A STRATEGIC INVESTMENT DECISION MODEL FOR LINE-HAUL OPERATIONS ON A DEVELOPING COUNTRY RAILWAY

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ABSTRACT

When a railway is being upgraded, several alternative investment proposals may be considered. This thesis describes the development and use of a computerised model to investigate the combined effects of such investments for a less developed country railway.

The work focuses on the Botswana line as a case study, but could be applied to any railway system with similar operating characteristics. It is designed to reflect the priorities of such systems, namely to have the capacity to haul traffic safely and at a low cost; with speed and frequency of service being considered less important. The model also allows for the inefficiencies in operations found in many such railways.

The model concentrates on lines rather than yards and is in three parts; an operations model; calculations to determine line capacity and general statistics; and a cost model.

Each stage of the model involves a development from previous theory on the subject. A train speeds model has been produced which gives results of acceptable accuracy from a simple data input. The train delay model reflects the types of delays found using both low and high technology trains working methods. The accuracy of both the speed and delay models was tested by running them separately from the rest of the model, using data from Botswana. Appropriate measures of capacity were developed. Cost equations were produced from information obtained from Botswana and Zimbabwe, and from general literature on the subject.

Example runs of the model were performed for illustrative purposes, representing the main investment proposals being considered in Botswana in 1982. It was possible to perform many runs quickly and easily, and thus to obtain much more information than was available in documents produced for Botswana using conventional investment appraisal methods.

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A listing of the FORTRAN program developed in this thesis is available as a technical note (J. Leonard, 1986) from the Institute for Transport Studies, University of Leeds, LS2 9JT.

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Glossary & Symbols

Abbreviations

ANOP	NRZ's costing system for the whole network
NRZ	National Railways of Zimbabwe
RR	Rhodesia Railways
SECT	NRZ's regional costing system

Symbols

note: the user of the model should choose one currency unit for all costs listed below. Zimbabwean dollars (Z$) have been used as an example here.

A	cross - sectional area of vehicles (square metres)
CADM	administration costs excluding those involved with trains working method (Z$)
CADTWM	fixed cost of trains working method administration (Z$)
CAMAIN	extra depreciation cost per main station (over and above that incurred at a minor manned station) (Z$)
CAN	the annual equivalent cost of capital (Z$)
CASTMN	annual depreciation cost per minor manned station (Z$)
CASTN	annual depreciation costs of all buildings required for trains working method (Z$)
CASTUN	annual depreciation cost per unmanned station (Z$)
CATWML	annual equivalent capital cost of trains working method equipment per crossing loop (zero for paper order) (Z$)
CATWMM	annual equivalent capital cost of trains working method equipment per manned loop (zero for Van Schoor and colour light) (Z$)
CATWMT	total annual depreciation costs of the trains working method (excluding the control centre) (Z$)
CB	coefficient of flange friction, swaying and concussion
CC	drag coefficient of air
CCREW	total crew costs (Z$)
CFT	coefficient of friction between wheel and rail
CFTRAC	fixed track maintenance costs per track-km (Z$)
CFUEL	cost per litre of diesel (Z$)

CLOCFX	the fixed element of locomotive costs (for running sheds or workshops) (Z$)
CLOCKM	maintenance cost per locomotive - km for locomotive (Z$)
CLOCNM	maintenance cost per locomotive per year (Z$)
CLOCTT	total mainline locomotive costs (for running sheds or workshops) (Z$)
CMNTRC	total track maintenance costs (Z$)
COIL	cost per litre of oil (Z$)
CPRES	the capital cost of the goods (Z$)
CRMAIN	extra recurrent cost per main station (over and above that incurred at a minor manned station) (Z$)
CRWHR	crew costs per train hour (Z$)
CRWKM	crew costs per train km (Z$)
CSCRAP	the scrap value of the goods (Z$)
CTMAIN	extra costs at main stations (Z$)
CTOTFL	total annual fuel costs (Z$)
CTOTOL	total oil costs (Z$)
CTWMMN	recurrent trains working method cost per manned loop (Z$)
CTWMRC	recurrent costs (operation and maintenance) of the trains working method (Z$)
CVTRAC,CPTRAC	describe variability of track maintenance costs per gross tonne - km (CVTRAC in Z$)
CWAGFX(2)	fixed element of running shed maintenance (Z$)
CWAGFX(1)	fixed element of wagon maintenance for workshops (Z$)
CWAGJO	workshop maintenance cost per carriage or wagon journey (Z$)
CWAGKM(IKMAT)	running shed cost per wagon - km (Z$)
CWAGNM(1,IKMAT)	annual workshop maintenance cost per wagon or carriage (Z$)
CWAGNM(2,IKMAT)	running shed cost per wagon or carriage (Z$)
CWAGTT(2)	total wagon and carriage running shed maintenance cost (Z$)
CYARD	total yard costs (Z$)
CYRFIX	total fixed costs in yards (Z$)
CYRVAR	variable yard cost per gross tonne (Z$)
DCROSS	average length of crossing loop (metres)
DCO	length of a continuous down grade (metres)
DISCRS	total track - km
EL	mechanical - electrical efficiency factor
FTF	adhesive force available to a train (kN)
G	gradient (%)

|GAVLIN| modulus average gradient of line (%)

GRUL ruling gradient (%)

IKLOC are locomotive types represented by integers from 1 to KRFLOC

IKMAT integers from 1 to KRFWAG representing wagon and carriage types

IWSHP takes the value 1 for workshops and 2 for running sheds

NO takes the value 1 for up trains and 2 for down trains

NOP the opposite direction to NO

NTYPE number of trains of each type, IT or JT

PA power of auxiliaries, (kW)

PGAV a constant expressing variability of fuel consumption

PL power of locomotive (kW)

RACBAL ratio by which speeds between VACPRE and VF should be reduced

RACLOW ratio by which speeds below VACPRE should be reduced

RACPRE ratio by which speeds at the speed limit VF should be reduced

RCAP a safety factor defining the proportion of capacity which can safely be taken up

RGT the ratio of average to allowed weight for a train

RINT the yearly rate of interest (%)

RLF unit level rolling resistance of first locomotive (kN)

RLIFTR years of track life lost per gross tonne carried

RLS unit level rolling resistance for second locomotive (kN)

RLUF ratio of unproductive to total locomotive hours

RMAINT(IKMAT) ratio of time spent in maintenance, overhaul and standby to total time for each wagon and car of type IKMAT

RMAXWT the ratio of maximum possible train weight to maximum allowed for each train type

RMNLOC(IKLOC) the ratio of time spent in maintenance and overhaul to total time for each locomotive of type IKLOC

RPRMET(NO,JT,IT) proportion of times that a train of type JT travelling in direction NO takes low priority in a meet with a train of type IT travelling in the opposite direction

RPROV(NO,JT,IT) proportion of times that a train of type JT travelling in direction NO takes low priority in an overtake with a train of type IT travelling in direction NO

RUG train resistance per unit tonne (kN)

RU train resistance per unit tonne, on the level (kN)

RWG unit rolling resistance of train load on the level (kN)

TACC(NO,JT) time to decelerate to and accelerate from a stop, for train of type JT travelling in direction NO (minutes)

TBLCLC(IKLOC,IT) block time for locomotives of type IKLOC pulling trains of type IT (minutes)

TBLCWG(IKMAT,IT) block time for wagons of type IKMAT on trains of type IT (minutes)

TCLOSE number of minutes per day for which the line is closed

TDELMT(NO,JT,IT) average delay to a train of type JT travelling in direction NO when it meets a train of type IT (minutes)

TDELOV(NO,JT,IT) average delay to a train of type JT travelling in direction NO when it is involved in an overtake with a train of type IT (minutes)

TE tractive effort (kN)

TEVMIN the tractive effort of a locomotive running at minimum continuous speed (kN)

THEAD time in excess of TPOINT/2 required as minimum headway between trains (minutes)

TIMAV(NO,JT) average journey time for a train of type JT travelling in direction NO, (minutes)

TIMIN(NO,JT) minimum journey time (that is journey time with no intersections) for train of type JT travelling in direction NO (minutes)

TOTTIM(NO,JT) uninterrupted journey time for train of type JT travelling in direction NO (minutes)

TPAP time taken to hand over paper orders (minutes)

TPOINT time taken to change points from the mainline to the crossing loop, and back to the mainline again (minutes)

TSAFE safety allowance for low priority train at an intersection, (minutes)

TSLOIT(NO,1) the point-to-point time in minutes for the goods train in direction NO, over the section between crossing loops which gives the largest value for TSLOIT(1,1) + TSLOIT(2,1)

TTOK time taken to exchange tokens (minutes)

TVEC(NO,JT,IT) a column vector whose elements are defined in the same way as XVEC but contain average delay times at each type of intersection (minutes)

TYARD(IKMAT) average yard time per trip for wagons of type IKMAT (minutes)

V speed of locomotive (kph)

VACPRE a user - defined speed between VMIN and VACPRE (kph)

VF speed limit for the line for a train (kph)

VMIN minimum continuous speed at which the locomotive can run without overheating, (kph)

W maximum load of train (tonnes)

WA weight per axle of vehicles (tonnes)

WAL the adhesive weight of each locomotive defined as the weight per axle multiplied by the number of powered axles (tonnes)

WGRKM total gross tonne - km

WGRSKM total gross tonne-km per year (traillling load only; excludes weight of locomotives)

WGRTOT the annual gross tonnes carried per year

WL weight per locomotive (tonnes)

WTRTOT number of gross tonnes per year excluding locomotives passing through yards

XA number of axles per vehicle

XB maximum number of axles over which brakes will work

XCAP maximum capicity in number of trains each way per day

XCAR(IKMAT,IT) total number of cars of type IKMAT required for train type IT

XCARRQ(IKMAT) number of wagons or carriages of type IKMAT required by the railway

XCOMAN(NO,JT) number of manned compulsory stops for train of type JT travelling in direction NO

XCOMP(NO,JT) number of compulsory stops for train of type JT travelling in direction NO

XCONTR the economic life of track if no traffic ran on it (years)

XCROSS number of crossing loops on the line

XFUEL a constant expressing variability of fuel consumption (litres)

XINTMX maximum number of intersections allowed between trains

XL number of locomotives per train

XLIFE economic life (years)

XLIFKL the kilometres which a locomotive can run before reaching the end of its economic life

XLIFL the economic life of a locomotive (years)

XLIFOBL the time it takes for a locomotive to become obsolescent (years)

XLIFOBW the time it takes for a wagon to become obsolescent (years)

XLIFTR the economic life of track (years)

XLIFW the economic life of a wagon (years)

XLOC(IKLOC,IT) is total number of locomotives of type IKLOC required for train type IT

XLOCKM locomotive - km per locomotive per year

XLOCRQ(IKLOC) number of locomotives of type IKLOC required by the railway

XMAN number of manned crossing loops

XMEET(NO,JT,IT) average number of meets per journey for a train of type JT travelling in direction NO with a train of type IT travelling in the opposite direction

XOIL oil consumption (litres per locomotive-km)

XOILKM total annual (locomotive-km)

XOTAKE(NO,JT,IT) average number of overtakes per journey for a train of type JT travelling in direction NO with a train of type IT travelling in the same direction

XRKMT number of train km

XSETLC(IKLOC,IT) number of sets of locomotives of type IKLOC of type IKLOC required for trains of type IT

XSETWG(IKMAT,IT) is number of sets of wagons of type IKMAT required for trains of type IT

XTEWPD(IT) number of trains of type IT each way per day

XTLCKM(IKLOC) number of locomotive-km for locomotive of type IKLOC

XTRHRT number of train hours per year

XTWGKM(IKMAT) wagon-km per year

XVEC(NO,JT,IT) the transpose of a column vector whose elements are defined by various types of intersection. Each element contains an expression for the average number of intersections of that type occuring between train (NO,JT) and trains of type IT during a journey for train (NO,JT)

XWAG annual number of wagon or carriage journeys

XWAGKM wagon-km per wagon per year

XWGTRN(IKMAT,IT) number of wagons or carriages of type IKMAT in train type IT (obtained from the operations model)

PART I - INTRODUCTION

CHAPTER 1

INTRODUCTION

1.1 Objectives and general description of the work

The objective of the thesis is to produce a computerised model which can be used to compare a series of alternative investment proposals under consideration for a less developed country railway. The model would be used in the initial stages of investment decision-making. It is therefore designed to be usable with fairly crude data, so that it can be used to make broad comparisons between different investment proposals, with a view to eliminating the least suitable of them. It is envisaged that a more detailed analysis, outside the scope of the model, would then be undertaken of the best proposals.

The choice as to which possible investment alternatives should be represented in the model was influenced by two factors; the likely importance of each alternative as an option for upgrading a less developed country railway; and the information available from the case study railway, Botswana. Characteristics of less developed country railways are discussed in Section 1.2 of this chapter, and the use of the Botswana line as a case study in Section 1.3. The model concentrates on line-haul operations rather than those in yards and terminals "because the expenses in infrastructure and equipment at terminals are usually minor compared with investments in rolling stock and track for main-line operation" (IBRD 1972). It is a model of a single-track line, since such lines form a large proportion of those found in less developed countries. The main investment alternatives considered are as follows:-

(i) A change in the type of trains working method. The methods considered are Paper Order in Facsimile working; Van Schoor token working; and Colour Light Signalling.

(ii) A change in the number of crossing loops on the line and/or their minimum length.

(iii) Improvements to track profile (gradient and curvature) and/or track weight, type of fastening and sleeper materials.

(iv) Changes in the size and/or speed of existing types of train, or the introduction of new train types, such as single commodity trains, or express trains.

(v) Introduction of new types of rolling stock.

These investments are often interrelated; for example both crossing loop lengths and type of rolling stock can affect train size. These interrelations will become clearer as discussion of the model proceeds throughout the thesis, and are summarised in Chapter 10. It is an important feature of the model that it can allow investigation of the effects of combinations of investments. The above list of investments is not exhaustive; in particular the model does not consider any type of traction apart from diesel working, and does not allow representation of the introduction of a second track.

The model examines the effect of each investment proposal on the capacity of the line, and on annual costs of running the line. It is in three parts:-

- An operations model, which predicts the trains required to carry a certain amount of traffic, and their journey times, with operating conditions dictated by the investments under consideration.
- Equations to measure the capacity of the line, and
- Equations for annual costs.

Both the cost and capacity equations use outputs from the operations model.

Each part of the model is designed to reflect the characteristics of a broad group of less developed country railways discussed in Section 1.2 of this chapter, and Section 2.2 of Chapter 2. These railways can be summarised as simple rail systems, often inefficiently operated with scarce resources; and often having only poor data available. Therefore, the operations model includes parameters representing the effects of inefficiency. Also, it models simple lines, with trains running at slow average speeds, and, as mentioned above, can represent low technology, simple train working methods, as well as more sophisticated colour light signalling. The capacity equations include a measure of capacity specifically designed to represent the limitations of simple trains working methods, along with more conventional measures. The cost equations represent less developed country working insofar as they are simple, and can be calibrated even when data is poor. The possibility of using shadow pricing in the cost equations is discussed in chapter 8 (shadow pricing is a cost-benefit analysis technique often applied to project appraisal in less developed countries). It is concluded there that the simplicity of the cost equations is such as to allow only a partial application of this technique, but that the majority of railways in any case use market prices in calculations with regard to investment decisions.

The model is a comparative statics model; that is, its output is in terms of cost and resource requirements which will be incurred in the long run when the railway has made all necessary adjustments to the new investment. It does not reflect the dynamic effects of changing operations such as the rate of change of numbers of staff or rolling stock from the old to the new optimum levels after an investment has been made.

Inputs to the model are stored in a number of separate files, according to certain criteria, including the investments by which they are affected. This file system facilitates the use of the model to investigate several combinations of investments. It, together with the structure of the model generally, is discussed more fully in Section 1.5 of this chapter. A demonstration of the use of the model to investigate combinations of investments is given in Chapter 10.

1.2 Characteristics of less developed country railways

1.2.1 Types of railways

Three broad types of less developed country railway may be defined:-

(i) Sophisticated networks, carrying a mixture of commodities and passengers, such as the railways of India and Pakistan. These tend to be in countries with relatively high levels of industrialisation (White 1983), and have quite high traffic densities.

(ii) Simple networks, carrying one or two commodities, often with no fixed timetable, typically linking mines to ports.

(iii) Simple networks, carrying a variety of commodities and passengers, in several train types (for example slow goods, mixed passenger and goods express, passenger) with a fixed timetable. Characteristics of such networks will be dictated by the nature of the less developed country in which they are operating. In the poorer less developed countries, traffic volumes are usually low; whereas in the more prosperous ones they may be increasing (White 1983). This is discussed further in chapter 2.

The Botswana line, and the other, surrounding "Cape Gauge" railways of Zimbabwe, Zambia, Zaire, Tanzania's Tazara line, Swaziland, Mozambique, Malawi, and Angola's Benguela line are of the third type. These countries are all fairly poor, and traffic volumes on their railways tend to be low. South African Railways, also part of the "Cape Gauge" network, are more sophisticated.

1.2.2 Problems found on railways in less developed countries

The term "less developed country" encompasses a broad range of countries with various levels of economic activity and industrialisation. This is discussed in detail in Section 2.2 of Chapter 2. Those in the Southern African region are characterised by general poverty, political upheaval, and changes in the economic role of the railway. This causes three major problems in operating the railways:-

(i) Scarcity of resources
(ii) Inefficiency
(iii) Poor quality data

These problems are interrelated. Scarce resources are a major source of inefficiency in operations, and, in turn, inefficient use of resources makes them scarcer. Inefficiency in terms of the railway not fulfilling the transport goals of the country, lead to it being unable to generate revenue to finance the further acquisition of resources. The poor quality of data is often due to inefficiency and leads to more inefficiency by making it difficult to set and monitor managerial goals.

The characteristics of countries in Southern Africa also affect the goals of operation of the railway. Transport volumes are low, and competition from road transport often relatively unimportant. This means that the aims of the railways are likely to be limited to "providing sufficient capacity, keeping equipment in service, etc., with potential traffic being turned away" (White 1983). Aims which are of importance in more developed countries having to provide a service which can compete with road transport, may be not only unattainable but also unnecessary in poorer countries. The model will not therefore concentrate on measures of quality of service such as speed, frequency, and, for passengers, comfort.

The representation of the three problems and the operational goals mentioned above was discussed in general terms in Section 1.1 and will be discussed in detail in various chapters of the thesis.

1.3 Botswana as a case study

The railway in Botswana was considered to be suitable as a case study for the following reasons:-

(i) It is typical of the third group of developing country railways described in Section 1.2.1. It is a simple system, consisting of one main, single track line, joining Bulawayo in Zimbabwe via the border town Plumtree, with Mafikeng in South Africa via the border town Ramathlabama. (There are also two small branch lines not considered in the model). It carries a mixture of traffic, in different train types, to a fixed working timetable. Goods traffic predominates, and consists of a wide range of commodities. Running speeds are slow - the speed limit for the goods train, for example, is 60kph. It uses a simple trains working method; that of Paper Order in Facsimile.

(ii) The Botswana line has some of the problems of scarcity of resources, inefficiency and poor quality data typical of less developed country railways. It is therefore a suitable example to use when building a model which must represent these problems. Details of these problems as they affect Botswana are discussed in section 2.2 of chapter 2.

(iii) The Botswana line has been run by the National Railways of Zimbabwe (NRZ) since 1962 (NRZ : Planning 1980), but plans are now being made for Botswana to take over the line. This has advantages because it has meant that several investment alternatives have been considered, in reports by NRZ and various consultants, linked to the takeover. These reports investigate, among other things, changes in trains working method and size of trains, and information in some of them was of use in constructing the model.

(iv) The Botswana line is part of the Cape Gauge network; a network of the railways of nine southern African countries, listed in Section 1.2.1. Despite their political differences these countries trade with each other, and use each other's railways as transit routes. This, together with technical interdependence in the region has resulted in many similarities among the railways. "Operating practices are similar, and there is sufficient uniformity of motive power to allow locomotives to be readily lent by one railway to another. Wagon designs developed in one country are frequently copied elsewhere... there is a large degree of compatibility of brakes and couplings throughout the network". (RGI 1981).

An investment model of a railway designed with the Botswana line as a case study, therefore, is likely to be applicable, with modifications, to a number of less developed country railways; particularly those in the Southern African region.

1.4 Data collection

Much of the information used in constructing the model was collected during a two month stay with National Railways of Zimbabwe from March to May 1982. In addition, use was made of the general literature on the subject of railway modelling and costing, and this is discussed in Chapter 2.

