 27 28 29
40                      [km/h] imposed speed
---------------------------------------------------------------
0     0
0     0
time :
000000      240000
set  :
5 6 24 25
30   km/h
----------------------------------------------------------------
```

SPEED RESTRICTION, NOTCH AND LOCOMOTIVE ASSIGNMENT FILE

```
FIXED HEADWAY IF GIVEN,OTHERWISE TIMETABLE VALUES :-
0       [s] !!!!! use timetable values
==========================================================================
QR2-G-TRAIN simulator identifier :
             QR         identifier : E559
--------------------------------------------------------------------------
VERTICES                ARRIVES AT     WAITS FOR      MN/LP         LD/MT
--------------------------------------------------------------------------
1 [62                    ] 00 :-15     00 : 00        1             1 E559
2 [61 60                 ] 00 : 07
2 [59 58                 ] 00 : 25
2 [57 56                 ] 00 : 34
2 [55 54                 ]
2 [53 52                 ] 00 : 45
2 [51 50                 ] 00 : 58
2 [49 48                 ] 01 : 10
2 [47 46                 ] 01 : 30
2 [45 44                 ] 01 : 47     00 : 05
2 [43 42                 ] 01 : 57     00 : 03
3 [41 40 39              ] 02 : 08     00 : 18
2 [35 34                 ] 99 : 99     99 : 99        1             1 EF10
2 [33 32                 ] 02 : 40
2 [31 30                 ] 02 : 50
2 [29 28                 ] 03 : 00
2 [27 26                 ] 03 : 10
2 [25 24                 ] 03 : 20
2 [23 22                 ] 03 : 30
2 [21 20                 ] 03 : 37
2 [19 18                 ] 03 : 45
2 [17 16                 ] 03 : 56
2 [15 14                 ] 04 : 05
2 [13 12                 ] 04 : 10
2 [11 10                 ] 04 : 22     00 : 00
--------------------------------------------------------------------------
1                       ENTRY
00 :-15                 from AROONA to ROCKLANDS
==========================================================================
QR2-G-TRAIN simulator identifier :
             QR         identifier :EK61 , EF12
--------------------------------------------------------------------------
VERTICES                ARRIVES AT     WAITS FOR      MN/LP         LD/MT
--------------------------------------------------------------------------
1 [68                    ] 00 : 01     00 : 00        1             1 EK61
2 [67 66                 ] 00 : 19
2 [65 64                 ] 00 : 35
2 [63 62                 ] 00 : 50
2 [61 60                 ] 01 : 00
2 [59 58                 ] 01 : 15
2 [57 56                 ] 01 : 25
2 [55 54                 ]
2 [53 52                 ] 01 : 40
2 [51 50                 ] 01 : 56     00 : 06
2 [49 48                 ] 02 : 20     00 : 05
2 [47 46                 ] 02 : 40
2 [45 44                 ] 02 : 53
2 [43 42                 ] 03 : 00     00 : 02
3 [41 40 39              ] 03 : 15     00 : 15
2 [35 34                 ] 99 : 99     99 : 99        1             1 EF12
```

```
2 [33 32              ] 03 : 41
2 [31 30              ] 03 : 50
2 [29 28              ] 04 : 12
2 [27 26              ] 04 : 22
2 [25 24              ] 04 : 37
2 [23 22              ] 04 : 45
2 [21 20              ] 04 : 50
2 [19 18              ] 04 : 56
2 [17 16              ] 05 : 08
2 [15 14              ] 05 : 15     00 : 15
2 [13 12              ] 05 : 45     00 : 07
2 [11 10              ] 06 : 05     00 : 00
---------------------------------------------------------------------
1                     ENTRY
00 : 01               from TRYPHINIA to ROCKLANDS
=====================================================================
QR2-G-TRAIN simulator identifier :
            QR        identifier :9467 , 9F14
---------------------------------------------------------------------
VERTICES              ARRIVES AT    WAITS FOR     MN/LP          LD/MT
---------------------------------------------------------------------
1 [76                 ] 00 : 00     00 : 00       1              1 9467
2 [75 74              ] 00 : 07
2 [73 72              ] 00 : 15
2 [71 70              ] 00 : 28     00 : 17