The nature of data requirements for the operations model was different from that for the cost equations. Information required for the operations model was, to a great extent, the sort of information that the railway requires for its own uses. It was therefore usually readily available both from NRZ and from the general literature on railway operations.

Collecting the information necessary to construct and calibrate cost equations, on the other hand, presented difficulties for several reasons. Firstly, as discussed in Chapters 2 and 8, the standard of general literature is poor, even in developed countries. Secondly, as also discussed in Chapter 8, a costing system will vary according to the purposes for which it was designed. While NRZ has a costing system (ANOP and SECT) it is used for different purposes, and is therefore different in nature, from that required in this thesis. Thirdly, good cost equations require data for several years, and NRZ's records were often only available for one or two years. Fourthly, much of the information required was confidential.

Therefore, information on costs came from a variety of sources, often from unsigned, untitled, undated written documents; from verbal interviews; or from consultants' reports which were themselves based on imperfect information. This problem is discussed more fully in Chapter 9, where cost equations are calculated using information from NRZ. It is concluded there that despite these problems, the quality of information obtained was probably higher than that used in other literature on costing in less developed countries.

Where information was obtained from interviews reference is not made to the individual concerned in the text. Instead, an alphabetical list of people interviewed is given in Appendix 1.

1.5 Structure of the model

1.5.1 Calculations

The model is written in Fortran 77. Calculations are done in a series of subroutines, called sequentially by a main program. The first six subroutines form the operations model. Then there is a subroutine to calculate line capacity, and two to calculate rolling stock requirements, and statistics required for the cost equations, respectively. Finally, five subroutines are used in the calculation of annual costs. The name of each subroutine, and a brief description of the calculations done in it is given in Table 1.1.

Table 1.1 Calculations in subroutines

Subroutine name	Calculations
	The operations model
TRWAG	Conversion of traffic input for each train type, in terms of net tonnes of commodities and number of passengers per year to be carried, into gross tonnes per year, and number of wagon journeys per year for each wagon type. (The definition of train types is described in more detail in Chapter 3).
TRMAX	Maximum possible gross trailing load for each train type. Actual weight of each train type may then be defined as any proportion of maximum weight.
TREWPD	Number of trains each way per day, or per week.
TRNPER	Uninterrupted journey times for each train type in each direction.
TRLOOP	Number of crossing loops on the line, and journey times between loops.
TRWAIT	Length of time spent stationary per journey per train type, and average journey time per train type in each direction. Different equations for delay times are used for each trains working method.
	Capacity measures
TRCAP	Calculation of up to three different values for maximum capacity, as chosen by the user, based on:- - minimum headway between trains, dictated by time taken on the longest section of the line. - maximum number of meets and overtakes per train journey (particularly important with low-technology trains working methods) - maximum delay times Calculation of percentage utilisation of the above maxima.
	Resources and statistics
TRROLL	Number of locomotives, wagons and coaches of different types required by the railway.
TRRES	Conversion of outputs from previous subroutines into statistics required in the cost equations, such as gross tonne - km, train - hours, etc.
	Annual costs
CRROLL	Maintenance and depreciation of rolling stock
CRTRACK	Maintenance and depreciation of track
CRTWM	Maintenance, depreciation and operation of the trains working method, and of stations.
CRREST	Yard, crew, fuel, oil, and administration
CRTOTAL	Total of the above costs.

1.5.2 Input Files

As mentioned in section 1.1, inputs to the model are grouped into files according to certain criteria. These criteria can be listed as follows.

Investments

- Trains working methods, and information on crossing loops
- Train types
- Track profile
- Track weight, type of fastenings and type of sleepers.

Other

- Traffic levels
- Parameters describing efficiency of railway operations, and general railway operating characteristics.
- Economic life of capital goods.

Eleven input files are used; each one representing a different criterion or group of criteria from the above list. The contents of these files are given in Appendix 2.

1.5.3 Building and testing the model

Each subroutine can be run separately, using data from a file containing values for all variables which, when the model is run as a whole, are passed across from other subroutines. It is thus possible to test the accuracy of results from each subroutine. Discussion of such tests is included in various chapters of the thesis.

1.5.4 Outputs from the model

Outputs from the model are split into four files:-

(i) A general file, giving capacity measures, percentage utilisation of capacity, and total annual cost.

(ii) Journey times, including non - stop journey times, and delay times due to various factors, for each type of train in each direction.

(iii) Rolling stock requirements

(iv) Annual costs broken down into categories, such as locomotive depreciation, locomotive maintenance, track renewal, track maintenance, etc.

Examples of these files are given in Chapter 10.

It is envisaged that the general output file would be used each time the model was run, and that the other files would be used for extra information as required.

1.6 Structure of the thesis

The thesis is structured in five parts. Apart from this chapter, the first part contains Chapter 2, which discusses the background to the model and previous work relevant to the thesis. Part Two describes the various parts of the operations model, and discusses how they were created and tested. Part Three contains chapters on estimating capacity, calculating rolling stock requirements, and obtaining values for general statistics. Part Four discusses costs. Each chapter in Parts Two Three and Four contains discussion of the literature relevant to that chapter. Part Five contains a chapter on running the model, giving examples of its use in modelling both the situation in Botswana at present and the effect of various combinations of investment. It also contains a chapter drawing conclusions from the work.

CHAPTER 2

BACKGROUND AND PREVIOUS WORK

2.1 Introduction

This chapter covers three topics; problems found on railways in less developed countries, models of railway operations, and railway costing, in sections 2.2, 2.3 and 2.4 respectively. Conclusions to the chapter are given in section 2.5. The problems identified in section 2.2 are discussed in the remaining sections.

2.2 Problems found on railways in less developed countries

2.2.1 Introduction

The term less developed country implies a country where personal incomes, and levels of industrialisation, are lower than in a developed country. This term encompasses a wide range of countries, which White (1983) has classified as follows:-

- Relatively prosperous countries, with high per capita income, such as Malaysia and Argentina. The sophistication of the rail network in such countries often depends on the time at which it developed, and the nature of competition from road transport.
- Countries with low per capita income, but relatively extensive industrialisation, such as India, Pakistan, Bangladesh and Egypt. As mentioned in Chapter 1, these countries often have a sophisticated rail network.
- The poorer countries, with small populations, and no or little oil money, such as Sudan, Tanzania and Zambia.

The countries of the Southern African region (excluding South Africa), and indeed most of Africa, can be described as belonging to the third of the above groups, that is, the poorest countries with little industrialisation. The rest of the discussion in this chapter therefore concentrates on this group. In section 2.2.2 general problems in these countries, and the way those problems affect the railways, are discussed. In Section 2.2.3 examples of problems affecting the Southern African region are given. Section 2.2.4 provides a conclusion as to the features of railway operation which should be represented in the model developed in this thesis.

2.2.2 Problems found in the poorer less developed countries

The main factors affecting less developed countries in Southern Africa can be described as follows:-

- General poverty
- Changes in the economic role of railways since they were first built.
- Political change.

General Poverty

The countries of Southern Africa suffer from shortages of capital, foreign exchange and skilled labour. This affects resources available to the railway. There may be a shortage of some capital equipment. Maintenance of equipment is often a problem, due to a lack of both artisans and spare parts. White (1983) points out that, with regard to locomotives in particular, the problem is often exacerbated by the fact that equipment comes from many different sources, as a result of "tied" aid, so that several different types of technology have to be maintained Furthermore, there may be a lack of experienced managerial staff.

White (1983) discusses the way in which general poverty affects the traffic density on railways. "High oil costs severely limit input of other goods ..... and low prices for goods which such countries produce (agricultural products, ores such as copper) aggravate the problem. Traffic volumes thus tend to be low."

Changes in the economic role of railways

Taborga (1980) discusses the problems which arise because most less developed country railways were built before any major road network was developed. Railways tend to provide a more generalised service than is optimal, carrying traffic which could be more efficiently transported by other modes. Also, because railways tend to have had a monopoly over transport, this has led to inefficiency in investment decisions and in the institutions responsible for railways. Increasing competition from roads has led to a decline in the financial position of railways, and to many of them being subsidised as a consequence.

In the poorer less developed countries competition from roads may still be weak: "..Given the limited development of road transport within such countries, the share of traffic carried by rail may be quite high and thus these countries' economies are dependent to a significant degree on the state of the rail service" (White 1983) This does not necessarily contradict the assumption, however, that the monopoly position of rail has led to inefficient investment.

Political changes in less developed countries

Problems arise because most less developed country railways were built by Europeans and tend to reflect European requirements in their design. In Africa and South America there is a "strong emphasis on what are known in Brazil as "export corridors" [lines running inland from the ports which] reflects the fact that those southern continents were regarded primarily as a source of raw materials by the organisations - mainly European - which built the line ... lack of intracontinental links ... [has led to the] ... basically unhealthy ... [situation] that trade between neighbouring countries in Africa should be far less than with Europe or North America." (Diagne 1977)

Many less developed country railways have found that when they became independent they were faced with the dual problems of loss of resources to the railway, as European support was withdrawn, and a railway system which does not fulfil their new transport needs.

2.2.3 Examples of problems in the Southern African Region

The most striking causes of problems affecting the Cape Gauge network have been the many political changes in the Southern African Region. These have included the following:-

- The Unilateral Declaration of Independence (UDI) in Rhodesia (now Zimbabwe) in 1965, and subsequent international sanctions.
- The splitting of Zambian Railways from those of Southern Rhodesia (now Zimbabwe) in 1967 (NRZ 1982)
- The war in Rhodesia in the 1970's
- Mozambique's independence in 1975
- The closing of the border between Rhodesia and Mozambique in 1976, and its reopening after Zimbabwean independence.
- The war in Mozambique

- The end of the war in Rhodesia, and subsequent creation of the independent state of Zimbabwe in 1980
- Increasing industrial and political unrest in South Africa.

These changes have affected both traffic demand, and resources available to the railway. Changes in traffic demand have occurred both because of changes in the economic activity of countries,. affecting domestic demand, and because of changes in the preferred transit routes of the land-locked countries. For example, the amount of traffic transported on Zimbabwe railways in million net tonne - km declined from 6358 in 1976 to 5588 in 1978, but increased to 6864 in 1980 and 6611 in 1981 (NRZ 1982) This is largely due to changes in levels of economic activity. Both Mozambique and Botswana have been affected by Zimbabwe's changes in choice of traffic route. The big change in Mozambique occurred after Rhodesia's UDI: "Mozambique once carried 75% of Southern Rhodesia's external trade to the sea - about 1.5 million tonnes per year ... Now 90% of Zimbabwe's import - export traffic passes through South Africa" (RGI 1981) Since 1980 attempts have been made to lessen Zimbabwe's dependence on South Africa and re-establish routes through Mozambique. However, for reasons discussed below, Mozambique's trades and ports are now run down. Also, Zimbabwe is dependent on South African Railways for technical help, so it is proving difficult to make that change. Botswana is a transit route to South Africa from Zimbabwe, and in 1979-80 about 70.1% of its traffic was transit, 2.5% export and 14.7% import, the remaining 12.7% being local traffic (Transmark 1980) As such, it is extremely vulnerable to any changes in other countries' choices of transit routes.

With regard to resources available to railways, these are some of the problems in the region:-

- The splitting of Zambian Railways from those of Southern Rhodesia in 1967 (NRZ 1982) left Zambia with inadequate management centres to run a railway.
- Sanctions in Rhodesia after UDI prevented capital stock and spares being bought. While the infrastructure was maintained fairly well despite this, it did lead to a shortage of rolling stock and motive power. The motive power problem has since been exacerbated because: "a number of skilled artisans and technicians left the country around the time of independence ...

As a result, out of a total fleet of 255 diesel and 110 steam locomotives,...[NRZ]... typically have 130 and 50 respectively in traffic each day." (RGI 1981) By 1982, the exodus of skilled staff had not reduced, and had reached such a pitch that there were not even enough skilled staff left to train new workers.

- South Africa may have problems due to industrial unrest and guerrilla warfare.
- Mozambique has severe problems due to staff shortages; according to Mr. Z Palla de Lima, Deputy Director-General of DNCPF, "we lost 3500 experienced and skilled men in the first two years after independence, in 1975, which was 80% of our experienced manpower from drivers and guards up to qualified engineers. We are making a tremendous effort to train people for these jobs, but it takes time". (RGI 1981) It has also suffered war damage; its ports are "currently run down, inefficient, and underutilized." (RGI 1981), and it is undercapitalised; "It is estimated that Mozambique will need to spend at least $100 million on its railways, and about the same on port development" (Transport 1980)

2.2.4 Features of railway operations to be modelled

The conclusions to the above discussion, in terms of the way that the problems of a country in the Southern African region should be interpreted in a model of its railway, have already been listed in chapter 1. They are as follows. Three sources of operating problems should be represented; scarcity of resources, inefficiency, and poor quality data. The aims of the railways being considered are likely to be those of producing required capacity at minimum cost. Aims associated with railways to which more resources are available, and which experience greater competition from road, are likely to be relatively unimportant. Hence train speeds, frequencies and other measures of quality of service, may have low priority, except insofar as they affect the capacity of the line.

The discussion in the remaining sections of this chapter will include examination of the treatment of these features in the literature.

2.3 Models of railway operations

Arjang A Assad (Assad 1980) provides an overview of railway modelling, in which he distinguishes between three types of railway activity which may be modelled:-

- yard activities; the operations performed in classification or marshalling yards.
- line activities; the operations affecting the journey of a train between yards.
- the interaction between line and yard policies.

He then suggests dividing these operations models into:-

- strategic models, which aid decision-making on resource acquisition in the long-term.
- tactical models, which focus on resource allocation in the medium term, and
- operational models, used to make decisions on the day-to-day activities of the railway.

It is literature on strategic (i.e. investment) models of line activities which is of interest in this thesis.

In the following chapters, the discussion of each stage of the model produced is accompanied by a literature review on the topic; therefore, when such literature forms a specific paper on one issue only its discussion is left entirely to the relevant chapter. Only those sources which describe models of line operations as a whole are discussed here. In fact, there are only three such models. Firstly, there is the work of E R Petersen and the Canadian Institute of Guided Ground Transport, who produced an Extended Railcar Network model (see, e.g. CIGGT 1976). Secondly, there is the Australian Railway Research and Development Organisation's National Rail Investment Study (ARRDO 1983 (i),(ii) and (iii)), which uses some of Petersen's work. Thirdly, there is the World Bank model of Colombian railways (IBRD 1970) produced as part of the Harvard Transport Program (Kresge and Roberts 1971).

The following description of these models includes a discussion of the extent to which they can incorporate a representation of the problems affecting less developed country railways. The ways in which these problems might be represented in operations models are as follows.

Scarce resources This is likely to affect the general construction of suitable operations models, which might be expected to simulate simple rail systems. Also, models could include "low technology" operations; for example, the use of steam locomotives, or of simple trains working methods.

Inefficiency The inclusion of some sort of representation of the effects of inefficiency is crucial if results of modelling railway operations in less developed countries are to be at all accurate. This is a point stressed in the Overseas Development Administration's Railways Sector Appraisal Manual (ODA 1982). This manual was written in order to give economists with no special knowledge of railways, general information about the rail sector in less developed countries, and says: "Any assessment of the achievable capacity of the railway ... needs to rely heavily on an assessment of operational performance, and a wide range of performance indicators has been developed and normally collected by most railway systems. It would be difficult to overemphasise the importance of making proper use of performance indicators to identify and monitor trends in the efficiency of the railway operation." Such performance indicators should therefore be included in models of railway operation.

Poor data The fact that data may be poor means that the model should be constructed in such a way as to be able to function with fairly crude inputs. Even in models of developed countries, Assad (1980) points out that data requirements can be a problem, requiring "substantial effort," and providing; "severe barriers to effective implementation of the models", although he says that problems are worse in costing than in modelling operations. A strategic model of the type being developed in this thesis must also take simple inputs because it is likely to be used before the finer details of an investment are known. On the other hand, the model must not be so simple that it is unable to model railway operations realistically.

Aims of the railway Operations models might be expected to concentrate on questions affecting line capacity, rather than on those affecting quality of service.

The first two models to be described below; the Extended Railcar Network Model (CIGGT 1976) and the Australian Rail Investment Study (ARRDO 1983 (i),(ii) and (iii)), were in fact designed for developed country railways. Nevertheless, they, together with the World Bank model, are now described with reference to the previous discussion. (This description includes some references to the model developed in this thesis, which is described as "The Botswana model" for brevity, despite the fact that it is designed to be usable on several railways).

The Extended Railcar Network Model (CIGGT 1976)

The Railcar Network model is described as "a planning tool for testing the effects of plant, traffic or operational changes to the mainline position of a railway system, including the physical links and principal yards." Thus, it is broader in its scope than the Botswana model,and, while it can be used for the same purpose - to examine line upgrades - the nature of this examination is different, as discussed below.

The CIGGT line model takes number of trains each way per day, and their uninterrupted journey times as inputs to the model. The Botswana model, by contrast, calculates these from a demand input expressed in terms of net tonnes, and it is these that the planner is expected to use in the evaluation of various investments. No cost equations are included in the CIGGT model, neither does it output some of the statistics, such as gross tonne-km required for such equations.

The CIGGT model as a whole, therefore, includes considerations not required for the Botswana model (yard and network modelling) and excludes considerations which are required (e.g. conversion of net tonnes to gross tonnes and train requirements; calculation of train speeds; cost equations.) Petersen's work on modelling train delays on single-track lines, however, is relevant, and the paper which explains the theory behind this modelling (Petersen 1974) is discussed fully in chapter 5.

The discussion in chapter 5 examines the appropriateness of Petersen's paper for the Botswana model. Several adaptations are suggested, and discussed in detail there, some of which could be regarded, to some extent, as being due to the fact that the CIGGT model is not designed for a less developed country. For example, Petersen's model concentrates mainly on lines with high technology, colour light signalling systems. Also it does not allow explicit representation of the effects of inefficiency.

ARRDO's models for National Rail Investment in Australia

ARRDO produced a study designed to "bring together the evidence sustaining a case for capital investment in the National Mainline Rail Network ... It had to be carried out within very tight time constraints. Although the initial design for the study involved a duration of two and a half years, ARRDO was faced with the need to complete it in less than 12 months" (ARRDO 1983(i)). The study was in two parts; a National Overview Study, which produced an operations model of the whole of the Australian railway system; and a Specific Links study which "prepared a case for investment in the Melbourne - Sydney - Brisbane - Cairns mainlines along the East coast." The Specific Links study contained an operations model similar to that used in the National Overview study, and some cost and revenue equations. Discussion of both operations models is combined in this section. The cost equations from the Specific Links model are discussed in section 2.4. The revenue equations are not discussed as they are irrelevant to this thesis.

Both models used a highly aggregated representation of the rail network and its traffic flows. Five railway systems with up to 1600 stations on each and carrying up to 250 commodity types were represented as a network of 250 nodes (groups of stations) and 20 commodity classes. The first step in these models; to determine optimal traffic flow over the network; is outside the scope of this thesis, and will not be discussed further here.

Unlike the CIGGT model, both ARRDO models calculate trains requirements from data on traffic flows, net to gross conversion ratios, and maximum train size as a function of "ruling grades, available locomotive power and passing loop constraints" (ARRDO 1983(ii)). Like the CIGGT model, however, ARRDO uses uninterrupted journey times as an input. ARRDO does not produce its own methodology for train delay times. It suggests either using Petersen's delay model

(Petersen 1974), or more complicated simulation models, discussed further in chapter 5 of this thesis and dismissed there as requiring too detailed a data input to be usable for the Botswana model. Delay times from the relevant model are used to "produce delay curves which show the ratio of the delay time to the free running transit time on a given line section." It is these delay curves which are used in their model so that "the anticipated congestion delay associated with forecast traffic levels can then be estimated by selecting the appropriate value from the delay function curve and multiplying it by the free running transit time."

Line capacity is then determined by comparing maximum allowed delay with actual delay. As discussed previously, and also in Chapter 6 of this thesis, this is probably an inappropriate measure for many less developed countries where speed of service is often not of critical importance.

Rolling stock requirements are then calculated. Only locomotive requirements are considered as a function of train journey times; "wagon capacity requirements are calculated using known wagon turnaround times (assumed relatively independent of train delays related to track capacity)" (ARRDO 1983(ii)). The model used for these calculations is time-related, that is "the model maintains an inventory of the locomotives and wagons which are available for the freight task ... updated by the model for each year analysed. The ages of all locomotives and wagons are increased and the availability of locomotive classes, which decreases with age, is calculated." As stated in Chapter 1, this thesis is concerned with building a "comparative statics model", which produces average annual costs, and is not therefore concerned with time - related variation in resource requirements.

To conclude, the sections of the ARRDO models which have similarities with the Botswana model are those on converting demand into train requirements, calculating train delays and line capacity, and calculating rolling stock requirements. However, none of the work was usable in this thesis, for the following reasons:-

(i) The representation of demand, in terms of tonnages carried, was too aggregated in the ARRDO model.

(ii) The work on train delays contains no methodological development from that of Petersen.

(iii) As mentioned earlier, the line capacity measure is not regarded as the most relevant for a less developed country.

(iv) It is on the one hand considered necessary to relate wagon requirements to train speed, and on the other hand considered unnecessary to relate rolling stock requirements to age.

In general , the lack of a model for uninterrupted train speeds means that the effect of changes of line gradient, locomotive power, or maximum size of train cannot be considered.

The World Bank Model of Colombia

The Harvard Transport Program, of which the Railway Model of Colombia is a part, was designed as "a model or series of interacting models, which can effectively simulate an economy and its transport network." The preamble to the description of the Transport Program shows that it is designed as an investment model (or strategic model, to use the terminology established earlier in this chapter). It also shows that one of the main purposes of building the Program was to demonstrate a systems approach to transport planning. "The manner in which investment should be allocated to transportation cannot be established, at least in principle, without understanding the relationship of transportation to other economic activity ... This implies that any comprehensive, long - run transport plan will need to take into account the interdependency between the transport system and the general economy as well as the systems or interactions effects within the transport network itself." (Kresge & Roberts 1971)

Two interacting models are used in the Harvard Transport Program; a macroeconomic model, and a transport model. The transport model has four modal submodels; Highway, Rail, Transfer and other. (Kresge & Roberts 1971). It is the rail submodel which is of interest to this thesis, and is discussed further below. The above discussion was provided to show the context in which the rail model was designed; as part of an overall transport investment model, it hence takes some of its inputs from, and provides most of its outputs to, other models for further processing.

The rail model is discussed in a World Bank Paper (IBRD 1970). It "is used to develop the operational costs and performance measures for a single track rail link" (IBRD 1970) A link is defined, for the transport models in general, as follows; "If it is assumed that all economic activity takes place within cities or villages .... then the spatial aspects of the transportation process may be represented by means of a network composed of links and nodes. The links correspond to transport routes, the nodes to cities or producing regions" (Kresge & Roberts 1971). Hence in the case of the railway, the model is one of operations on a line between major marshalling yards.

The link performance measures are a direct output from the railway operations model, and the operating costs an indirect one, produced from cost equations which use statistics from the operations model. Discussion of the cost equations is left until section 2.4 of this chapter.

The link performance measures are not defined in the World Bank paper, but they state there that they are "in the same format as the Highway and Transfer Model" (IBRD 1970). For the transport system as a whole, these measures include, for each type of vehicle, waiting time, time spent travelling, vehicle-miles, and ton-miles. Also output from the operations model are wagon, carriage & locomotive requirements. The operations model used to produce these figures is based on the following assumptions:-

- That the railway concerned carries all its traffic in trains of the same weight and speed.
- That the weight of these trains is the maximum that can be hauled by the locomotives up the ruling gradient of the link.
- That the speed of the trains is determined by the average gradient and overall speed limit for the whole link, and
- That the delays to trains are caused only by meets

The World Bank model of Colombia was applied to Thailand railways (IBRD 1972). This application included adaptations of the model, the most important of which were:-

- To allow two train types running at different speeds to be represented, one passenger and one freight. They do not explicitly state whether they modified the delay model to allow for overtakes between trains, but they do allow for the priority of one train over another at meets.

- To allow trains to be run at less than their maximum weight (or as they put it, "increasing the minimum allowable number of daily trains to a level exceeding the minimum consistent with minimum costs").

The model was then tested in Thailand "with a series of trial runs designed to obtain results that matched known data and that verified the model's accuracy in detail" (IBRD 1972). They accepted 10% as a reasonable level of accuracy and found that the only figures predicted within that level were car-km and train-km. (If figures for locomotives are separated into those for diesel and those for steam, then figures for diesel locomotives required and diesel locomotive-km are within 10% accuracy. However, since the figures for steam locomotives were very inaccurate (see below), all figures for locomotives should be treated with caution).

Figures for average speed were 40% too fast for freight trains and 21% too fast for passenger trains. IBRD commented: "Comparisons of average speed are not meaningful because the figures provided by the Railway and the model are based on different concepts. The Railway figure is the average overall speed between two points including stop and yard time, but the figures from the model refer only to average running speed while underway, considering only delays because of meet." In other words, the accuracy of the speed calculations has not been tested. The other outputs produced show the following levels of accuracy:-

number of steam locomotives required	-28%
number of diesel locomotives required	-7.2%
steam locomotive - km	-22.9%
diesel locomotive - km	-0.047%
passenger car requirements	-0.12%
freight car requirements	-59.17%

These severe underestimates are explained in the Thailand work as being due to the fact that "terminal (yard and shunting) operations have not been simulated." (IBRD 1972). However, the equations used to produce figures for locomotive and car requirements include variables for time spent in yards by the equipment (IBRD 1970), so that it should have been possible to estimate these requirements accurately. It is only locomotive-km in yards which are not included in the model.

The conclusion drawn from calibrating the Thailand model is that "the results of the calibration process show that the simulation model represents reasonably well the workings of the rail system" (IBRD 1972). This point can be contested in the light of the above discussion; the only statistics produced with any accuracy; those for car-km and train-km; could be obtained directly from functions of net tonnes carried, journey length, wagon payloads and numbers of wagons per train, and do not use the more complicated outputs from the model; that is, those involving speed.

The Thailand application also discussed problems of data aggregation. Their comments on cost data are considered in section 2.4 of this chapter. On the operations side, the main difficulty encountered was; "in defining average and maximum gradients it was difficult to choose for each link a single number to represent the effect of gradients on operating costs and performance, since many links cross both flat and hilly terrain." Other problems, such as the fact that only four wagon types are allowed, were mentioned, but it was pointed out that only a trivial change in the model would be required to change this.

In conclusion, five points can be made about the model, the last three directly related to the extent to which it addresses the problems of less developed country railways.

(i) Insofar as it is an investment model, it is similar in aim to the Botswana model although the fact that it is built as part of a larger model affects output somewhat. Most noticeably, there is no test for capacity of the line.

(ii) By far the most important criticism of the model is that its representation of a railway is oversimplified to the point where it can predict no important statistics with accuracy.

(iii) With regard to the modelling of low technology systems, the modified Thailand model allows for steam as well as diesel locomotives. No specific attempt is made to model simple trains working methods.

(iv) There is no systematic addressing of problems of inefficiency. In particular, speed and delay calculations are based on the system running perfectly.

(v) The input data requirements are simple; in fact, too simple in that not only do they produce a model with inaccurate results, but there are sometimes severe problems choosing suitable values for data, because of the level of aggregation required.

2.4 Railway costing

Railway costing systems can be designed for any one of several purposes. Sander (Sander 1974) suggests the following list:-

"(i) Setting of realistic prices (rate - making)

(ii) To provide data for profit analysis of existing and potential business, which in the case of a railway will include not only rates and fares, but also line, section and service profitability.

(iii) Cost control

(iv) To permit evaluation of economies to be secured from operating and technological changes.

(v) To provide data needed for comparison of costs between the different transport modes required in the consideration of alternatives.

(vi) To provide data for evaluation of further capital investment."

Of these aims, (vi) is likely to be most relevance to this thesis, although (iv) may also have some bearing.

The aim of a costing system, and, in particular, whether it is designed to consider qualitative changes in railway operations, will affect the units used to express variability of costs. An example may make this clear. NRZ's own costing system, ANOP, (ANOP 1981/82) is designed mainly for purpose (i) (rate-making). As such, it is based on the assumption that no major changes in operating characteristics will occur. Taking its treatment of fuel costs as an example; in ANOP they are expressed as a function of tractive-effort hour. In fact, as the discussion in chapter 8 will show, fuel costs are affected by gross tonne - km and gradient of the line. However, tractive effort - hour is an adequate unit of variability for ANOP's purpose since, provided train weights and speeds, and the profile of the lines remain the same, it is a reasonable proxy for gross tonne - km and gradient of the line.

Some work on railway costs is irrelevant to this thesis simply because of this difference in aims and therefore units of variability of costs. Jeremy Drew's cost model of the Colombian system is an example of this (Jeremy Drew 1978). It is designed to evaluate network changes in terms of the opening of some lines and closing of others. As such, no major qualitative change in operations is assumed, and it is stated with regard to the conclusions reached on evaluations made using his model; "it must be emphasised that these conclusions are specific to Colombian railroads and to the operating methods and the rolling stock they employ"

Even when costing systems have investment as an aim the approach taken may not be the same as that used in this thesis. For example, previous to their 1983 work, quoted in section 2.3, and referred to later in this section, the Australian Railway Research and Development Organisation did a study which examined the effects of investment in several different types of capital equipment (ARRDO 1981). Investments considered included replacement of locomotives, wagon, track or signalling equipment. These investments were examined separately in terms of changes occurring in all railway costs provided no other investments were made. In other words, marginal cost equations specific to each investment were derived. For example, the locomotive maintenance cost equation used in the study of investment in locomotives is a function of gross tonne-km and age of locomotive. In the study of investment in wagons with a higher gross to tare ratio, however, locomotive maintenance costs are represented by an equation expressing the proportion of these costs saved as a function of the proportional lowering of gross tonnage being hauled.

For this thesis, cost equations are designed to reflect the effects of changes in any investments. This, plus the fact that an operations model is used and can show changes in levels of output caused by the investment, means that the effect of combinations of investments on total costs can be examined, rather than, as with the ARRDO 1981 work, the effects of single investments on marginal costs.

In general, then, the work on costing of most relevance to this thesis is that which looks at the general variability of costs, rather than providing proxy units of variability which are valid only under certain specific operating conditions, and which looks at total costs rather than marginal costs. There is little such work available (a problem discussed later in this section). The cost equations from ARRDO's specific links model, quoted in section 2.3 (ARRDO 1983(i),(ii)&(iii)), might have been expected to be of use. However, their work was for a developed country, and thus for a railway with a very different cost structure. Also, they produce strong disclaimers as to their ability to develop a methodology on costing; the severe 12 month time limit to their study has already been mentioned. This meant that they had to rely on previous work on the subject, about which they say: "The understanding of cost causal relationships and consequent life-cycle costs for even the most important of assets is limited." In their own study, cost equations "known to be questionable, have been used in the absence of anything better" (ARRDO 1983 (iii)).

The main works of relevance are Sander's manual on Railway Traffic Costing (Sander 1974), written mainly for use in less developed countries, and Majumdar & Blore's work on Sri Lankan Railways (Majumdar & Blore 1981). The cost equations from the World Bank Railway model of Colombia (IBRD 1970) have only minimal relevance, as there are major problems with them. These three works are discussed in Chapter 8, both in general terms, and in terms of individual cost equations produced. Only brief summaries of them are therefore given here. Sander's work is in the form of a general discussion of railway costs, and does not usually include specific cost equations. His discussion of the factors affecting the variability of costs is broad ranging, drawing on data from several railways, many of which are in less developed countries.

Majumdar & Blore's work encompasses both road and railway costing in Sri Lanka and is designed to establish the best modal split for traffic, and hence the best area for investment. As such, the equations it establishes are often useful for this thesis, being designed to aid investment decisions. However, they tend to stress the importance of economies of scale, since they are concerned to establish optimal quantities of traffic to be moved by the railway as opposed to by road, an aim outside the scope of the Botswana model. The poor quality of data available to them was notable throughout the work, as will become clear in the discussion of their specific cost equations in chapter 8. The cost equations in the World Bank's model of Colombia (IBRD 1970) suffer from the same problem as the rest of that model; that is, they are oversimplified to the point where they do not accurately reflect the behaviour of railway costs. This will become clear in the discussion of individual costs in chapter 8. The application of the World Bank model to Thailand (IBRD 1972) does not discuss the quality of the cost equations specifically. However, it produces a table showing the interrelations between operating conditions and costs, indicating those operating conditions which affect costs but are not measured by the model. Although they do not say so, this is usually due to poor cost equations; for example the model does not measure the effect of train speeds on crew costs because it uses train-miles and not train-hours as the unit of variability of this cost. Thailand's calibration of the model gives no indication of the accuracy of the cost equations obtained because: "The differences found between simulated and actual costs reflect only the differences between simulated and actual performance characteristics. For example, the cost input in the model for car maintenance (car maintenance costs per car-km) was obtained by taking the total car maintenance costs from the Railway's cost statistics and dividing it by the actual total car-km. Thus, if the simulation model obtains a total of car-km which is equal to the actual car-km, the simulated total car maintenance costs will be, by definition, equal to the actual figure" (IBRD 1972).

Having discussed the type of cost equations suitable for the Botswana model, it is now necessary to examine the problems which are likely to occur in producing and using them. The most important problem is a general lack of information on railway costing even in developed countries. Assad, speaking of developed countries, says that "costing has been a notorious difficulty on railroads" (Assad 1980). His point is echoed by ARRDO's comments on the limited understanding of cost causal relationships, quoted earlier in this section. In less developed countries, the problem is often exacerbated by poor record - keeping; "Third World Railways seldom have much expertise in accurate costing, and may be deficient in expertise needed to conduct technical appraisals." (ODA 1982) The detailed discussion of Sander's and Majumdar and Blore's work in chapter 8 will show that they encountered this problem.

Data availability affects both the initial formation of equations and their subsequent use. The application of the World Bank railway model in Thailand discusses the problems of calibrating cost equations. It is clear from this discussion that the costs normally available in railway accounts are inadequate for use even in equations as simple as those of the World Bank. Also, sometimes, over-simplification of cost equations can make calibration more difficult rather than less because it leads to problems in deciding the best aggregate value of a parameter. "The most difficult and, in a way, dubious aspect of the data interpretation required to apply the rail simulation model was the treatment of operating costs. The available data were the calculations made by the State Railway, which follow the ICC cost rules. Railway costs are mainly accounting costs, geared to the determination of total system expenses and to a disaggregation of these expenses into as many cost items as possible. But the rail simulation model requires economic costing .... Therefore the Railway's cost information had to be adapted for use in the rail model .... Many of the basic allocations (made in this adaptation), such as between fixed and variable component, or between different types of equipment, are derived from the Railway cost accounts. These allocations are estimates made by the Railway, based on their experience and that of other railways. They have not been derived from proper statistical costing, and as such have many limitations." (IBRD 1972)

The issue of how the problems listed in section 2.2 as facing less developed countries will affect the type of cost equations produced is now discussed.

On the question of inefficiency in operations in less developed countries, cost equations will not usually be sophisticated enough to allow explicit inclusion of efficiency parameters, but the calibration of costs using data obtained within the country will implicitly contain this information.

Representing the effect of scarce resources on economic choice through the manipulation of costs is discussed in the literature on cost-benefit analysis (see, eg Layard 1972). Cost-benefit analysis makes use of shadow rates of exchange and interest rates in situations where scarcity of foreign exchange and capital, respectively, cause these rates to be undervalued in the market. Shadow wage rates are also used; whether they are lower or higher than actual wage rates depends on whether labour is considered to be too scarce or too plentiful. Use of cost-benefit analysis, therefore, depends on cost equations being expressed in terms of the labour, foreign exchange and capital resources of which they are composed. Such equations are more complicated than those likely to be used in the model, and therefore full use of cost-benefit analysis is neither intrinsic to the structure of the model, nor likely to be possible when the model is applied. In the latter case, the user calibrating the model may occasionally be able to adjust the data they are using to allow for "shadow" rates for some resources, but this is likely to be an exceptional case. The choice of whether to use cost-benefit analysis in railway costing in any case depends on government policy towards the railway, and hence the railway's economic aims. It also depends on whose behalf; the government, the railway, or a consultant; the model is being used. In chapter 9, the calibration of the model using Botswana and NRZ data is described. In this case, market prices are used, since the railway's objectives are set in terms of market prices, and its records kept in these terms.

2.5 Conclusions

The general conclusion with regard to literature available on the subject of investment modelling for railways must be that little is available even if the literature on developed as well as less developed country railways is considered. Many of the cost models which might at first seem relevant are not because they look at investments "piecewise", considering the effect of one investment or costs if all other railway operations remain unchanged.

An operations model is necessary in order to avoid this "piecewise" effect as it can simulate the system effects of a combination of investments. The only operations model with this aim are the World Bank Model of Colombia, and ARRDO's network model. The reasons why the World Bank model was regarded as inadequate to fulfil this aim, and the ARRDO model largely irrelevant to the requirements of this thesis, were discussed in section 2.3. No operations model exists which fulfils the basic requirements for an investment model of a simple less developed country railway, like the one running through Botswana. These requirements may be listed as follows:-

- To model the line - haul operations of a simple railway system, using simple trains working methods.
- To allow the explicit inclusion of performance indicators to quantify the effects of inefficiency in railway operations found on many less developed country railways.
- To produce accurate results for statistics to be used in cost equations.
- To calculate the capacity effects of various investments
- To be useable with a fairly simple data input.

With regard to costs, much of the work on railway costing must be discarded as having been designed with different aims to that required in this thesis. Cost equations for the Botswana model must be constructed as functions of all the main factors affecting them, and as total, not, marginal cost equations. Cost equations using "proxy" units of output which only express their variables under certain specific operating conditions are not adequate for a system examining qualitative changes in operations.

The literature indicates that data availability on costs is likely to be poor. This means that cost equations for the Botswana model must be fairly simple in construction, even if this means the exclusion of some of the minor factors affecting variability.

PART II - OPERATIONS MODEL

CHAPTER 3

CONVERTING DEMAND INTO TRAIN REQUIREMENTS

3.1 Introduction

Traffic demand is represented in the model as an input of a series of net tonnages and number of passengers carried. It is assumed that the types of train in which traffic is to be carried are dictated by the nature of the traffic; for example passengers must be carried by passenger or mixed trains, and perishable goods in express trains. Therefore, the demand for each type of train is input separately. The definition of train types has thus first to be established, and this is done in Section 3.2. In Section 3.3, the conversion of traffic input into gross tonnes carried, and number of wagon journeys required to carry it, is discussed. In order to work out the number of trains required to carry this traffic, and also, later in the model, to calculate train speeds, gross trailing loads of trains must be known. The establishment of maximum gross trailing load is discussed in Section 3.4. The allowed trailing load for each train type can then be defined as any proportion of the maximum, and this allowed load is used to established number of trains per day required, as discussed in Section 3.5. A conclusion to the chapter is given in Section 3.6.

3.2 The specification of train types

3.2.1 Introduction

The way in which train types are defined affects not only the calculations in this section of the model, but also the modelling of train speeds and delays, discussed in Chapters 4 and 5 respectively. The characteristics of a train which define it as a separate type must therefore be established with reference to all relevant calculations. In order to do this, the types of train found in Botswana and the rest of the NRZ network are first described, in Section 3.2.2. In Section 3.2.3 the factors affecting definition of a train type in the model are listed, and discussed in terms of how accurately they reflect the situation in Botswana.

3.2.2 Train types in Botswana

The train types which run in Botswana are:-

Passenger

Mixed passenger and goods

Goods

The following observations can be made about these trains, from the working timetable (NRZ:WTT 1981(i)):-

- Each train has separate point-to-point timings, the goods trains being the slowest.
- Goods trains form the majority of trains; there are eight goods trains running the full length of the line, plus one running five days per week and three running very short distances each day, compared with one daily mixed train, and one passenger train twice a week.
- The mixed train carries urgent and perishable goods.
- The number of goods trains required per day or week is estimated directly from traffic requirements in the direction of heaviest traffic, the same number of trains being run in each direction. However, planning documents simply assume an input of one passenger train twice weekly and one daily mixed train in each direction. (NRZ:WTT 1981(iv))

The train types which run in Zimbabwe are much the same as on the Botswana line, with goods trains predominating, and the same number of trains being run in each direction. However, some extra information is available from timetables of the whole NRZ network (NRZ:WTT 1981(ii) and (iii)):-

- An additional train type, the company liner, is run on some parts of the network. These trains usually take one or two commodities, in one direction only, in special wagons, bringing these wagons back empty.
- Some goods trains are timetabled as "conditional"; that is, they only run when there is enough demand for them.
- The mixed train is not always designated as the one to carry urgent and perishable goods; sometimes an "express goods" train is run. However, point-to-point timings for express goods trains are the same as those for other goods trains; thus they are only express insofar as they spend less time stopping en route.