2 [69 68              ] 01 : 05
2 [67 66              ] 01 : 21
2 [65 64              ] 01 : 37
2 [63 62              ] 01 : 48
2 [61 60              ] 02 : 03
2 [59 58              ] 02 : 34
2 [57 56              ] 02 : 43     00 : 07
2 [55 54              ]
2 [53 52              ] 03 : 08     01 : 40
2 [51 50              ] 05 : 10
2 [49 48              ] 05 : 26     00 : 11
2 [47 46              ] 05 : 55
2 [45 44              ] 06 : 05     00 : 10
2 [43 42              ] 06 : 25     00 : 20
3 [41 40 39           ] 06 : 55
2 [35 34              ] 99 : 99     99 : 99       1              1 9F14
2 [33 32              ] 07 : 07     00 : 08
2 [31 30              ] 07 : 30     00 : 30
2 [29 28              ] 08 : 15
2 [27 26              ] 08 : 26     00 : 04
2 [25 24              ] 08 : 42
2 [23 22              ] 08 : 52
2 [21 20              ] 09 : 00
2 [19 18              ] 09 : 05
2 [17 16              ] 09 : 25
2 [15 14              ] 09 : 35
2 [13 12              ] 09 : 44     00 : 02
2 [11 10              ] 10 : 02     00 : 00
---------------------------------------------------------------------
1                     ENTRY
00 : 00               from WALTON to ROCKLANDS
=====================================================================
QR2-G-TRAIN simulator identifier :
```

STRUCTURE OF TIME/ROUTE TABLE FILE

```
QUEENSLAND RAILWAYS STAGE 2
ELECTRICAL SECTION FILE
14  ELECTRICAL SECTIONS
7  SUBSTATIONS
=========================================================================
SUB 1 OONOOIE DOWNSIDE
1         2          2000.0       5          6          3866.0    UPLINE,UP DIRN
6         5          1134.0       2          1             0.0    UPLINE,DN DIRN
21        22         2000.0       24         25         3866.0    DNLINE,UP DIRN
25        24         1134.0       22         21            0.0    DNLINE,DN DIRN
-------------------------------------------------------------------------
1 2 3 4 5 6 47 21 22 23 24 25 77
=========================================================================
SUB 1 OONOOIE UPSIDE
 5        6          3866.0       10         11         5392.0    UL,UD
11        10         4845.0        6          5         1134.0    UL,DD
24        25         3866.0       29         30         5392.0    DL,UD
30        29         4845.0       25         24         1134.0    DL,DD
-------------------------------------------------------------------------
5 6 7 8 9 10 11 24 25 26 27 28 29 30
=========================================================================
SUB 2 WANDOO DOWNSIDE
10        11         5392.0       13         14         10684   UL,UD
14        13         1036.0       11         10          4845.0  UL,DD
29        30         5392.0       32         33         10684.0  UL,DD
33        32         1036.0       30         29          4845.0  DL,DD
-------------------------------------------------------------------------
10 11 12 13 14 29 30 31 32
=========================================================================
SUB 2 WANDOO UPSIDE
13        14        10684.0       16         17          9242.0   UL,UD
17        16         3097.0       14         13          1036.0   UL,DD
32        33        10684.0       35         36          9242.0   DL,UD
36        35         3097.0       33         32          1036.0   DL,DD
-------------------------------------------------------------------------
13 14 15 16 17 32 33 34 35 36
=========================================================================
SUB 3 COPPABELLA DOWNSIDE
16        17         9242.0       20         56          7520.0   UL,UD
56        20         2226.0       17         16          3097.0   UL,DD
35        36         9242.0       39         40         20279.0   DL,UD
40        39         2226.0       36         35          3097.0   DL,DD
-------------------------------------------------------------------------
16 17 18 19 20 56 35 36 37 38 39 40
=========================================================================
SUB 3 COPPABELLA UPSIDE
20        56         7520.0       57         58          1392.0   UL,UD