3.2.3 The representation of train types in the model

The definition and representation of train types in the model as a whole assumes the following:-

- A separate train type must be defined for each group of trains which have in common all of the following:-

  Number of locomotives of each type per train

  Speed limits and point-to-point timings

  Traffic to be carried

  Priority over other train types at meets and overtakes

  Number and length of compulsory stops

  Such a definition, applied to NRZ's trains, means that not only are passenger, mixed and goods trains defined as specific train types; the express goods trains are defined as of a different type from the ordinary goods trains, because of differences in priorities of meets and overtakes, and company liners form several different train types, according to the type of traffic they carry.
- The traffic to be carried by each train type is treated as a completely separate input, and can be made up of any mix of commodities and passengers
- The number of trains each way per day or week required for each train type is calculated from traffic requirements in the direction of heaviest traffic, and the same number of trains is assumed to run in each direction. There is no facility provided for merely stating the number of trains required of a certain type, as is done for passenger and mixed trains on NRZ, as this is likely to be an exceptional case, based anyway on an original decision which paid regard to traffic requirements.
- Point-to-point timings (that is, the times taken for trains to travel distances between crossing loops) are based on the assumption that each train type carries the same weight in each direction. This means that point-to-point timings of company liner trains may be slower than actual speeds in the direction in which wagons are carried empty. The model could be adapted to allow for a change of train weight in each direction; this has not been done because the relative number of company liner trains, and thus the effect of a change in their speeds, is

likely to be small. Also, the point-to-point speeds of such trains cannot be tested for Botswana since none run there.

- The theory developed in Chapter 5 requires that trains be assumed to leave at regular intervals; thus the average number of trains each way per time interval must be the same, but need not be integer. Dispatch of different train types must also be regularly spaced. This means that the model can represent trains running on certain days of the week only, provided that they run at regular intervals over the week. The model cannot represent uneven working - for example less trains being run over the weekend - nor can it represent the line being closed for any length of time per week (The model does allow for a few days of closure per year; the error introduced by allowing for this is likely to be minimal). Conditional trains cannot be represented, as they would affect regular dispatch.
- Strictly speaking, the case of trains not running the full distance of the line is not represented, because of the effect of such trains on evenness of dispatch. They could be represented as fractional trains, but the accuracy of such representations has not been tested in Botswana, because of their relative unimportance. Inaccuracies introduced by such a representation could be quite large.

3.3 Conversion of traffic input into annual gross tonnes and wagon journeys

3.3.1 Introduction

Calculations involved in the conversion of the traffic input are described in Section 3.3.2. An example of the use of those calculations, with data from NRZ and Botswana, and a discussion of the accuracy of the results, are given in Section 3.3.3.

3.3.2 Calculations

Calculations for number of wagon journeys, average values for wagon characteristics, and gross weights, are described in turn below. The representation of service vehicles is then discussed. It should be noted that all calculations are done for one direction of travel only; that in which traffic is heaviest.

Wagon and coach journeys

For each commodity carried by each train type, the number of wagon or coach journeys required per year is calculated by dividing the net weight of a commodity by its payload, or, in the case of passengers, dividing the annual number of passengers by the number of passengers per coach. The type of wagon or coach used to carry a commodity is defined by the nature of the commodity, and the proportion of wagon journeys which will be empty is defined for the line. It is therefore possible to calculate the number of journeys required of each wagon and coach type, for use later in the model when rolling stock requirements are calculated.

Average values for wagons and coaches

Average weight, cross-sectional area, length, and number of axles of wagons and/or coaches are calculated for each train type. They are used in the formulae for train weights and speeds, described in Section 3.4 of this chapter, and Chapter 4 respectively. In fact, three average weights are required; full wagon/coach weight, tare weight, and average weight of full and empty wagons/coaches combined.

Gross weights

Gross weights to be carried by each train type are obtained from net weights to be carried, number of wagon/coach journeys and tare weights of wagons and coaches. Total gross weight to be carried by the railway is then also calculated.

Service vehicles

The calculations described above do not, at this stage, include the effect of service vehicles. This is because the number of service vehicles is defined per train, and the total number of service vehicles used therefore depends on the number of trains each way per day; a figure not yet calculated. Figures for number of wagon journeys and gross weights of service vehicles are therefore added later in the model. The effect of service coaches on the average values for wagons/coaches described earlier in this section is assumed to be small enough to ignore.

3.3.3 Using Botswana data to test the equations

The model can be set up to take any number of commodities in the traffic input, and any number of wagon and train types. For Botswana, the traffic was divided into 81 commodities, plus passengers. Fourteen wagon types and one coach type were used. All this information is listed in Appendix 2. Three train types were defined; goods, passenger and mixed.

The traffic input is taken from an internal planning document (NRZ:WTT 1981 (iv)) which estimates net tonnes of commodities to be carried in 1981/82 by goods trains. Traffic input for the mixed and passenger trains is, as stated in Section 3.2, not estimated by NRZ; instead they merely state a requirement of one mixed train per day and two passenger trains per week. Therefore, for the purposes of this model, a traffic input for these train types was defined such as to give the correct number of trains.

A payload for each commodity, plus a reference number indicating the type of wagon used to carry it (NRZ:1983) are part of the information given in Appendix 2. So, too, are the tare weight, length, cross-sectional area, and number of axles for each wagon and coach type; and estimates for the number of passengers per coach and average weight of each coach.

The estimated number of empty wagons carried by goods trains for the year 1981/82 was part of the information contained in the planning document mentioned earlier (NRZ:WTT 1981 (iv)). Once the number of full wagon journeys had been calculated, therefore, it was possible to "work backwards" in order to obtain a value for the ratio of empty to full wagons. The value obtained for this ratio was 0.424.

Results of calculations are given in Table 3.1 where it has been possible to compare them with estimates available from NRZ.

Table 3.1 Results of calculations concerning the conversion of the traffic input.

Variable	Result obtained from model	Value of NRZ estimate	Source of NRZ estimate	Difference bet. model & NRZ (%)
Average wagon weight (tonnes)				
Goods train	39.38	44		
Mixed train	41.15	44	NRZ:MOW 1978	10.5
Pass train	42.15	44		
Tare weight	18.95	20	NRZ:WTT 1981(iv)	5.25
Gross tonnes				
Tot gross tonnes exc empty wagons	1586779.6	1639795	NRZ:WTT 1981(iv)	3.23
Tot gross tonnes inc empty wagons	1852068.19	1919795	NRZ:WTT 1981(iv)	3.53

The fact that all the calculated figures are within 10.5% of NRZ's estimates, and most are within 5.25%, is considered acceptable, particularly since NRZ's own estimates and calculations must be regarded as typical rather than exact, for reasons now explained.

With regard to average wagon weights; the value for averages is likely to change rapidly, as both rolling stock and traffic mix change. NRZ have many different wagons within each type. For example, the Rhodesia Railways wagon book (RR:ME) shows drawings of approximately forty types of general purpose wagons. In a situation where stock is shared not only throughout NRZ but throughout the whole Southern African region, and where old stock is being replaced presumably with slightly different wagons within the same broad type, it is not possible to give definitive standards for wagons.

With regard to gross tonnages, the reason there was any discrepancy at all between figures obtained by the model and NRZ's estimates is that the planning document (NRZ:1981(iv)) used a series of net to gross conversion rates, for each commodity, and these were not used by the model. The reason they were not used is that the model requires other, linked information on wagon types, such as their tare weights. This other information had to be obtained from another source

(NRZ 1983) and, for consistency, payloads from the 1983 source were also used. (note : net to gross conversion factor = (payload+tare weight)/payload)

It should be noted that the model adds the weight of service wagons to gross weights at a later stage, and that this extra weight is not represented in Table 3.1. It is clear, also that this weight is not included in NRZ's estimate of gross tonnes (NRZ:WTT 1981(iv)). However it is considered that a more accurate representation of gross weights is obtained if service wagons are included.

The above discussion indicates the problem of coordinating data coming from many different sources within a railway, and sometimes having values which are inconsistent with each other. It is a problem which recurred in many areas of calibration of the model, and was particularly evident in the calibration of the cost equations as described in Chapter 9 and the confidential annexe. It is discussed in more detail there.

3.4 Train weight

3.4.1 Introduction

The maximum possible weight for a train is limited by physical factors, such as the power of locomotives, and the length of crossing loops. These factors are discussed in Section 3.4.2. An allowed weight for each train type is then stipulated on most railways, less than or equal to the maximum possible weight depending on required train speeds. Since it is not possible to load trains consistently to the allowed weight, trains can be expected to carry loads which are on average slightly less than those allowed. Representation of allowed and average train weight is discussed in Section 3.4.3. Testing the section of the model which calculates train weights is discussed in Section 3.4.4.

3.4.2 Factors affecting maximum train weight

The following factors can affect the maximum weight of a train:-

(i) Minimum length of crossing loop

(ii) Maximum gross trailing load due to power of locomotive(s) and train resistance on the ruling gradient.

(iii) Maximum length and load due to braking

(iv) Drawbar pull

(v) Wheel-rail adhesion

The model contains equations for the maximum weights which trains of each type carry due to several of the above factors. The smallest of these maxima is then taken to be the limiting maximum weight. Factors (i) to (v) are discussed below in terms of their representation in the model.

(i) Minimum length of crossing loop

Since the model assumes that all trains can use all crossing loops on the line, each train must be shorter than the shortest crossing loop. Thus the maximum number of wagons which a train can carry will be given by the length of the crossing loop, less the length of any locomotives, divided by the average length of a wagon. The maximum weight is then obtained by multiplying the maximum number of wagons per train by their average weight.

(ii) Maximum weight due to tractive effort and train resistance

The force available to a locomotive to pull a train is known as its tractive effort. The resistive force which a train exerts is known as the train resistance. Both these forces are a function of the speed of the train. Train resistance is also a function of the mass of the train, and of the gradient of the line on which it is travelling. Expressions for tractive effort and train resistance are used twice in this thesis. In this section they are used to obtain a value for the mass, and thus the weight, of the train, given a minimum value for speed (VMIN; see below). In Chapter 4 they are used to obtain values for train speeds on various gradients, given a value for the mass of the train. The expressions for tractive effort and train resistance must therefore be suitable for use in both circumstances, and the form they should take is now discussed.

Tractive effort

The Botswana model represents diesel-electric locomotives only. For such locomotives, tractive effort can be represented by the formula:-

$$TE=\frac{3.6(PL-PA)(EL)}{V} \quad \text{(Hay 1977)} \qquad \text{Equation 3.1}$$

where:-

TE = tractive effort in KN
PL = power of locomotive in KW
EL = mechanical-electrical efficiency factor
V = Speed of locomotive in kph
PA = power of auxiliaries, in KW (often assumed to be zero)

The accuracy of this equation for NRZ's locomotives can be tested, since information is available on the tractive effort of NRZ's DE2 locomotive; the type of locomotive most commonly used in Botswana; at various speeds (RR:ME 1976). Appendix 3 lists this information together with the computed values for tractive effort using equation 3.1, and the percentage error of the computed values. Two values for EL are used in these calculations. EL=0.822 is recommended by Hay (Hay 1953). Despite the age of this publication, the value for efficiency of locomotives is considered to be valid for the DE2 locomotive, which was manufactured between the years of 1955 and 1958. EL=0.886 is the value obtained by substituting VMIN and TEVMIN into equation 3.1, where VMIN is the minimum continuous speed at which the locomotive can run without overheating, and TEVMIN is the tractive effort at that speed. For the DE2 the values of VMIN and TEVMIN are 21.8kph and 160.2KN respectively (NRZ:ME undated(i))

Within the speed range 20kph to 65kph, the percentage error using EL=0.886 is always less than 5%. Using EL=0.822 errors of up to 10.24% are encountered. Outside this speed range, the errors resulting from using equation 3.1 become large using both values of EL, but are worse for EL=0.886.

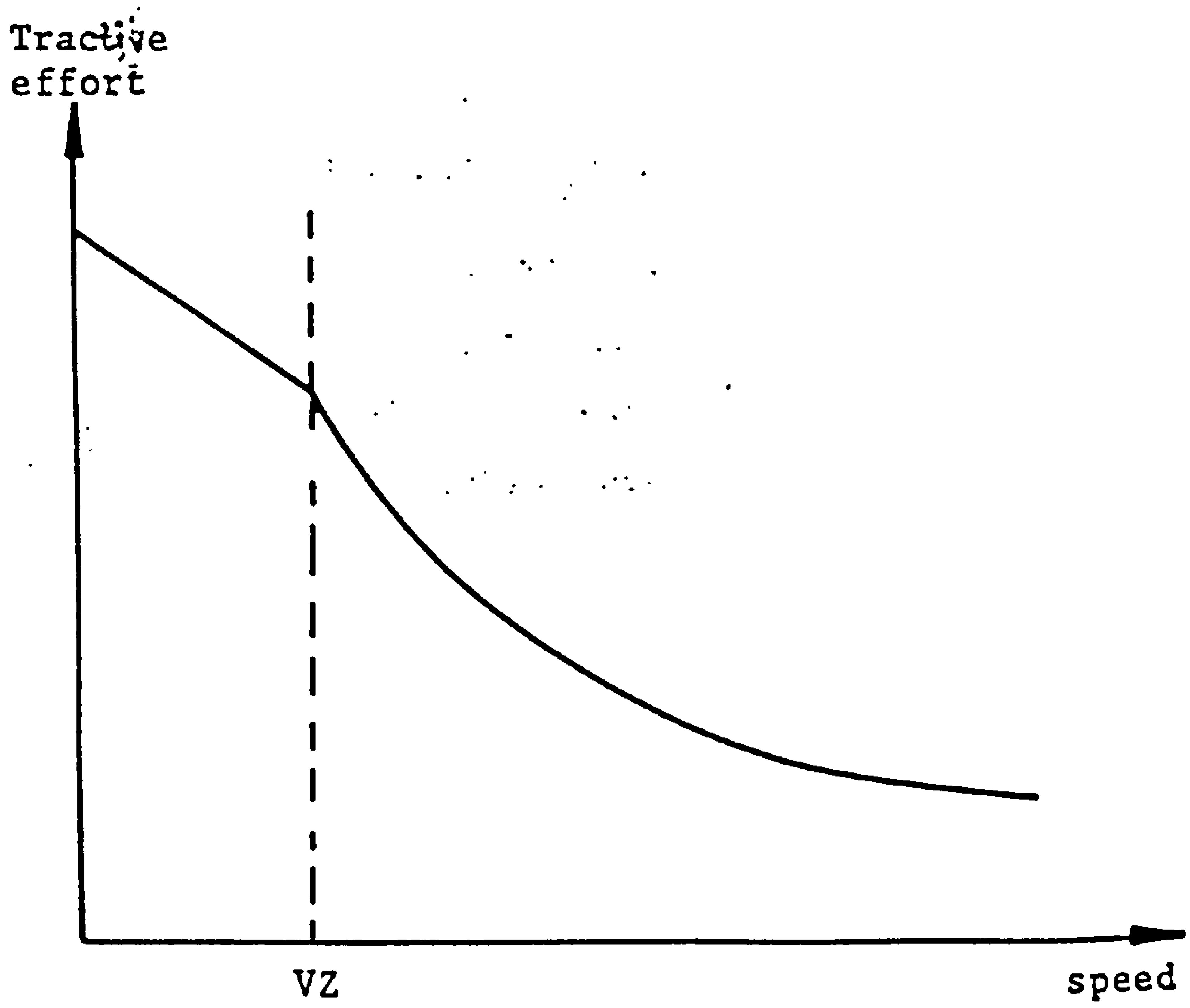
Given these inaccuracies at high speeds the question arises whether Equation 3.1 should be used to represent tractive effort. It has been decided to use this formula, for two reasons:-

- The majority of trains in Botswana travel within the speed range 20-65kph most of the time; the goods trains having a speed limit of 60kph. Inaccurate representation of trains on the present line using this formula is thus limited to a minority of trains; the mixed and passenger trains with speed limits of 75-80 kph respectively; on that minority of sections where trains are running at just below their speed limit. While increased train speeds should be one of the features that the model can represent, an increase to 70kph for the speed for the majority of the traffic most of the time is regarded as adequate for the type of railway being modelled.

- If the formula is not used, input requirements to the model become more complicated; a user wishing to examine the effects of a change of locomotive type would have to input a range of values for the tractive effort at different speeds, instead of just the power of the locomotive. Given that the formula is to be used, a choice must be made between the two values EL=0.822 and EL=0.886. The value EL=0.886 is chosen, because, as will become clear in Chapter 4, train speeds in Botswana rarely exceed 65kph, and, as previously stated in this chapter, trains cannot travel at continuous speeds of less than 20kph.

According to equation 3.1, tractive effort would be infinite when the train was stationary. In fact, tractive effort varies with speed roughly as shown in Figure 3.1:-

Figure 3.1 Variation of Tractive Effort with Speed

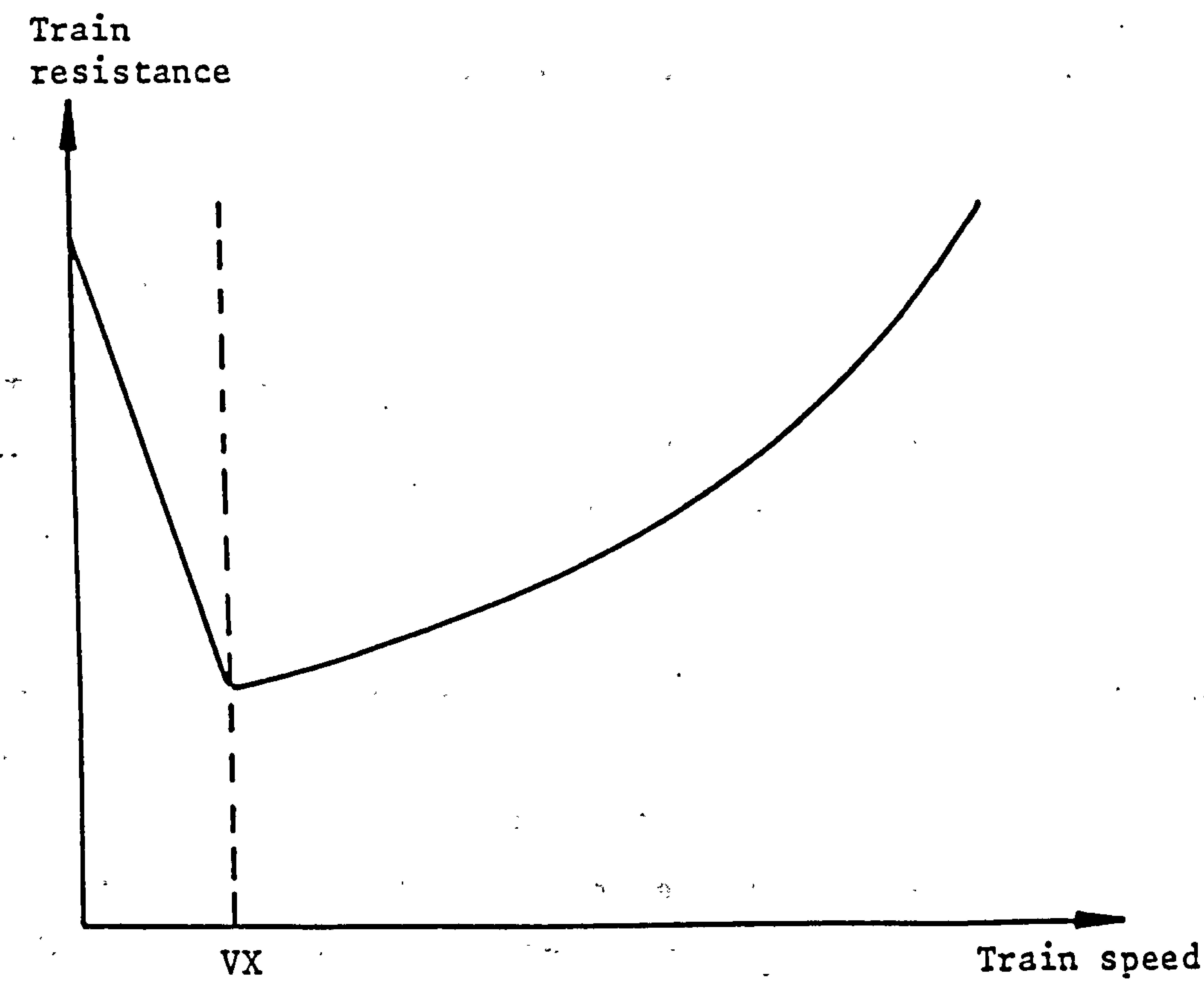


The line to the left of VZ is difficult to represent mathematically, whereas the line to the right of VZ is represented by Equation 3.1. From Appendix 3, VZ can be taken to have the value 10 to 15kph.

Train resistance on level track

The resistance varies with speed roughly as shown in Figure 3.2, for trains running on level ground:-

Figure 3.2 Variation of Train Resistance with Speed



VX is the very low speed at which train resistance at rest, known as starting resistance, is overcome. Starting resistance is usually expressed as a constant per tonne. Hay recommends a value of 0.137KN per tonne (WW Hay 1953), and NRZ a value of 0.08829KN per tonne.

For train speeds above VX, train resistance is usually expressed as a polynominal of V, train speeds. Two formulae are available for this, one is a formula used by NRZ in calculation of train performance which "gives a very good approximation in the range applicable" (RR:ME 1972). This is given by:-

$$RU = 0.02109 + 0.00000415V^2 \qquad \text{Equation 3.2}$$

where RU is train resistance per unit tonne. (Using an updated formula, (RR:ME 1976))

Secondly, there is the more general Davis formula:-

$$RU = 0.00636 + \frac{0.129}{WA} + (CB)(V) + \frac{(CC)(A)(V^2)}{(WA)(XA)} \qquad \text{Equation 3.3}$$

where WA = weight per axle of vehicles in tonnes
A = cross-sectional area of vehicles in square metres
CB = coefficient of flange friction, swaying and concussion
CC = drag coefficient of air
CB and CC vary with vehicle type
XA = number of axles per vehicle
V = speed of locomotive in kph

The Davis formula is an experimental one, and so, too, is NRZ's. The use of the Davis formula "should be properly restricted to speeds no greater than 40-50mph. Above those speeds the error ... becomes excessive" (WW Hay 1953). Since 50mph is equivalent to 80kph, the speed range for the Davis formula is roughly the same as that for the formula for tractive effort (Equation 3.1), and will be similar to the "range applicable" for NRZ, reinforcing the point that the model can only be accurately used for speeds of up to 70kph, and should not be used in its present form to model trains whose speeds are above 80kph for any length of time.

A choice had to be made between using NRZ's formula for train resistance, or the Davis formula. The greater generality of the Davis formula makes it more suitable for the model, but on the other hand the NRZ formula is likely to have been tested using NRZ trains. Tests described in Chapter 4 show that the results of computing train speeds for Botswana using the Davis formula are similar to those using NRZ's formula. The Davis formula is therefore used in the Botswana model.

Train resistance on a gradient

Train resistance on a gradient is given by its mass multiplied by the component of the acceleration due to gravity acting in the direction of the gradient. Strictly speaking, the component of acceleration due to gravity will be 9.81 ms^{-2} multiplied by the sine of the angle between the slope and the horizontal. For small angles, however, such as those found on railways, the sine is approximately equal to the tan, and thus:-

$$RUG = 0.0981\ G \qquad \text{Equation 3.4}$$

where RUG = resistance per unit tonne in KN

G = gradient, expressed as a percentage

Curved track also affects train resistance; this is important in calculations of train speeds, and is therefore discussed in Chapter 4, but is not included in the calculations in this chapter.

Total train resistance on a gradient is thus given by the unit resistance on the level plus the unit resistance due to the gradient, multiplied by the train's mass.

Equating forces for tractive effort and train resistance

Within the range of speeds for which equations 3.2 and 3.3 hold, train resistance varies directly with speed. Tractive effort varies inversely with speed. Thus the maximum train weight will be that which can be hauled up the maximum gradient at the lowest possible speed, VMIN. Values for VMIN are given by NRZ for each locomotive, and for diesel-electric locomotives are within the range 15-23kph. At these speeds equations 3.1, 3.2 and 3.3 are valid. In general, it can be assumed that if the locomotive(s) on a train have enough power to haul a load up a continuous gradient at VMIN, then they can also start hauling the load from rest. The equation for maximum load due to train resistance is therefore given by:-

$$W = \frac{(TEVMIN)(XL)-(WL)(RLF) - (XL-1)(WL)(RLS)-(XL)(WL)(0.0981\ GRUL)}{RWG + 0.0981\ GRUL}$$

Equation 3.5

where RLF, RLS and RWG are unit rolling resistances in kN on the level for first locomotive, second locomotive, and train load respectively, obtained by substituting the relevant values for WA, A, CB and CC into equation 3.3.

TEVMIN, in kN, is the value of TE calculated in equation 3.1 with

V = VMIN and

EL = 0.886, mechanical-electrical efficiency factor

XL is the number of locomotives per train

WL is the weight per locomotive in tonnes

GRUL is the ruling gradient expressed as a percentage

W is the maximum weight of the train in tonnes

This value for W will be tested in the model.

(iii) Maximum length and load due to braking

Three factors associated with braking influence the maximum length and load of a train. They are:-

- The maximum number of axles over which the braking system can be expected to work.
- The maximum acceptable stopping distance for a train travelling at a given speed on a given downgrade.
- On a long downgrade, the maximum load that can be braked to constant speed for the whole length of the grade without causing an unacceptable temperature rise in the wheels.

These three factors, and their relevance to Zimbabwe and Botswana are discussed below:-

The maximum number of axles over which the braking system can be expected to work.

The length of the train is limited by the length over which the vacuum can be sustained in vacuum brakes, or air pressure differences maintained in air brakes. In Zimbabwe, vacuum brakes are used, and a maximum length of 200 axles is stipulated. This is a practical limit for Zimbabwe, not an absolute limit; in South Africa, for example, longer trains using vacuum brakes have been made possible by glueing pipes onto metal ends and thus avoiding leakage.

In the model, maximum train weight due to number of axles, XB over which brakes work is calculated as being XB multiplied by the average weight per axle.

<u>The maximum acceptable stopping distance for a train travelling at a given speed on a given downgrade</u>

For given values of maximum speed and ruling gradient, and known parameters for the braking equipment, maximum stopping distance will depend on the length and weight of the train, if some rolling stock is braked, or the average axle weight of wagons and coaches, if all rolling stock is braked. Most railways, including those of the Southern African network, have brakes on all stock. The average axle weight of wagons allowed due to braking in this case is in general far larger than the average axle weight allowed for other reasons, such as the weight of the track. The effect of maximum acceptable stopping distance on train weight is not, therefore, accounted for in the model.

<u>Continuous braking on a long downhill gradient</u>

As explained prior to the derivation of equation 3.4, on a gradient of G%, the acceleration due to gravity acting down that gradient is 0.0981 G metres per second per second. When a train is already travelling at the maximum allowable speed on a downgrade, it is necessary to reduce this acceleration to zero, by braking. For a train of mass W tonnes, the braking force required to do that is 0.0981(W)(G) kN. If the downgrade continues for a distance DCO metres, then the total work done by the brakes is 0.0981(W)(G)(DCO) kJ. This work is converted into heat in the brakes and wheels. The heat can be expressed as a function of the mass, specific heat, and temperature rise in the wheels, and as such equated to the expression for work done in braking the train. This gives an equation linking the weight of the train with the temperature rise in the wheels, and it is thus possible to determine the maximum weight of train, given the maximum allowable temperature rise in the wheels.

However, the problem of wheels overheating because of braking only occurs on a few railways with very heavy trains and long, continuous downhill gradients. The problem would not occur in Botswana, since the line there has a relatively flat profile, and there is no evidence to suggest it is a problem on the rest of the NRZ network. It is therefore omitted from the model.

(iv) Drawbar pull

In some circumstances, load can be limited to the maximum force which it is possible to exert on the drawbar between a locomotive and its trailing load. Where only one locomotive is used, the entire resistance of the train acts as a force on the drawbar. Where more than one locomotive is used, the force exerted will depend on how the locomotives are placed. If they are all placed at the head of the train, then the entire train will exert a force on the drawbar behind the last trailing locomotive; if the locomotives are distributed at distances down the train the force on any one drawbar will be less. Since there is no information on drawbar pull available from Botswana, its effects are not accounted for in the model.

(v) Wheel-rail adhesion

It was stated, in the discussion on tractive effort and train resistance, that if there was enough tractive effort available to haul the train at minimum continuous speed up the ruling gradient, it could be assumed that there was enough tractive effort to start the train from rest. In fact, the force available to a train when starting from rest is likely to be limited, not by tractive effort, but by wheel-rail adhesion.

The adhesive force available to a train is defined by the expression:-

$$FTF = 9.81(WAL)(CFT)(XL) \qquad \text{Equation 3.6}$$

where XL is the number of locomotives
WAL is the adhesive weight of each locomotive in tonnes, defined as the weight per axle multiplied by the number of powered axles.
CFT is the coefficient of friction between wheel and rail.

Values for CFT can be obtained from the expression

$$CFT = 0.35 \frac{(1 + 0.02V)}{(1 + 0.04V)} \qquad \text{Equation 3.7}$$

where V is train speed in kph.

An expression for the maximum weight of a train due to the adhesive force available at rest is obtained by equating FTF with the starting resistance of the train. FTF is obtained from Equation 3.6, with CFT taking the limiting value of 0.35 for V = 0. As discussed in the section on train resistance, the value for starting resistance of the train, in KN, is given by the expression:-

$$0.08829\ W + 0.0981\ GRUL$$

where W is the weight of the train in tonnes, and

GRUL is the ruling gradient expressed as a percentage.

The resultant expression for W is used in the model.

As the speed of the train increases, the force available from the locomotives becomes limited by their tractive effort. The maximum weight of train due to adhesion at VMIN was calculated to make sure that adhesion was not critical at this speed. This was done by equating FTF, (with CFT calculated at VMIN), with train resistance at VMIN, where expressions for train resistance were as discussed earlier. Results of such calculations gave values for train weights which were consistently larger than those obtained by equating tractive effort with train resistance at VMIN, and by equating adhesive force at rest with train starting resistance. Therefore, maximum weight of train due to adhesion at VMIN is omitted from the model.

3.4.3 Representation of allowed and average train weight

As discussed in Section 3.4.1, trains will not always be run at their maximum weight. An allowed weight per train type is likely to be stipulated which also takes account of required speeds. A ratio, RMAXWT, is therefore defined for each train type in the model, and is the ratio of maximum possible train weight to maximum allowed. It is common practice on railways like the Botswana line to carry the majority of traffic in heavy goods trains. Such trains will be fairly near to the maximum allowed; that is, RMAXWT will be equal, or nearly equal, to 1 for such trains. However, lighter, faster trains may also be run; this is the case on the Botswana line, as discussed in Section 3.4.4. The allowed weight will be the one used when train speeds are estimated on a line. It is therefore the weight referred to in Chapter 4 of this thesis.

Daily fluctuations in traffic will mean that not all trains are loaded to their allowed weight on all occasions. This is important when calculating the number of trains required to carry a certain amount of traffic. Therefore, a second ratio is defined; the ratio of average to allowed weight for a train type (RGT).

3.4.4 Using Botswana data to test the equations

The model allows any number of locomotive types to be defined. Up to four locomotive types are used on the Botswana line, and all of them are diesel electric. They are called the DE2, DE3, DE4 and DE6. (NRZ:WTT 1981(i) and NRZ: Planning 1981). They have similar tractive effort, and any of them can be used with any train type. Therefore, only information on the one most commonly used in 1982 was input to the model. This was the DE2; an old locomotive of obsolescent design.

For each train type, number of locomotives per train has to be specified, and the type of locomotives. As stated above, the only type considered in this run of the model was DE2. At present, all trains in Botswana use one locomotive per train (NRZ:WTT 1981(i)). Maximum number of axles over which the brakes will work also has to be input. As stated in Section 3.4.2, the maximum for Botswana is 200 axles.

With regard to information on the line, values for the ruling gradient and shortest crossing loop are required. For Botswana these are 1.25% and 414m respectively.

Information is not directly available as to the values for RMAXWT, the ratio of maximum to allowed train weight, since NRZ publish no figures for maximum train weight. Values for allowed train weights can be obtained or estimated from Botswana's working timetable (NRZ:WTT 1981(i)), and are given in Table 3.2. If the model's own calculations are compared with these allowed weights it seems likely that the allowed weight for the goods train is the maximum possible, that is, RMAXWT = 1 for the goods train. Since the other train types are pulled by the same locomotive, and subject to the same physical limits on crossing loops, brakes, etc, their maximum possible weight is likely to be of the same order of magnitude as that for the goods train. RMAXWT for these two trains can therefore be obtained from the ratio of their own allowed weight to that of the goods train. This gives values of RMAXWT = 0.7 for the mixed train and RMAXWT = 0.595 for the passenger train.

NRZ's planning department use a value for the ratio of average to allowed weight RGT = 0.82. (NRZ: Planning 1981)

A full set of inputs for this, and all other sections of the model is given in Appendix 2.

Results

Results of calculations for maximum and allowed train weight are given in Table 3.2.

Table 3.2 Results of calculations for maximum and allowed train weight (tonnes)

Variable	Result obtained from model	Value of NRZ estimate	Source of NRZ estimate	Error in model result (%)
Maximum train weight				
goods train	985.855			
mixed train	988.604			
pass train	990.750			
Allowed train weight				
goods train	985.855	1000	NRZ:WTT .1981(i)	1.41
mixed train	692.023	700	NRZ:WTT 1981(i)	1.14
pass train	589.496	595	NRZ:WTT (all figs for DE2 locomotive)	0.93

Note: The working timetable stipulates the allowed size of passenger train by number of bogies (17 are allowed) rather than by weight. However, it is possible to estimate this weight, since the allowed size of the mixed train is stipulated both as a weight, and as a maximum number of axles (80). Bogies have 4 axles, and if it is assumed that the passenger train has approximately the same weight per axles as the mixed train, its allowed weight will be 85% of that for the mixed train.

Results for allowed train weights are thus within 1.4% of NRZ's estimates. It could strictly be argued that, since the model's result for maximum train weight was used in the calculation of values for RMAXWT, the model has not been properly tested. However, all NRZ's values for allowed train weights are at or below those stipulated by the model. Also, it is very likely that the goods trains are run at the maximum possible weight (RMAXWT = 1). Therefore, the model's results are considered satisfactory.

3.5 Number of trains required

3.5.1 Calculations

For each train type, the annual number of trains required is calculated by dividing the annual gross weight carried per train type by the average gross weight of traffic carried per train. The number of trains per day is then given by the annual number of trains divided by the number of days per year for which the line is open. This may give a fractional result. A fractional number of daily trains can actually occur on a line if some trains do not run every day. However, this fractional number must be rounded up such that, within a certain time-cycle the number of trains is a whole number. For example if, as in Botswana, some trains run only on certain days of the week, fractional trains per day must be rounded up to the nearest one-seventh.

3.5.2 Testing the model in Botswana

Using values of 1000, 700 and 595 gross tonnes for the trailing load of goods, mixed and passenger trains respectively, and using the value 0.82 for ratio of gross to tractive, results obtained for the number of trains required to carry the net tonnages discussed in Section 3.3.3 (NRZ:WTT 1981(iv)) are as shown in Table 3.3.

Table 3.3 Results of calculations for the number of trains each way per day

Variable	Result obtained from model	Value of NRZ estimate	Source of NRZ estimate	Error in model result (%)
Number of trains each way per day				
goods	6.857	6.3	NRZ:WTT 1981(iv)	8.84
mixed	1	1	NRZ:WTT 1981(i)	0.0
passenger	0.286	0.286	NRZ:WTT 1981(i)	0.0

As stated in Section 3.3, the traffic input for the goods and mixed trains is calculated such as to produce values of one mixed train per day and two passenger trains per week. Thus, no error is obtained with these results.

The reasons for the discrepancy between estimates for number of goods trains in the model and those in the planning document are threefold. Differences in calculations of gross tonnages were discussed in Section 3.3, as was the fact that the planning document does not allowed for service vehicles. Also, the planning document has a different value for gross to tractive (0.87) from that in general use for Botswana.

The planning document suggests that less trains are required in Botswana than run according to the working timetable. The working timetable stipulates that ten trains per day should run; eight goods trains and one mixed train per day, plus one goods train five days per week, and one passenger train running on the days when the goods train does not run (NRZ:WTT 1981(i)). For the purposes of testing the model of train delays, the number of trains stipulated in the timetable must be used. This illustrates the importance of being able to test the accuracy of each part of the model seperately, as described in Section 1.5 of Chapter 1. (See Table 1.1 for how the model is divided into subroutines).

3.6 Conclusion

The calculations described in this chapter are all similar to the calculations done within NRZ, mostly by the planning department. The equations used by the model are sometimes of a slightly different form from those used by NRZ. Sometimes this is because it is preferable to generalise the equations so that they can be used on other railways (as in the calculation of train resistance, for example). In other cases it is because information was not available directly from NRZ (as in the calculation for wheel-rail adhesion, for example).

Results obtained by the model sometimes showed discrepancy from NRZ's estimates. This was either because of the difference in formulae discussed above, or because a choice had to be made between two values of a variable available from two different sources within NRZ.

In these circumstances, it is not possible to say that NRZ's estimates are more accurate than those in the model. The reason for making comparisons between the model's output and information from NRZ was largely to check the correctness of orders of magnitude. All of the model's estimates were within 10.5% of these used by NRZ, and most were within 5.25%. This is considered satisfactory.

CHAPTER 4

TRAIN SPEEDS

4.1 Introduction

Values for train journey times are required in order to calculate the capacity of the line, as discussed in Chapter 6, rolling stock requirements, as discussed in Chapter 7, and crew costs as discussed in Chapter 8. Journey times from one end of the line to the other can be regarded as the sum of times spent travelling between crossing loops and stations (point-to-point times), and times spent waiting at them (waiting times). Values for these times are available from Botswana's Working Timetable (NRZ:WTT 1981(i)). It is not possible to make these times a direct input to the model, however, because they are affected by many of the investments, listed in Chapter 1, which are the model's main inputs. For example, locomotive power, track gradients and train weights affect train speeds directly, and track profile affects speed limits. Waiting times are affected by the trains working method, and the number of crossing loops.

Train times must therefore be calculated by the model in such a way as to give results of acceptable accuracy for the requirements described earlier in this section, while using a fairly crude data input such as is likely to be available to the user of the model. Calculations are in two parts; those for point-to-point times, and those for train delays. Point-to-point times are discussed in this chapter, and train delays in Chapter 5. In both cases, the equations used are designed to predict the point-to-point and waiting times as planned in the timetable; it is also necessary to represent the effect of late running on these times, and this is discussed at the end of Chapter 5.

In this chapter, a review of previous work on train speeds (used in calculating point-to-point times) is given in Section 4.2. The model of train speeds developed for this thesis is discussed in Section 4.3, and tests of its accuracy in Section 4.4. General conclusions to the chapter are given in Section 4.5.

4.2 Literature review

Accurate models of speeds, known as train performance models, have been created for many railways, including the Botswana line (Transmark 1980) and most, if not all NRZ lines (NRZ 1972 and 1976). They involve simulating the way a train reacts to every gradient change, speed limit, and compulsory stop on the line, and are used to make fairly detailed planning decisions. For example, they can be used in the initial drawing up of new timetables; although it should be noted that the point-to-point times used in the final versions of NRZ's timetables are the results of running test trains on the lines. The level of accuracy of these models is beyond the requirements of the model described in this thesis, and the level of detail required of the inputs, particularly with regard to track profile, precludes their use here.

A less detailed representation is used in the World Bank model of Colombia (IBRD 1970). They take a section of line, define its average gradient, GAV, and then assume that the train speed for the whole of that section is, on average, the speed at which the train would travel with no net acceleration or deceleration, sometimes known as the balance speed. This assumption allows a mathematical expression to be formed which equates the forces acting in the direction of travel of the train with those acting in the opposite direction. Since forces acting on a train are a function of speeds, this equation can be solved for each section to give a value of train speeds.

The forces which the World Bank include in their equation are those due to tractive effort, train resistance on a level straight track, and train resistance due to gradient. As stated in the working paper applying the model to the Thailand railway system (IRBD 1972) "the effects of curves .... are not taken into account in the model". The original Colombian model makes no mention of speed limits in its description of equations, but the Thailand application mentions maximum speed as an input, so presumably the speed of the train on the section is taken to be the smaller of the balance speed and the speed limit.

The sections over which balance speeds are defined in the World Bank model are links; that is, the sections between nodes of a network, where a node is a point from which two or more lines branch. According to such a definition, the whole of the Botswana line would be defined as one section. Examination of the map showing the links defined for the Thailand application reveals the longest to be about 300km; almost half the length of the Botswana line. This was regarded as presenting a problem; ".... in defining the average and maximum gradients, it was difficult to choose for each link a single number .... since many links cross both flat and hilly terrain" (IBRD 1972).