58        57         6951.0       56         20          2226.0   UL,DD
39        40        20279.0       42         43         19911.0   DL,UD
43        42         1019.0       40         39          2226.0   DL,DD
-------------------------------------------------------------------------
20 56 57 58 39 40 41 42 43
=========================================================================
SUB 4 MORANBAH SOUTH DOWNSIDE
42        43        19911.0       45         46             0.0   RIVR,UD
46        45         2000.0       43         42          1019.0   RIVR,DD
42        48        16763.0       49         50         17976.0   BLTH,UD
50        49          681.0       48         42             0.0   BLTH,DD
```

42 43 44 45 46 48 49 50

SUB 4 MORANBAH SOUTH UPSIDE

49	50	17967.0	51	52	13952.0	BLTH,UD
52	51	4543.9	50	49	681.0	BLTH,DD
49	50	17967.0	51	52	13952.0	DUMMY
52	51	4543.0	50	49	681.0	DUMMY

49 50 51 52

SUB 5 MT.MCLAREN DOWNSIDE

51	52	13952.0	53	54	27931.0	BLTH,UD
54	53	15164.0	52	51	4543.0	BLTH,DD
51	52	13952.0	53	53	27931.0	DUMMY
54	53	15164.0	52	51	4543.0	DUMMY

51 52 53 54

SUB 5 MT.MCLAREN UPSIDE

53	54	27931.0	54	55	0.0	BLTH,UD
55	54	2000.0	54	53	15164.0	BLTH,DD
53	54	27931.0	54	55	0.0	DUMMY
55	54	2000.0	54	53	15164.0	DUMMY

54 55

SUB 6 PEAK DOWNS DOWNSIDE

57	58	1392.0	59	60	677.0	GERK,UD
60	59	18828.0	58	57	6951.0	GERK,DD
57	58	1392.0	59	60	677.0	DUMMY
60	59	18828.0	58	57	6951.0	DUMMY

57 58 59 60

SUB 6 PEAK DOWNS UPSIDE

59	60	677.0	64	66	15875.0	GERK,UD
66	64	4653.0	60	59	18828.0	GERK,DD
59	60	677.0	64	66	15875.0	DUMMY
66	64	4653.0	60	59	18828.0	DUMMY

59 60 61 62 63 64 65 66

SUB 7 NORWICH PARK DOWNSIDE

64	66	15875.0	67	68	1875.0	GERK,UD
68	67	15507.0	66	64	4653.0	GERK,DD
64	66	15875.0	67	68	1875.0	DUMMY
68	67	15507.0	66	64	4653.0	DUMMY

64 66 67 68

SUB 7 NORWICH PARK UPSIDE

67	68	1875.0	72	75	11217.0	GERK,UD
75	72	7548.0	68	67	15507.0	GERK,DD
67	68	1875.0	72	75	11217.0	DUMMY
75	72	7548.0	68	67	15507.0	DUMMY

67 68 69 70 71 72 73 74 75

ELECTRICAL SECTION FILE FOR STAGE 2

APPENDIX 7

LIMITATIONS OF TECHNIQUE :

PREDICTION OF HARMONIC CURRENT LOADING AT TRACTION SUBSTATIONS

An attempt is made to use the simulation model to estimate the harmonic currents. The method developed is based on the measurements done by QR. Even after a number of modifications in the train driving methods of the model, it still proved impossible to match the given vertex to vertex runtimes better than ± 5 minutes. The results produced to this level of detail proved to be inadequate for a study which require a timing match better than ±1 minute. The report given in this appendix summarizes the findings of this study.

PREDICTION OF HARMONIC CURRENT LOADING AT TRACTION SUBSTATIONS

INTRODUCTION

The appendix gives a summary of the work undertaken to modify the network simulator in the Traction Research Group of the University of Birmingham in order to incorporate the simulation of harmonic currents produced by the locomotives at a traction substation. The objective was to produce a sequence of values for the 1 minute, 5 minute and 30 minute averages of the 3rd, 5th and 7th harmonic currents run at the substation and compare these values with measured results over known windows of the timetable.

MODIFICATIONS TO THE NETWORK SIMULATOR

Representation of the Measurement Data

Information was provided by QR regarding the current spectra for a Comeng locomotive. New routines were produced to allow the simulator to read tables from the data provided of harmonic current, as a function of speed and locomotive load current, with the Line Voltage assumed to be constant at 25kV. This is achieved using a three dimensional real array:

1st Dimension : 1st, 3rd, 5th, 7th harmonics
2nd Dimension : speed 0 to 70 kph with 5km increments
3rd Dimension : load current rms values from 0 to 10 increments

If a harmonic current value is not given in the table an approximate value is calculated either by linear interpolating between two known values or extrapolating using two preceding values of harmonic currents. The tables provided by QR were therefore filled in and extended prior to the simulated runs.