No indication is given of the accuracy achieved in the World Bank model; the model was not tested in Colombia at all, and the Thailand application did not test for point-to-point times separately. Average train journey times in Thailand, including waits, were compared with those predicted in the model; this involved adding minimum journey times derived from the model described in this section, to waiting times predicted by a model which will be discussed in Section 5.2 of Chapter 5, and testing the accuracy of the two models in aggregate. Even then, it was concluded that no meaningful comparison could be made. This will be discussed further in Section 5.2. An estimate of the accuracy of the World Bank model of train speeds for the Botswana line forms part of the discussion in the conclusion to this chapter, Section 4.5.

4.3 The model of train speeds and point-to-point times

4.3.1 Introduction

The representation of train speeds in the model is similar theoretically to that used by the World Bank, in that the balance speed of a train over a section is calculated, and compared with the speed limit for that section. It differs from the World Bank model as follows:-

(i) Sections are user defined; that is, there are no special criteria like the World Bank one that sections must be full lengths of lines between nodes. The number of crossing loops per section has to be defined, for the purpose of calculating the slowest train time between crossing loops, used in the formula for track capacity (see Chapter 6). Any number of crossing loops - including zero - are allowed per section, and the model then makes the following assumptions about the spacing of such loops:-

- the user is not expected to input loops at the beginning and end of the line as the model will assume that stations exist there, but that these are not used for trains crossing and overtaking.
- where any loops are defined for a section, it is assumed that one loop occurs at the end of the section, (with the exception of the last section on the line for the reason given above), and that there is no loop at the beginning of the section.

While the above assumptions make it convenient to define the end of some sections such as to coincide with the position of a crossing loop, this should not affect the length of sections chosen. It would be possible, for example to have five sections defined between two crossing loops, in which case the first four sections will have an input of zero for number of crossing loops, and the fifth an input of one crossing loop. Equally, it would be possible to have a section defined such that it contains, say, eight crossing loops. This means that sections can be chosen such that there are no major changes of gradient and curvature along their length. The lengths of section will be defined by the level of accuracy of data available to the user, and would in general be expected to be very much shorter than those defined by the World Bank.

(ii) The effect of track curvature is represented in the model. This variable can affect both train resistance and speed limits, as described in Section 4.3.2, where it is concluded that speed limits alone will be used as representation of the effect of curvature.

(iii) In addition to the speed limit defined for each train type for the line as a whole, speed limits can be defined for sections. These speed limits will usually be due to track curvature, weak sections of track, or safety considerations in built up areas. (this last being unlikely to have much effect in a country like Botswana, with low average train speeds and a very small population). Where a speed limit is defined for a section, it is assumed to be effective over the whole of that section.

(iv) Allowance is made for the fact that the variables discussed above are not the only ones affecting train speeds. Other factors tending to slow trains down include:-

- temporary speed limits, not available as part of the input to the model, due to weak sections of track, and safety considerations.
- driving practices, such as minimising acceleration, and deceleration, and "zig-zag braking" as described by NRZ (NRZ 1976), where a train on a downgrade is slowed to below the speed limit and brought back up to maximum speed.
- train resistance due to curves.

Point-to-point times as recorded in the timetable allow for these, and any other unknown factors by means of a "recovery allowance". The representation of the effect of these extra factors in the model is by means of a function describing the likely reduction of speeds due to them. The derivation of this function, and values for its parameters is described in Section 4.3.4.

4.3.2 The effects of curvature

The effect of curvature on train resistance

In some railways the effects of curvature on train resistance are dealt with by expressing curvature as an equivalent gradient, and then issuing track information in terms of "compensated" gradients which would give the equivalent resistance to that of an uphill gradient and curve combined. A problem with this method is that, if trains travel in both directions on the line, the downhill grades will not be the negative of the uphill compensated grades in the opposite direction; and this complicates the track data input to the model.

NRZ, however, issue curvature information separately from that on gradients. They use the following formulae to express unit resistance due to curvature:-

$$\text{unit resistance per tonne} = \frac{17.977 \text{ kN}}{\text{DCURVE}^{1.21}}$$ where DCURVE is the radius of curvature in metres

plus, if W, the weight of train, is more than 1000 tonnes:-

$$(0.000001635W + 0.008175)\ \frac{1}{W}\ \text{kN} \quad \text{(NRZ 1976)}$$

Equation 4.1

Speed limits due to curves of various radii are specified by NRZ, (NRZ 1976) and these are listed in Table 4.1.

Table 4.1 NRZ's speed limits due to curvature

Radius of curve(m)	Speed limit (kph)
120.696	35
181.044	40
261.508	50
362.088	60
462.668	65
563.248	75
663.828	max speed

The representation of curvature in the model

In considering the effect of curvature on a section, account must be taken of the fact that curves are usually defined over small lengths of line - curves in Botswana are typically between 100 and 400m long (RR undated). This distance is likely to be small compared with the line sections which the user is likely to define in order to run the model; for example, for the test run described in this chapter, the Botswana line was divided into sections whose lengths varied between 3.429km and 19.085km (see Appendix 2). Furthermore, the number of curves occurring per section can vary greatly. The problem therefore arises as to whether it is possible to represent the "average" curvature of a section. This is likely to be a more difficult concept than that of average gradient which, for sections of a few kilometres in length, is fairly easy to define.

In deciding how to represent curvature under such circumstances, it is worth considering further how the two effects of curvature - on speed limits and train resistance - would affect speeds as derived by a "balance speed model", if the input for curvature of a section was based on the smallest radius curve, rather than the average curve for that section, as the former would be easier to define. Both the speed limit and the extra train resistance due to a curve on a section would be represented by the model as if they affected the train uniformly for a whole section. In the case of speed limits this is a reasonable assumption; the train must decelerate to a speed limit and accelerate from it, and is therefore likely to be slowed down for a length of its journey which is larger than the length of the curve. In cases where there are several curves of roughly the same radius on a section the train will be travelling at speeds near to the speed limit due to the curves for the whole of the section. In the case of train resistance due to curvature, on the other hand, the extra train resistance would only take effect for the length of a curve, so that representing its effect as continuing for a whole section of line would be an exaggeration. It should be noted that train resistance due to curves will only show an effect in the model on those sections where the "balance speed" of the train is less than, equal to, or slightly more than the speed limit; at faster speeds, a change in balance speed due to curves will not matter, as it will be "overruled" by the speed limit.

It was concluded that, if train resistance due to curves was omitted, but speed limit due to curves included in the model, this would allow the line input to the model to be based on the smallest curvature of each section; a value which, unlike "average curvature" is likely to be obtainable directly from track profile information made available by the railway. In fact, the input on curvature is in the form of the speed limit due to the smallest curvature of the section (see Appendix 2). The user of the model should be aware of the way in which this information is used by the model, so that he or she can modify the input in exceptional cases - for example, on very long straight sections with only one or two small curves the speed limit due to those curves might be omitted from the model, or increased above its actual value.

4.3.3 Calculations in the train speed model

Balance speed

The forces used in the equation from which balance speed of the train is derived are as follows:-

- Tractive effort of the locomotives, which is always in the direction of travel of the train.
- Train resistance on the level, which is always in the opposite direction to that of travel of the train.
- The force due to the component of acceleration due to gravity acting on the train's mass down the gradient of the line. This is positive in the direction of travel of the train on a downhill gradient, and in the opposite direction on an uphill gradient.

These were the forces which were described in Section 3.4.2, part (ii), in calculating the maximum gross trailing load due to power of locomotives and train resistance. The expressions derived there for tractive effort (equation 3.1), train resistance on the level (equation 3.2 or 3.3), and train resistance due to gravity (equation 3.4) are used again here. The equation of forces used in this chapter is therefore similar to that described in equation 3.5 in Chapter 3, except that average gradient, GAV, of a section replaces ruling gradient, GRUL; the weight of the train is now a known variable, WABS, and replaces W, and train speed V, is now the unknown variable and replaces VMIN. This gives the following equation:-

$$\frac{3.6(XL)(PL)(EL)}{V} = (WABS)(RMAXWT)(RWG+0.0981\ GAV)+(WL)(RLF)+(XL-1)(WL)(RLS) \qquad \text{Equation 4.2}$$

where symbols are as discussed in Chapter 3, viz:-

WL weight of locomotive in tonnes
XL number of locomotives per train
PL power of locomotive in kN
RMAXWT ratio of maximum possible train weight to maximum allowed weight
EL mechanical-electrical efficiency factor
V speed in kph
RLF, RLS and RWG : expressions for unit rolling resistances on the level for first locomotive, trailing locomotives, and train load respectively, obtained from equation 3.3. These equations are second-degree polynomials in V, and results are in kN

By multiplying equation 4.2 through by V, a cubic in V is obtained. It is found that, for all values of GAV likely to be found on a railway, there is only one real, positive value for V that will solve this equation. This is taken to be the balance speed for V.

There was discussion in Section 3.4.2 of Chapter 3 as to whether to use NRZ's or the Davis formula for train resistance. It was stated there that the NRZ formula was likely to provide a more accurate representation of train resistance in Botswana, having been derived in Zimbabwe, but that the more general Davis formula would be preferable provided it produced similar results in the model. Therefore, tests were done using both train resistance formulae in equations for maximum weight and train speeds, and deriving results using Botswana data. Results obtained for train weight were within 0.59% of each other. Those for train speeds up to 80kph (the maximum speed for which it is suggested the model can be used - see Section 3.4.2 of Chapter 3) were within 5% of each other. This discrepancy is considered acceptably small, and the Davis formula is used in the model.

Speed limits

The balance speed for each train type on each section is compared with two speed limits; the section speed limit where one exists, due to curves, weak sections of track and general safety considerations, and the overall speed limit for the line. The section speed limit is taken to be the same for all train types, whereas the overall speed limit for the line is defined for each train type. This follows NRZ practice. The train speed for the whole section is taken to be the smallest of the balance speed and the two speed limits. The model obtains values for train speeds in both directions. The time spent on the section is then found by dividing the length of the section by the train speed on that section. Running time on the line in each direction for each train type is found by summing the relevant section times.

The effect of other variables

Other factors likely to reduce train speeds were listed in Section 4.3.1 of this chapter. Explicit representation of all such factors requires a more detailed data input than is desirable for the type of model being developed in this thesis. Therefore, their effect is represented by a function describing an overall reduction in average speeds from those derived from the balance speed formula, and from speed limits. An account of the derivation of this function, and of values for its parameters is given in Section 4.3.4.

4.3.4 Deriving a function for explanatory variables not explicitly represented

The derivation of a function for explanatory variables not explicitly represented in the model involved the following stages:-

a) The model of train speeds was run without using the function being derived here. Initial values for point-to-point times thus obtained were compared with those in the Working Timetable.

b) A formula was derived for retardation of the train due to unknown explanatory variables. The method employed to do so can be summarised as follows:-

(i) A hypothesis was made that the line of best fit on a graph of actual point-to-point times versus average gradient of sections is similar in shape to the graph obtained from running the model of point-to-point speeds. That is, below a certain "cut-off", or critical gradient, train speeds will be unaffected by gradient, since the balance speed on these gradients will be faster than the speed limit. Above the critical gradient speeds will vary inversely with gradient.

(ii) Different values for the critical gradient were tested using regression analyses, and the one giving the best results was selected. The regression analyses are described in detail below.

(iii) Results obtained from the balance speed model were compared with those obtained from the regression analyses, and an expression for unknown variables was developed to describe the difference between the two.

Stages a, b(ii), and b(iii) are described in turn below.

a) Obtaining initial values for point-to-point times

Information on track profile is input according to line sections which, as discussed in Section 4.3.1, should be chosen such that there are no major changes of gradient and curvature along their length. The relative flatness of the Botswana line meant that sufficient accuracy could be obtained by defining sections such that there was one crossing loop per section. The average gradient, speed limit, and length of each section is part of the information given in Appendix 2.

In addition, an overall speed limit for the line is input for each train type; for Botswana these are 60kph for the goods train, 75kph for the mixed train, and 80kph for the passenger train.

Information on power of locomotives, train weight, etc has already been discussed in Chapter 3.

The results of running the model with the above information are discussed here for the mixed and goods trains only. The reason for this is that NRZ only defines maximum train weight for two train types; as discussed in the footnote to Table 3.2 in Chapter 3, the maximum weight of passenger train had to be estimated. Since point-to-point times depend on train weight, this variable must have a known value in tests of accuracy of the train speeds model. Note that this does not mean that the passenger train was omitted from the general application of the model to the Botswana line; only from the analysis described in this section.

The graphs in Appendix 4 show speeds computed by the model, and actual point-to-point speeds as given in the working timetable, plotted against average gradient of each section.

As expected, results obtained by the model are, on average, faster than those in the Working Timetable. There is also a large spread of speeds at any one gradient. Both of these phenomena are assumed, in the subsequent analysis, to be due to factors affecting speed which are not represented by the model. These factors were listed in Section 4.3.1. It should be noted that the inaccuracy introduced by the simplicity of the representation of train movements in the model, as a series of speeds which are uniform for a section of line, is not tested.

b(ii) The regression analyses

Regression analyses were done separately for the mixed and goods trains, using only those sections with identical speed limits of 75kph for the mixed train or 60kph for the goods train. Four gradients were tested as possible critical gradients; 0.25%, 0.16%, 0.07% and 0.0%. Sections were divided into two groups according to whether their average gradient was above or below the critical one. A regression analysis was performed on both groups. For the low gradient group a linear regression was used, as an expression for no relationship between gradient and speeds would take the form of a horizontal straight line. For the high gradient group, the relationship between GAV and V is an implicit cubic derived from Equation 4.2. Since this cannot be expressed in the form:-

$$GAV = \text{a function of } V$$

an empirical form for the relationship of GAV with V was established, as follows. By inspection of Appendix 4, computed results are similar to a linear or quadratic form, in the range in which gradients affect speeds. Therefore linear and quadratic regressions were done on the high gradient group. Linear and quadratic regressions were also done on a group containing all sections with identical speed limits.

Results of the regression are shown in Appendix 5. It was found that the parameter estimates for some groups using the quadratic regressions were not statistically significant; therefore quadratic equations were rejected in favour of linear ones. For goods speeds, R^2 for the group with GAV $>$ 0.16% was the largest, and for mixed speeds, R^2 for the group with GAV $>$ 0.25% was the largest. This is not inconsistent, as the critical gradient is determined by a comparison of the speed on that gradient with the line speed limit for the train, and both of these are different for the different trains. R^2 was low on all "low gradient" groups, as to be expected for regression where $\hat{b}$ takes values close to zero.

<u>b(iii) Deriving an expression to describe reduction in speeds due to unexplained variables</u>

The expression derived in this section is based on a comparison of speeds predicted by the model and speeds predicted by statistical analysis of actual speeds. The comparison is done in two parts. For sections below the critical gradient whose speed limits are that of the line as a whole, average speeds are compared with speed limits, since the point-to-point model predicts that trains travel at the speed limit on such sections. For sections above the critical gradient, the predicted values for speeds obtained from the linear regression of speeds on average gradients, described earlier, are compared with the balance speeds on that gradient. Results are given in Table 4.2.

Table 4.2 Comparison of speeds predicted by the model with those predicted by statistical analysis of actual speeds

critical gradient (%)	average speed (kph)	speed limit (kph)	average speed as a fraction of speed limit
	GOODS	TRAIN	
0.16	48.725	60	0.812
	MIXED	TRAIN	
0.25	61.138	75	0.815

section gradient (%)	speed predicted by regression analysis (kph)	balance speed (kph)	speed predicted by regression as fraction of balance speed
	GOODS	TRAIN	
0.406	43.659	45.241	0.965
0.373	44.485	47.037	0.945
0.268	47.115	53.502	0.881
0.208	48.617	57.750	0.842
	MIXED	TRAIN	
0.406	48.738	57.771	0.844
0.373	50.538	59.710	0.846
0.268	57.216	66.444	0.861

Table 4.2 also gives statistically predicted speeds as a proportion of speeds predicted by the model. This shows that the model's predictions are more accurate at lower speeds. This is consistent with the likely effect of most of the extra explanatory variables on speeds, mentioned earlier in the chapter; unknown speed limits on sections, driver tendency to minimise acceleration and deceleration, and zig-zag braking on downgrades, are likely to have less of a retarding effect where train speeds are already slow. (Train resistance due to curvature, on the other hand, would be expected to have an effect on all sections where the balance speed of a train was less than the speed limit - thus the results obtained from the model suggest that train resistance due to curvature has relatively little effect on speeds).

The expression describing the relationship between statistically predicted speeds and speeds predicted by the model must have the following qualities:-

- it must modify the values for speeds obtained by running the model with Botswana data in such a way as to produce a more accurate final output for the model.
- it must be of such a form that the user of the model can easily define parameters for the expression applicable to any other situation in which the model is run.

Clearly, the expression must be of a form such as to produce a larger reduction in speeds the higher the speeds. A choice has to be made as to whether the expression should be a continuous or discontinuous function. A discontinuous function was chosen. This was because, even had there been an obvious continuous function which would describe the speed reduction for Botswana, such a function would not necessarily have been readily applicable elsewhere.

The function chosen takes the form of defining three speed ranges, and, within each range, a proportion by which speeds should be reduced. A "smoothing" function is also used, in order to avoid the anomaly of speeds at the top of one range being reduced by less, and consequently having a higher final result, than higher initial speeds at the bottom of the next range. Thus, for example, the function as used for the Botswana line in its present state is as follows:-

- At the speed limit, VF, for the line for a train (60kph for the goods train, 75kph for the mixed train, and 80kph for the passenger train), initial values of speeds are multiplied by RACPRE = 0.81.
- For speeds between VACPRE, where VACPRE = 45kph, and the speed limit VF, initial values of speeds are multiplied by RACBAL = 0.85. If the result is greater than VF x RACPRE, it is set equal to VF x RACPRE.
- For speeds up to VACPRE, where VACPRE = 45kph, no adaptation is made to the initial values of speeds obtained by the model; in other words they are multiplied by RACLOW where RACLOW = 1.0. Where this gives a result greater than VACPRE x RACBAL, speeds are set equal to VACPRE x RACBAL.

The user can define values for VACPRE, RACLOW, RACBAL and RACPRE. This would probably involve a test run on sections where some prior information is available on speeds, and the user may wish to perform the statistical analysis described in this section, as this was mainly required in order to obtain the best initial form for the function. Where the user was unable to calibrate the model in this way, the values used for Botswana could be taken as a basis, and modified by guesswork; for example if track was in a poorer state than in Botswana, the values of all ratios could be reduced.

Three points may be noted about the expression for reducing train speeds derived in this section. Firstly in defining speed ranges the model only allows the range between the mimimum speed, VMIN, and the speed limit VF to be split into two; 0 to VACPRE and VACPRE to VF. It would only require a small adaptation to the model to increase the number of speed ranges, but this has not been done because it is unlikely that a user of the model would have accurate enough information to provide a more detailed input. Secondly, VACPRE, RACLOW,RACBAL and RACPRE are assumed to take the same values for all train types. Again, the model could easily be adapted to allow them to be defined separately for each train type, but this has not been done because of the fact that it would require a more detailed input. Thirdly, the derivation of the expression was based on analysis of those sections of the Botswana line whose speed limit due to curvature was equal to or more than the line speed limit for the train. As Appendix 4 shows, the small number of sections at each speed limit below that for the line makes it difficult to perform statistical analyses on such sections. Speeds on these sections are therefore treated in the same way as speeds on other sections.

4.4 Accuracy of the model

To recap on the discussion in Section 4.3, the final output from the model is obtained as follows:-

(i) The balance speed on each section of the line is calculated, at the average gradient for that section.

(ii) The smallest of the balance speed, section speed limit and line speed limit on each section is found.

(iii) The speed found in (ii) is reduced by means of the function described in Section 4.3.4.

Table 4.3 gives a comparison of total journey times as given in the working timetable with those obtained from running the model.

Table 4.3 comparison of total times as given in the working timetable with those obtained from running the model.

journey times (mins)	goods train south	goods train north	mixed train south	mixed train north	passenger train south	passenger train north
actual	846	839	710	724	686	704
predicted	840	863	720	737	693	707

The predicted results as shown in Table 4.3 are all within 2.8% of actual results. This type of accuracy can be expected in an initial calibration of the model, since the parameters in the function for speed reduction (VACPRE, RACLOW, RACBAL and RACPRE) can be given values such as to give good accuracy for total journey times. However, the graphs in Appendix 4, showing the spread of actual speeds which can be obtained at any given average gradient, indicate that this level of accuracy is likely to have occurred because errors have "evened out" over sections. Since this "evening out" process might not work in the same way with a different application of the model, the level of accuracy may be less in general, than was obtained with the test run. Also, the accuracy obtained in an application of the model will depend on the length of sections defined by the user, and the accuracy with which values can be obtained for section speed limits, and for VACPRE, RACLOW and RACPRE.

4.5 Conclusion

The model developed in this thesis allows speeds to be predicted from a simple set of data for track profile and train characteristics. It treats speeds as an explicit function of gradient and speed limits, including speed limits due to curvature. Other factors affecting speed are represented implicitly by a general function reducing speeds from the maximum dictated by the gradient or speed limit.

The only other model available which uses a simple data input is that of the World Bank, which has to be rejected as being too crude. On the Botswana line, for example, the World Bank model would have predicted train speeds at the overall speed limit for each train for the whole journey, giving journey times of the order of 25% too small.

With regard to testing the accuracy of the model in this thesis, Botswana data cannot be used as it has already been used to calculate values for the function for speed reduction. Further tests of the model's accuracy would therefore be desirable.

The model is regarded as useful and necessary because it makes speed prediction possible without the need for the very detailed data input used in the train performance models discussed in Section 4.2.

CHAPTER 5

TRAIN DELAYS

5.1 Introduction

This chapter is concerned with the representation of delays occurring during a train's journey. These can be divided into timetabled delay times, due to compulsory stops and the need to wait for other trains at meets and overtakes; and unscheduled delays. Timetabled delays are discussed in Sections 5.2, 5.3 and 5.4 of this chapter. Section 5.2 contains a literature review of other work on the topic. Section 5.3 discusses the development of a delay model for Botswana. In this model particular attention has been paid to producing equations for train delays for different types of trains working method. This is partly because the three different trains working methods being considered for Botswana (Paper Order, Van Schoor Token, and Colour Light) are likely to have different effects on total train delay times, and partly because previous work on the subject has been concerned with Colour -Light Signalling only. Section 5.4 discusses the accuracy of the model. Once scheduled delay times have been calculated, they can be added to point-to-point times, derived as discussed in Chapter 4, to give timetabled journey times. An allowance must then be made for the effects of late running, and this is discussed in Section 5.5. The chapter ends with conclusions in Section 5.6.

5.2 Literature review of models for train delays

Work on modelling timetabled delays falls into two groups; those models which simulate individual train movements to obtain exact numbers and lengths of stops for each train that runs on the line, and those models which use relatively simple mathematical models to obtain average figures for stops for each train type. Six models of the first type are described by Rudd and Storry (Rudd and Storry 1976). Models of the second type include those by Ove Frank (Ove Frank 1975), the World Bank (IBRD 1970) and E R Petersen (Petersen 1974).

The models described by Rudd and Storry all involve accurate knowledge of the dispatch time, point-to-point times, and time at compulsory stops, for each individual train. Behaviour at meets, overtakes and compulsory stops is simulated using complicated formulae designed to mirror the decision-making involved when timetables are drawn up by hand. These formulae are in terms of a priority system when a train is involved in meets and overtakes with other trains, and have to take account of requirements for maximum journey time, and start and finish times for that train. The priority system cannot be too rigidly applied to each meet or overtake, as account must be taken of the effect of each stop on subsequent journeys of trains. Rudd and Storry list several problems which occur with the models, such as build-up of bottlenecks, and very slow journey times of low priority trains, which can be avoided in real life by timetablers' discretion. Even if these problems were overcome, the accuracy required of inputs to such models makes them unsuitable for use in this thesis.

The model developed in this thesis therefore falls into the second category; developing average values for numbers and lengths of delays for each train type. Of the three models of this type listed earlier, the Ove Frank model is not discussed further here. This is because his model is designed for a type of railway very different from the Botswana line. Described as type (ii) in Section 1.2 of the thesis, the type of railway Frank is modelling normally carries very few commodities, usually in one direction only (for example from a mine to a port), bringing back empty wagons. Such railways often use a "merrygoround" approach rather than a fixed timetable. Ove Frank's model therefore assumes priority trains in one direction and is concerned with minimising their journey times.

The Petersen and World Bank models are similar in nature, in that they are designed for railways where there is no overall priority in one direction. Both models are designed for single track lines, and assume that trains stop only at intersections, where an intersection is a meet or overtake. No allowance is made for compulsory stops on the line. Equations are developed for number of intersections, and average time at intersections, and total journey time is then calculated. The general methods used are described below.

Number of intersections

Petersen and the World Bank derive equations for the number of intersections in a similar manner to each other, except that, since the World Bank assumes all trains are travelling at the same speed, it deals only with meets, whereas Petersen also derives equations for the number of overtakes. The World Bank theory for number of intersections can therefore be regarded as a special case within the Petersen theory, where there is only one train type. The Petersen equations depend on the assumption that the number of meets and overtakes encountered by a train depend on the average number of trains on the line during its journey. As such they are a function of the number of trains and their average journey times. The Petersen theory for the number of intersections is the one used in this thesis, and is reproduced in detail, using diagrams consistent with the rest of the model in this thesis, in Appendix 8.

Average time spent stationary at a stop

Both Petersen and the World Bank assume that the average time at a stop is the sum of a minimum switching time (for points and signals), plus an additional waiting time incurred because two trains do not arrive simultaneously at the crossing loop where a meet or overtake is to occur. In both models, switching time is an input. Waiting time is derived differently, however, as described below.

Both the World Bank and Petersen define waiting time as a function of point-to-point times between sidings. The way they do this differs. The World Bank defines a best and worst case, the best being when "no train ... [is] ... forced to stop at a siding", and the worst being when "inbound and outbound trains ... arrive at opposite ends of single track simultaneously. In this case one train ... [is] ... forced to wait for the opposing train to travel the distance between successive sidings." They then define three "intermediate situations" as being somewhere between the best and the worst case, and associate each of these three situations with a type of signalling system. The reason for this association is not explained in the text. It implies a situation where trains do not run to a predetermined timetable, but are dispatched according to traffic requirements, the efficiency of this dispatch depending on the signalling system. The unclear theoretical basis of this model, and the fact that it probably assumes no predetermined timetable, makes it unsuitable for the present thesis.

The Petersen definition of a function for waiting time is considered more theoretically justifiable than the World Bank's. It forms the basis for the function used in the Botswana model, and as such is described in Section 5.3.4 and Appendix 7.

Total journey times

The product of number of intersections with average delay at intersections can be used to obtain a value for total delay time per journey. These can be added to the uninterrupted journey times, derived as described in Chapter 4, to obtain total journey times. However, it should be noted that the number of intersections is itself a function of total journey times. Both Petersen and the World Bank got round this problem of circularity by using an iterative method to obtain a solution. The same method is employed in this thesis.

Accuracy of the World Bank and Petersen models

As mentioned in the literature review of train speeds models (Section 4.2 of chapter 4 of this thesis), the World Bank Model was tested in an application on the State Railway of Thailand (IBRD 1972). However, the Thailand model only compared average journey times predicted by the model with actual journey times. Since average journey times include both train running times and times at delays, it is not possible from that work to judge the accuracy of either the train running times model or the train delay model in isolation. There are large differences between actual and predicted average speeds in Thailand as the figures from this study, reproduced in Table 5.1 below show.

Table 5.1 A comparison of predicted and actual speeds for the World Bank model of Thailand.

	Average speeds (kph)		
	Actual speeds	Simulation model	
		Passengers and car load freight	Less than car load freight
Freight trains	32	44.8	25
Passenger trains	43	52.1	

The authors of the work dismiss their own comparisons of average speed as follows:-

"Comparisons of average speed are not meaningful because the figures provided by the Railway and the model are based on different concepts. The Railway figure is the average overall speed between two points including stops and yard time, but the figures from the model refer to average running speed while underway, considering only delays because of meet."

The Petersen model of train delays has, as discussed in Chapter 2 of this thesis, been used as a component in a network planning model of the Canadian National and Canadian Pacific mainline railway systems. (CIGGT 1976) As such, Petersen states that: "For traffic planning studies the model adequately represents the delay characteristics of a line .... If, however, a detailed analysis of a line is required, then the more detailed simulation models are used." He does not give figures for the accuracy of the model.

5.3 A train delay model

5.3.1 Introduction

The train delay model described by Petersen forms the basis of the model used in this thesis. However, several important adaptations had to be made to Petersen's work in order to produce a model suitable for a less developed country railway like the one in Botswana. In Section 5.3.2 the assumptions that Petersen makes about the operation of a railway are discussed. It is concluded that, with regard to those assumptions not considered relevant to Botswana, one of the main sources of difference is the various trains working methods being considered for Botswana. In general, these have much slower switching times than those represented in Petersen's model. For this, and other reasons discussed in Section 5.3.2, the way in which different types of delay, such as switching time, waiting time, and compulsory stops, can coincide is given special attention in this thesis. Other required adaptations to Petersen's model are also discussed in Section 5.3.2.

Trains working methods being considered for Botswana are described in Section 5.3.3. A full list of types of delay encountered by a train is given in Section 5.3.4, and the ways in which these types of delay can be combined in Section 5.3.5. In Section 5.3.6, the equations for train journey times used in this thesis, which incorporate the considerations discussed in Sections 5.3.2, 5.3.3, 5.3.4, and 5.3.5 are described.

5.3.2 An examination of the assumptions used in Petersen's model in the light of their relevance to the Botswana line

The full set of assumptions both explicitly stated by Petersen, and implicit in his model, is listed in Table 5.2. Each of these assumptions was examined in the light of information available from Botswana, and most were deemed to be relevant.

The most important assumption which will have to be changed for the model of Botswana is number (ix); that the average time spent at a stop is the sum of a minimum switching time, plus an additional waiting time incurred because two trains do not arrive simultaneously at the crossing loop where a meet or overtake is to occur, thus causing one train to wait for the other. This assumption may have been justified for railways with high technology signalling systems, and therefore short switching times. The trains working methods being considered for Botswana can have very long switching times - of the order of 10-15 minutes. This means that the overlap between switching time and waiting time becomes significant.

Moreover, Petersen does not include compulsory stops in his model (see Assumption viii); presumably this would be added to other delay times as calculated by the model. This is likely to cause error, even on railways with high technology trains working methods as it does not allow for the fact that there is an overlap between waiting time and compulsory stops. On railways with low technology trains working methods there are in any case likely to be more compulsory stops; the Van Schoor token working method, for example, requires a train to stop at each crossing loop.

A further modification to Petersen's assumption of the average delay time per stop is required because, for two of the trains working methods being considered in Botswana, time spent at a stop depends on whether the stop is manned or unmanned.

Table 5.2 Assumptions in Petersen's model of train delays

(i) The model is for a single track line.
(ii) All trains run the full length of the line.
(iii) Any number of train types can be assumed to run on the line. Petersen defines train types according to their point-to-point speeds, directions, and priorities over other trains at intersections, where an intersection is a meet or overtake.
(iv) A priority system is defined between train types as a series of fractions between each two types expressing the proportion of times that one train type waits for (i.e. has low priority with) the other train type at an intersection.
(v) Dispatches of train types are uniformly distributed over the time period over which the timetable is defined. Distributions for each train type are independent. In other words, there is no flighting of trains.
(vi) Each train type is assumed to have a uniform running speed for the length of the line.
(vii) Crossing loops are assumed to be equally spaced along the line.
(viii) Trains stop only at intersections; that is, to allow a train in the opposite direction to cross (a meet) or to allow a train travelling in the same direction to pass (an overtake).
(ix) Average time spent at a stop is the sum of a minimum switching time, which is an input varying with the trains working method, plus an additional waiting time, incurred because two trains do not arrive simultaneously at the crossing loop where a meet or overtake is to occur, thus causing one train to wait for the other.
(x) Traffic levels are fairly low; in a later work (Petersen 1977) Petersen states that the model described here (Petersen 1974) cannot adequately represent the effects of congestion.
(xi) All crossing loops are long enough to accomodate the longest train running on the line, and can be used at meets and overtakes.
(xii) Since no limit is given to the number of trains that can be accomodated at a loop at any one time, there is an implicit assumption that there are several loops available at each site, long enough to accomodate a train.
(xiii) Permissive working is allowed at overtakes.
(xiv) Delays are planned to be as short as possibe; no safety allowance is included in timetables to allow a train which is behind schedule at one stop to catch up by the next.
(xv) Overlap time; the time elapsing between arrival of one train and departure of the other, from a crossing loop where a meet or overtake is to occur, is not allowed for.

Another required modification to Petersen's model is also indirectly related to the trains working method. Although the priority system between trains can be defined in the present model using Petersen's method (see assumption (iv) in Table 5.2), the way that priority system is incorporated into the equations for train delay must be changed. This is because two of the trains working methods being considered for Botswana have a rigid requirement in terms of the specific crossing loops at which trains have high or low priority. This is explained further in Section 5.3.4 and Appendix 7.

Assumption (xiv) that planned train delays are minimised would also seem, on a priori reasoning, to be unjustifiable. A safety allowance would be expected to be included in the timetabling for a railway such as the Botswana line, which places a low priority on speeds, has a trains working method which allows for little centralised control, and is likely to experience higher levels of inefficiency, and therefore unscheduled delay, than a developed country railway. (The problem of inefficiency in less developed country railways was discussed in Chapters 1 and 2 of this thesis). The representation of a safety allowance for train delays in the Botswana model forms part of the discussion in Sections 5.3.4 and 5.3.5.

Another factor accounted for in the Botswana model, but not allowed for by Petersen, is overlap time at intersections (see assumption xv). For two trains travelling in the same direction this includes minimum headway between them which can, for some railways, be quite large.

In addition to the above modifications, Petersen's model has to be adapted in order to fit in with the rest of the model developed in this thesis. Since the train speeds model discussed in Chapter 4 does not allow for the deceleration of trains to a halt, and their acceleration back to speed afterwards, an acceleration allowance has to be incorporated into the delay model.

5.3.3 Trains working methods being considered for Botswana

The present trains working method used in Botswana is that of Facsimile Paper Orders. When Botswana take over the line, trains will be run by newly trained crew, and there is debate as to whether the method will be sufficiently safe in such circumstances. Two other methods are therefore being considered; Van Schoor token working and Colour Light Signalling. Each of these methods is discussed below. Its method of operation is described, and then its effect on the following summarised:-

- Total number of stops for a train.
- Minimum switching time at stops. For all trains working methods, the minimum switching time takes different values according to whether the stop is due to a train being at a compulsory stop, or due to the train being the low priority train at a meet or overtake. The high priority train at an intersection is assumed

to stay on the main line, and therefore its switching time is the same as it would be if there were no intersection. For Paper Order and Van Schoor working, switching times take different values according to whether a loop is manned or unmanned.

(The concept of high and low priority trains is described in detail in Section 5.3.4. For this section it is sufficient to consider the low priority train to be the one which stops in the crossing loop at an intersection (meet or overtake) while the high priority train crosses or passes it).

A summary of switching times for all trains working methods is given in Table 5.4 in Section 5.3.4.

Facsimile Paper Order Working

Method of Operation

"The method of operation is for Train Despatchers at stations equipped with Facsimile machines to agree between themselves which trains should proceed and where trains will pass each other at passing loops or intermediate stations. This information is fed into a machine at the station in advance, and reproduced at the station in the rear. One copy is given to the driver, one retained at the station, and a third to the guard" (JWC 1978(i)).

"On receipt of the written train order, the train may leave [the] station ... Train crossings at unmanned crossing loops are regulated in different ways, i.e. there are different priorities ... a low priority train must clear the line for a high priority train, that is, it must enter the loop ... from the train order, the engine driver knows whether he can stay on the main line at the crossing point ... or not. The train that reaches it first stops before the entry points, the guard then sets these for the prescribed direction [note: in interviews with NRZ personnel it was stated that the driver sets these points]. The train then enters the track that it must use, the points are returned to the normal position (that is, to the main line setting) in the case of a train having entered a loop, and the route is then set up for the train travelling in the opposite direction, in that the guard walks forward to the other set of points, sets them, and signals that the oncoming train may pass with a green flag. After the train in the opposite direction has passed, he sets the exit points to the correct position for his train, and his train can then leave the crossing area.

When he has set the exit points to their normal position, the guard returns to his guard van and orders the engine driver to continue the journey by train radio." (Deconsult 1981)

Effect on number of stops

Trains must stop at some stations to pick up new facsimile paper orders. However, there are no absolute limits on the number of intermediate stations where this does not have to be done. Also, in interviews with people in NRZ's working timetable department, picking up paper orders was not given as one of the reasons for compulsory stops. Therefore, it can be assumed that paper orders are written such that they need only be picked up at places where there are compulsory stops for other reasons. At a meet or overtake, only one train has to stop. The paper working method, therefore, does not require any stops in excess of these already defined as compulsory stops, meets, or overtakes.

Effect on minimum switching time

Switching time at a compulsory stop for a train which is not a low priority train at an intersection

- At manned loops, paper orders have to be handed to the guard and driver, taking a time TPAP, where TPAP takes the value of 2 minutes for Botswana.
- At unmanned loops no action need be taken, so switching time is zero.

Switching time for the low priority train at an intersection

- At manned loops, paper orders have to be handed to the driver and guard. Points have to be set when the low priority train enters the loop, and again when it leaves, and then have to be set back to the main line. This takes a total time of TPOINT. Total switching time at this type of stop is therefore TPAP + TPOINT. The discussion of overlap times in Section 5.3.4 will show that TPOINT = 4 minutes for Botswana.

- At unmanned loops the guard on the train entering the loop has to set the points back to the main line (assuming they were set, on entry, by the driver), and then walk the full length of the siding to give the all-clear signal to the train taking the main line. NRZ at present allow 12 minutes per unmanned crossing loop for the train taking the loop. In the model developed in this thesis, crossing loop length is an input which can be varied. It is therefore desirable to obtain an expression for switching time in terms of average crossing loop length, DCROSS. NRZ's value of 12 minutes includes 4 minutes for TPOINT, the setting of points, and is for unmanned crossing loops with an average length of 440 metres. This information can be used to form an expression for switching time for the low priority train at an intersection as follows:-

$$0.018 \text{ DCROSS} + \text{TPOINT}$$

Van Schoor Token Block Working

Method of Operation

"The basic form of this system utilises an actual physical token. When a train runs from A to B, the stationmaster of A gives the engine driver a token (a rod) which he hands to the stationmaster of B on arrival. The token can then be handed to the driver of the train running in the opposite direction, this representing a permit to run from B to A.

In a somewhat sophisticated form of the token block system, neighbouring stations each have a token instrument from which a token can only be handed to the engine driver as a permit to proceed with the approval of the other station. No further token can be taken from the instrument until the token held by the engine driver has been replaced in one of the two instruments. The line is thus secure.

Token instruments allow a number of [consecutive] journeys in the same direction. To allow more flexible train operations, various alternatives that are based on this system have been developed ... [these include] ... so-called "crossing tokens" ... developed to allow trains to cross at unmanned stations.

The token system most favoured for Botswana is the Van Schoor system ... which ... does allow crossings at unmanned stations. At unmanned staions are so-called "interworking instruments" from which the token for the next block section must be taken on arrival" (Deconsult 1981).

Effect on number of stops

As stated in Deconsult's description of the Van Schoor method, quoted earlier, all trains must stop at all crossing loops, to pick up tokens.

Effect on minimum switching time

Switching time for a train which is not a low priority train at an intersection

- At a manned loop, the station-master has to hand a token to the guard, taking a time TTOK minutes. It is assumed that TTOK=2, as this is the time that Deconsult suggest.
- Switching time at an unmanned loop covers the time the guard takes to walk the loop, plus TTOK, the time taken to work the token. Hence switching time at an unmanned loop for a train which is not a low priority at an intersection is given by:-

$$0.018 \text{ DCROSS} + \text{TTOK}$$

Switching time for a low priority train at an intersection

- At a manned loop, the low priority train has to wait while points are changed, and tokens exchanged. Thus, switching time is given by TPOINT + TTOK.
- At an unmanned loop, the low priority train has to wait while points are changed, the guard walks the length of the line, and tokens are exchanged. Thus, switching time is given by:-

$$0.018 \text{ DCROSS} + \text{TPOINT} + \text{TTOK}$$

Colour Light Signalling with Centralised Traffic Control

The method of operation of Colour Light Signalling will be affected by the way it is controlled. A centralised traffic control system is used by NRZ. Control centres have access to detailed information on the state of the track including:-

- "track occupied or clear
- signal aspects
- block sections occupied or clear
- setting of points" (Deconsult 1981).

Thus, setting up of routes, setting of signals, etc., can be controlled from this centre.

Effect on number of stops

No extra stops, above those already defined as compulsory stops, are required because of the Colour Light Working method. Examination of the Working Timetables for those parts of the NRZ system worked by Colour Light shows that only one train has to stop at a meet or overtake. (NRZ:WTT 1981(ii) and (iii))

Effect on minimum switching time

Switching time at a compulsory stop for a train which is not a low priority train at an intersection

The fact that only one train has to stop at a meet or overtake suggests that there is a minimum switching time only when a new route is set up. Since it is assumed that trains stay on the main line when at a compulsory stop where they are not the low priority train at an intersection, there is no switching time at such a stop.