Calculation of Harmonic Current

The electrical power input of a single locomotive is already calculated within the simulator for the work being undertaken on the Demand Study, and therefore the line current is easily calculated from

$$\text{Line Current} = \frac{\text{Electrical Power Input}}{\text{Line Voltage} \times \text{Power Factor}}$$

The Power Factor at any speed is taken from data supplied by QR for the Comeng loco's, the data being divided into 3 speed regions and the curves fitted using the last squares technique. Auxiliary loads have not been taken into account in the line current calculation.

From the known speed of the locomotive (or train) a sequential search is carried out to find the two values of fundamental current in the tables which lie either side of the calculated current. The 5 km/hr range for the train speed is entered directly and each harmonic current is calculated by linearly interpolating three times. The result of each calculation is multiplied by the number of active loco's in order to obtain the current values.

Storage, Calculation and Output

New routines have been coded so that, at each update, the harmonic currents generated by each train in a feeding section are added arithmetically at the feeding substation (two electrical sections for each substation). At the end of each 30 minutes of run the estimates of harmonic currents are written to a file as average r.m.s. values over 1, 5 and 30 minute periods.

Loco Notch Assignments

Three types of trains are considered:

G trains	5 locomotives	Type 1
G trains	4 locomotives	Type 2
V trains	4 locomotives	Type 3

The speed controller has been substantially modified to allow more elaborate modelling of the given train driving technique and reconciling the type of information given in the notes from QR. Further modifications have been made whilst attempting to get as close a match as possible to the timetables provided.

The operation of the new speed controller is as follows:

(a) The parameters specific to each type of train are read in from the motor files. Typical values for the harmonic calculation runs are:

number of active locos :	4 or 5 for loaded train 2 for empty train
standard notch :	8 for loaded train 5 for empty train

These parameters are however overridden by the values read from the train driving technique files. The values read from this file are:

Empty trains:
2 locos between ports and Praguelands, running at nominally notch 6.
2 locos Praguelands to Jilalan.
All locos between Yukan and Hatfield at a nominal notch 6.

Loaded trains:
5 (nominal notch) All locos between Hatfield and Yukan running at nominal notch 5.

It should be noted that notch numbers are nominal and the speed controller can notch down as far as notch 2 and can also notch up to maximum to cope with the changing track geometry.

Assignment of New Speed Limits

We noted that different trains were moving at different speeds especially between Yukan and Jilalan (compare EV85 with EV75 in Friday 21.10.88 window) and the speed limit on the up and down lines between Yukan and Hatfield does not appear in the Civil Engineer's speed restriction files. A new file was created and new routines coded to assign new speed limits to all or to particular empty or loaded trains between a set of vertices during a given period of time. This new speed limit was then compared with other speed limits, i.e. signal, civil, braking curve in order to assign the target speed to the train.

The structure is a circular list which is flexible enough to store any number of static or dynamic train/speed/region/time assignments.

Train Timing Control

In the original configuration for the Demand Study the simulator resets the vertex arrival time of the trains by moving the time backward and forward for a specific train. This feature of the simulator keeps the deviations from the given timetable within an acceptable range but without changing the total energy consumption. This feature is not used for this study for the following reasons:

(a) The timing diagrams for the four 4-hours windows are relatively coarse and therefore intermediate values taken from them would be unreliable, (on a scale of a few minutes).

(b) The resetting feature inevitably causes short-term harmonic current dips while adjusting the train timings.

c) The runs are short, and therefore deviations from the timetable are not large, but could still amount to a minute or more.

LIMITATIONS OF THE TECHNIQUE

Modelling of the Driver Behaviour

The algorithm of the speed controller used is described below: (extracted from the program)

```
if train speed is within the error band
then COAST [∓ 1% around target speed]
ACCELERATION=-EFF GRD-TRN RES-CRV DRG (1)
else
if train speed is less than acceleration control
limit [+ 4% above the target speed]
then CALCULATE THE REQUIRED ACCELERATION
      if required acceleration is negative (braking)
      then do not brake but coast according to (1)
      else
      notch up or down to increase or decrease
      the acceleration rate. Notching up applies only
      to empty train and only if NOMINAL NOTCH is
      smaller than MAX EMPTY TRAIN NOTCH
      ACCELERATION = GRS ACC (SPEED, NOTCH, LOAD)
      -EFF GRD - TRN RES - CRV DRG (2)
else
if train speed is less than upper coasting
band [+ 6% above the target speed]
then COAST according to (1)
else BRAKE with standard braking rate.
```

In the equations (1) and (2) the variables used are:

EFF GRD = acceleration due to effective gradient, i.e. gradient force x acceleration due to gravity averaged along the train.

TRN RES = acceleration equivalent to train resistance.

CRV DRG = acceleration equivalent to curve drag.

GRS ACC = gross acceleration available as a function of speed, notch setting and empty or loaded train.

It should be noted that some redundancies are introduced to make the code easy to modify. If the train starts moving from standstill then value of the target speed can be increased until this speed is exceed [+2.6% for these runs] and also target speed can be increased if required [0% for these runs].

The nominal notch and the number of active locos are assigned by checking the load and the place of the train.

The speed controller described above controls around the target speed making new decisions at each update (currently 1 second), whereas a human driver is likely to be much more flexible in controlling the train's speed with changing track geometry and/or speed limits. For example it is obvious from the data files that between Yukan and Hatfield there exists a second downhill section where train under automatic control will coast for more than one minute. The expected current dip does no appear in the measured values due to the behaviour of a particular driver.

A better model of the human driver behaviour would be possible if enough data were available on average driver behaviour but it would still be very difficult to match simulated and measured values in the one minute range for a non-automated railway system.

Problems due to Assumptions Made

a) According to J. Wecker's notes on train driving empty trains switch all the locos on and set the notch to 7 between Yukan and Hatfield. However further information gained in January 1989 suggests that all locos are switched on but operated at notch 5 to keep within the speed limits. From investigations it appeared that notch 6 gave the best compromise between run time and maximum fundamental current.

b) Six standard train weights are used whereas such a standardisation may not always exist in practice. The values used are:

G TRAINS (5 LOCOS) :	10590	tonnes loaded
	2240	tonnes empty*
G TRAINS (4 LOCOS) :	10480	tonnes loaded
	2130	tonnes empty*
V TRAINS (4 LOCOS) :	9680	tonnes loaded
	2320	tonnes empty

* The original assumptions of 2450 and 2340 tonnes, were changed after the last conference call with QR.

c) Electrical efficiency is assumed constant at 85% where in practice it is a function of train speed.

d) The linear interpolation/extrapolation on measured currents and arithmetic summing of the individual currents may only give approximate values for the harmonic spectrum over the full range of load currents, line voltages and speeds encountered in practice. The effect of line voltage, for example, is not accounted for.

e) Train entry/exit and waiting times are extracted from a coarse train timing diagram if a single minute has to be considered.

f) The track geometry of the section of the track chosen for the validation exercise made it a difficult section over which to try and match simulated and measured results.

COMMENTS AND CONCLUSIONS

Software modifications were successfully incorporated and tested which accumulate 3rd, 5th and 7th harmonic average currents over 1, 5 and 30 min periods using look-up tables from measured data.

New train timing diagrams for the 4-hour windows were coded into data files and the simulator successfully run for these periods.

Following observations that the train performance as indicated on the train control diagrams was substantially different between trains and to the simulator output substantial modifications of the train driving algorithms in the simulator were undertaken in an attempt to correlate simulation and measured results.

With the modified train driving algorithms, it still proved impossible to match given times at stations to better than ± 5 mins. However we believe that the uncertainity in the times from the train control diagram is almost of this order, and therefore the results were produced to this level of timetable matching.

APPENDIX 8

PUBLISHED WORK :

INTERNATIONAL CONFERENCE ON

MAINLINE RAILWAY ELECTRIFICATION

SEPTEMBER 1989, YORK, ENGLAND

IEE CONFERENCE PUBLICATION - NUMBER 312, PAGE 378

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