Switching time for low priority train at an intersection

The time to set up a new route will be given the name TPOINT in this thesis. Examination of the relevant sections of NRZ's Working Timetable (NRZ:WTT 1981 (ii) and (iii)) show that TPOINT=3.

5.3.4 Types of delay time

To summarise and extend previous discussion in this chapter, delays to a train can be represented as a function of time spent as follows:-

- Waiting time, incurred because two trains do not arrive simultaneously at the crossing loop where a meet or overtake is to occur.
- Switching time, for the trains working method to be operated, and points changed, if necessary.

- Overlap time; a minimum time between arrival and departure of two trains involved in a meet or overtake.
- Compulsory stops, required by the railway for several reasons, such as the loading or unloading of goods, and the changing of crews.
- Acceleration time; the time allowed for a train to decelerate to a stop, and accelerate from it to full speed on the following sections.
- A safety allowance at meets and overtakes.

Each of these times is now discussed in turn.

Waiting times

As stated in Section 5.3.2, Petersen's model of waiting times forms the basis for that used in this thesis. It is based on the idea that there is a random spread between minimum and maximum waiting time when two trains are involved in a meet or overtake. Minimum waiting time occurs when the two trains involved reach a siding simultaneously. Maximum time occurs when one train arrives at the siding where the meet or overtake is to occur when the other train arrives at the next siding along the line.

Waiting time for each train type as defined by Petersen is a function of maximum delay time, and of that train's priority over other trains. Petersen's priority system, translated into the notation used in this thesis, is given in Table 5.3. (All tables referred to in this section (Section 5.3.4), are given at the end of the section).

The derivations of expressions for delay times used in this thesis are given in Appendix 7, and the results are reproduced in Table 5.3. In deriving these expressions, two changes were made to Petersen's work as follows.

(i) The way in which the priority system is incorporated in delay times varies according to the trains working method. Petersen assumes that timetablers will plan train waits so that, within the confines of the priority system, trains wait at the nearest possible crossing loop. In this thesis, Petersen's assumption is considered justified for Colour

Light working, but not for Paper Order working or Van Schoor token working. This is because the latter two trains working methods have rigid rules as to which train has priority at an intersection according to whether a loop is manned or unmanned, and thus a timetabler has heavier constraints as to which train must stop.

(ii) Deceleration time to stops, and acceleration time from them are incorporated into waiting times.

Switching times

Switching times required for each trains working method were discussed in detail in Section 5.3.3 of this chapter. Expressions derived in that discussion are summarised in Table 5.4, below.

Overlap times

Trains involved in an intersection cannot arrive or leave a crossing loop at the same time as each other, due to the fact that points have to be switched, and, in the case of trains travelling in the same direction, there must be a minimum headway between trains. Two overlap times are therefore defined.

$$\text{Overlap time at meets} = \frac{\text{TPOINT}}{2}$$

$$\text{Overlap time at overtakes} = \frac{\text{TPOINT}}{2} + \text{THEAD}$$

where TPOINT is time to change points from one route to another and back again, and

THEAD is the time in excess of TPOINT/2 required as minimum headway between trains.

In Botswana an overlap time of 2 minutes is required for a meet giving a value of TPOINT=4 minutes. The small number of overtakes occuring in Botswana make it difficult to obtain a value for THEAD, but a value of 1 minute will be assumed.

Compulsory stops

Compulsory stops required on the Botswana line at present were assessed by analysing stops for all trains in the Working Timetable, and isolating compulsory stopping time from the other times defined in this section. This analysis used the equations developed in Appendix 8 and discussed in Section 5.3.6. Table 5.6 shows some of the results of that analysis, and compares delay times due to compulsory stops with other delay times and average journey times. It can be seen that compulsory stops form at least half the delay time for each train type.

In addition to the compulsory stops already defined in Botswana, the Van Schoor token working method would, if introduced, require all trains to stop at all crossing loops, to pick up tokens.

Acceleration time

The time taken for a train to decelerate to, and accelerate from a stop is an input to the model, which can take different values for different train types. This is regarded as a sufficiently accurate way of representing this time, since it is the method used by NRZ when planning the working timetable. They use an allowance of 2 minutes acceleration time for each train type.

Safety allowance at meets and overtakes

As stated in Section 5.3.2, it is to be expected that timetablers would add a safety allowance to waiting time at meets and overtakes, to allow a certain amount of late running to occur without any deviation from the timetable. In Botswana the mixed and passenger trains have high priority over the goods trains. Examination of the Working Timetable (NRZ 1981(i)) shows that the high priority trains do not stop at meets, implying that there is no safety allowance incorporated into delay times for such trains. The low priority goods trains, on the other hand, often have fairly long waiting times.

Therefore, the Botswana model is constructed in such a way that the lower priority train at each intersection waits for an additional time as a safety allowance. It should be noted that a safety allowance on one train at an intersection can "absorb" late running from either train.

No information was directly available from Botswana as to the size of this safety allowance. Therefore, a value was obtained as follows. The delay model was run using data from Botswana, but without a safety allowance. The results were compared with actual delay times in order to estimate the best value for the safety allowance. The model was then rerun as a double check. This process is described and discussed further in Section 5.3.6.

Table 5.3 The priority system for trains, and waiting times at meets and overtakes

The Priority System

RPRMET (NO,JT,IT) is the proportion of times that a train of type JT travelling in direction NO takes low priority in a meet with a train of type IT travelling in the opposite direction.
RPROV (NO,JT,IT) is the proportion of times that a train of type JT travelling in direction NO takes low priority in an overtake with a train of type IT in direction NO.

This definition assumes train types, as defined in Section 3.2.3 of Chapter 3, are represented as a number in two counters, IT and JT. The direction of travel of a train is also defined as a number, NO, which takes the value 1 for up trains and 2 for down trains. If another counter, NOP, is used to define the opposite direction to NO (i.e. NOP=3-NO), then it follows from the above definition that:-

$$\mathrm{RPRMET\ (NO,JT,IT)} = 1 - \mathrm{RPRMET\ (NOP,IT,JT)}$$
$$\mathrm{RPROV\ (NO,JT,IT)} = 1 - \mathrm{RPROV\ (NO,IT,JT)}$$

Waiting Times

TDELMT(NO,JT,IT): average delay to a train of type JT travelling in direction NO when it meets a train of type IT

Paper Order

$$\left\{\frac{(\mathrm{XCOMP(NOP,IT)} \times \mathrm{TACC(NOP,IT)} + \mathrm{XCOMP(NO,JT)} \times \mathrm{TACC(NO,JT)})}{\mathrm{XCROSS}} + \frac{(\mathrm{TOTTIM(NO,JT)} + \mathrm{TOTTIM(NOP,IT)})}{(\mathrm{XCROSS} + 1)}\right\} \times \frac{\mathrm{RPRMET(NO,JT,IT)}}{2}$$

Van Schoor

$$\left\{(\mathrm{TACC(NOP,IT)} + \mathrm{TACC(NO,JT)} + \frac{(\mathrm{TOTTIM(NO,JT)} + \mathrm{TOTTIM(NOP,IT)})}{(\mathrm{XCROSS} + 1)}\right\} \times \frac{\mathrm{RPRMET\ (NO,JT,IT)}}{2}$$

Colour light

$$\left\{\frac{(\mathrm{XCOMP(NOP,IT)} \times \mathrm{TACC(NOP,IT)} + \mathrm{XCOMP(NO,JT)} \times \mathrm{TACC(NO,JT)})}{\mathrm{XCROSS}} + \frac{(\mathrm{TOTTIM(NO,JT)}+\mathrm{TOTTIM(NOP,IT)})}{(\mathrm{XCROSS} + 1)} \times \mathrm{RPRMET(NO,JT,IT)}\right\} \times \frac{\mathrm{RPRMET(NO,JT,IT)}}{2}$$

TDELOV(NO,JT,IT): average delay to a train of type JT travelling in direction NO when it is involved in an overtake with a train of type IT.

Paper Order

$$\left\{\frac{(\mathrm{XCOMP(NOP,IT)} \times \mathrm{TACC(NOP,IT)} + \mathrm{XCOMP(NO,JT)} \times \mathrm{TACC(NO,JT)})}{\mathrm{XCROSS}} + \left|\frac{(\mathrm{TOTTIM(NO,JT)} - \mathrm{TOTTIM(NO,IT)})}{(\mathrm{XCROSS} + 1)}\right|\right\} \times \frac{\mathrm{RPROV(NO,JT,IT)}}{2}$$

Van Schoor

$$\left\{\mathrm{TACC(NOP,IT)} + \mathrm{TACC(NO,JT)} + \left|\frac{(\mathrm{TOTTIM(NO,JT)} - \mathrm{TOTTIM(NO,IT)})}{(\mathrm{XCROSS} + 1)}\right|\right\} \times \frac{\mathrm{RPROV(NO,JT,IT)}}{2}$$

Colour light

$$\left\{\frac{(\mathrm{XCOMP(NO,IT)} \times \mathrm{TACC(NO,IT)} + \mathrm{XCOMP(NO,JT)} \times \mathrm{TACC(NO,JT)}}{\mathrm{XCROSS}}\right.$$

Table 5.3 continued

$$+ \left| \frac{(TOTTIM(NO,JT)-TOTTIM(NO,IT))}{(XCROSS + 1)} \right| \times \left. \frac{RPROV(NO,JT,IT)}{(XCROSS + 1)} \right\} \times \frac{RPROV(NO,JT,IT)}{2}$$

Symbols	
XCROSS	number of crossing loops on the line.
	For a train type of JT travelling in direction NO:-
XCOMP(NO,JT)	number of compulsory stops.
TACC(NO,JT)	time to decelerate to and accelerate from a stop.
TOTTIM(NO,JT)	uninterrupted journey time.
RPRMET(NO,JT,IT)	proportion of times the train takes low priority when meeting a train of type IT.
RPROV(NO,JT,IT)	proportion of times the train takes low priority when involved in an overtake with a train of type IT.

Table 5.4 Summary of switching times
Trains working method

		Paper Order	Van Schoor	Colour light
Type of stop	Type of loop	Expression for switching time		
Compulsory stop where train is not low priority train at an intersection	manned	TPAP	TTOK	0
	unmanned	0	0.018xDCROSS + TTOK	
low priority train at intersection	manned	TPAP+TPOINT	TTOK+TPOINT	TPOINT
	unmanned	0.018xDCROSS +TPOINT	0.018xDCROSS +TPOINT+TTOK	
Definition of variable	name of variable	Value for variable (time in minutes, distance in meters)		
Time to exchange paper orders	TPAP	2	-	-
Time to switch points to new route, and back to main route	TPOINT	4	4	3
time to exchange tokens	TTOK	-	2	-
average length of crossing loop	DCROSS	440	440	

Table 5.5 Overlap times between trains

Overlap time at meets

Points must be switched back after allowing the low priority train to enter the crossing loop before the high priority train can leave. Thus, TPOINT/2 must elapse between the arrival of the low priority train, and departure of the high priority train. Similarly, TPOINT/2 must elapse between departure of the low priority train and arrival of the high priority train.

Where the high priority train is not at a compulsory or trains working method stop, its arrival and departure times are simultaneous; thus the low priority train must arrive at least TPOINT/2 minutes earlier than the high priority train, and depart at least TPOINT/2 minutes later. If the high priority train is at a compulsory stop, the order of arrivals and departures does not matter, provided a minimum time of TPOINT/2 elapses between them.

Overlap time at overtakes

As with meets, TPOINT/2 is required between the arrival of the low priority train and departure of the high priority train. However, this time may not be sufficient to ensure that a minimum headway is maintained between two trains on a section of the line. If THEAD is defined as the time in excess of TPOINT/2 required as overlap time, then the time that must elapse between the arrival of both the high and low priority train is THEAD+TPOINT/2. The same time must elapse between the departure of the two trains.

Table 5.6 Train delay times and journey times

Times in minutes	Goods		Mixed		Passenger	
	Up	Down	Up	Down	Up	Down
Average delay at compulsory stops per train which would occur if there were no meets/overtakes	218.534	217.134	288.621	283.5097	188.006	170.001
Average overall delay per train	428.778	357.222	310	313	191	173
Average journey time	1274.778	1196.222	1020	1037	850	850

5.3.5 Combinations of delay times

Any train stop will usually involve a combination of the types of delay time discussed in Section 5.3.4. To repeat the list given in that section, delay times are:-

- Waiting time
- Switching time
- Overlap time
- Compulsory stops
- Acceleration time
- Safety allowance

Some of these delay times can occur at the same time; for example, a waiting time incurred because a train is waiting for another to arrive at a meet can occur while that train is at a compulsory stop. In this case the model should not add the two times, but take the larger of the two as the time for which the train is actually delayed. Other delay times cannot occur together; for example the safety allowance is always added to other delay times; would be lost if it was combined with them.

The way in which each combination of delays is represented is discussed in Appendix 6.

5.3.6 Equations for train journey times

In sections 5.3.2 to 5.3.5, the types of train delay which can occur, the way in which these are combined, and the way in which they vary according to the trains working method, were discussed. this information is now used to produce equations for total train journey times.

In the model, the total journey time for a train is calculated as follows:-

- Minimum journey time, made up of the uninterrupted journey time, plus time at compulsory stops, is calculated.
- For each train type, the total number of meets and overtakes per journey is calculated.
- Since, as the discussion in Sections 5.3.3, 5.3.4, and 5.3.5 showed, delay at a meet or overtake is influenced by many factors, it is not possible to calculate a single average delay

per meet or overtake. Instead, equations for average delay with each possible combination of factors are derived, and these form the elements of a vector TVEC.

- Total number of meets and overtakes are apportioned according to the probability of occurrence of each combination of factors influencing average delay times, into a vector XVEC, whose elements are defined similarly to those in TVEC.
- The average journey time for a train can then be derived, using the following equation:-

$$\mathrm{TIMAV(NO,JT)} = \mathrm{TIMIN(NO,JT)} + \sum_{\mathrm{IT}=1}^{\mathrm{NTYPE}} (\mathrm{XVEC(NO,JT,IT)}.\mathrm{TVEC(NO,JT,IT)})$$

Equation 5.3

where:-

TIMAV(NO,JT)	is the average journey time for a train of type JT travelling in direction NO.
TIMIN(NO,JT)	is the minimum journey time (when no intersections occur) for a train of type JT travelling in direction NO. This was discussed at the beginning of this section.
XVEC(NO,JT,IT)	is the transpose of a column vector whose elements are defined by the various types of intersection discussed in Table 5.8. Thus XVEC has six elements for Van Schoor and Colour Light working, and twelve for Paper Order working. Each element contains an expression for the average number of intersections of that type occurring between a train (NO,JT) and trains of type IT during a journey for train (NO,JT).
TVEC(NO,JT,IT)	is a column vector whose elements are defined in the same way as XVEC, but contain average delay times at each type of intersection.
NTYPE	is the number of trains of each type, IT.

The discussion in the rest of this section follows the same sequence as the calculations in the model; that is, the calculation of minimum journey time is first discussed. This is followed by an account of the derivation of equations for total numbers of meets and overtakes. Elements of the vectors TVEC and XVEC are then discussed.

Minimum journey time (TIMIN(NO,JT))

The symbol TIMIN(NO,JT) will be used to define the minimum journey time for a train of type JT travelling in direction NO.

The calculation of uninterrupted journey times was described in Chapter 4. To these must be added delay times at compulsory stops. As discussed in previous sections in this chapter, the average delay time at a compulsory stop is made up of the stipulated compulsory stopping time, plus the relevant switching time (as given in Table 5.4), plus the acceleration time. Multiplying this average delay time by the average number of compulsory stops per train journey gives the total stopping time per journey due to compulsory stops.

For the Van Schoor token working method, for reasons discussed in Section 5.3.3, extra time must be added because trains stop at all crossing loops to pick up tokens. The average time taken per stop to do this is the switching time plus acceleration time, and the number of times such a stop occurs per journey is given by the number of crossing loops on the line, less those already defined as compulsory stops.

It should be noted that, for Paper Order and Van Schoor working, number of compulsory stops, and average time per stop, must be calculated separately for manned and unmanned loops. The same applies to trains working method stops for Van Schoor working.

Total number of meets and overtakes

The total number of meets and overtakes encountered by a train during its journey from one end of the line to the other is a function of the train's own journey time, and of the number of trains of each type, and their journey times. The functions are derived in Appendix 8 and result in the equations given in Table 5.7, below.

Table 5.7 Equations for number of meets and overtakes

$$XMEET(NO,JT,IT) = \frac{XTEWPD(IT)}{(1440 - TCLOSE)} \times (TIMAV(NOP,IT) + TIMAV(NO,JT))$$

Equation 5.1

$$XOTAKE(NO,JT,IT) = \frac{XTEWPD(IT)}{(1440 - TCLOSE)} \times |(TIMAV(NO,IT) - TIMAV(NO,JT))|$$

Equation 5.2

where:-

XMEET(NO,JT,IT)	is the average number of meets per journey for a train of type JT travelling in direction NO with a train of type IT travelling in the opposite direction.
XOTAKE(NO,JT,IT)	is the average number of overtakes per journey for a train of type JT travelling in direction NO with a train of type IT travelling in the same direction.
XTEWPD(IT)	is the number of trains of type IT each way per day.
TIMAV(NO,JT)	is the average journey time for a train of type JT travelling in direction NO.
NOP	is the opposite direction to NO.
TCLOSE	is the number of minutes per day for which the line is closed.

These equations are the ones used by Petersen and it should be noted that as stated in Section 5.2.2, they must be solved by an iterative method, since they use average delay times as an independent variable. Petersen in fact defines two types of intersection with different average delay times; meet and overtake. He multiplies the number of each of these types of intersections by the average delay at that type to obtain a value for total delay.

Elements of the vectors TVEC and XVEC

Discussion in Sections 5.3.3, 5.3.4 and 5.3.5 showed that, for the Botswana model, several other factors affect average delay at an intersection, in addition to whether that intersection is at a meet or overtake. A full list of these factors is given in Table 5.8, below. It is concluded in that table that six types of intersection can be defined for both the Van Schoor token working and Colour Light Signalling systems. Twelve types of intersection can be defined for the paper order system.

Table 5.8 Factors affecting average delays at an intersection

The average delay time for a train at an intersection can be affected by the following factors:-

(i) Whether the intersection is at a meet or overtake.
(ii) Whether that train, or the train it is meeting, is at a compulsory stop. Three situations can occur here with differing effects on delay time:-
- The train under consideration is at a compulsory stop (it is then immaterial, from the point of view of delay time whether the other train is at a compulsory stop).
- The train under consideration is not at a compulsory stop, but the other train is.
- Neither train is at a compulsory stop.
(iii) Whether the intersection occurs at a manned or unmanned loop.

For all three trains working methods, (i) and (ii) have an effect. This means that six types of intersection must be defined; to take account of the two types of intersection defined by factor (i) multiplied by the three types defined by factor (ii). As discussed in Section 5.3.3, delay times for Paper Order and Van Schoor token trains working methods vary according to whether a loop is manned or unmanned. However, this section is only concerned with the extra delay time due to intersections. For the Van Schoor token working method, switching time at an unmanned loop is the same regardless of whether an intersection occurs at that loop or not (see Section 5.3.3 and Table 5.4). The extra delay time due to Van Schoor working is not therefore affected by whether the loop is manned or unmanned. For Paper Order working, however, extra delay time is affected by whether the intersection is at a manned or unmanned loop (factor (iii)). These two alternatives multiplied by the six types of intersection discussed give twelve types of intersection for the Paper Order trains working method.

Elements of TVEC(NO,JT,IT) and XVEC(NO,JT,IT) are discussed below, according to how they are affected by the factors defined in Table 5.8, that is:-

(i) Whether the intersection is a meet or overtake.

(ii) Whether either train involved in the intersection is at a compulsory stop.

(iii) Whether the intersection occurs at a manned or unmanned loop.

The equations used for each element of TVEC(NO,JT,IT), for each train working method, are given in full in Appendix 9, and those for XVEC(NO,JT,IT) in Appendix 10.

TVEC(NO,JT,IT)

The discussion of the elements of TVEC(NO,JT,IT) makes use of the information on delay times given in Sections 5.3.3, 5.3.4 and 5.3.5. Considerations involved in their derivation can be summarised according to factors (i), (ii) and (iii) mentioned above, as follows:-

(i) Whether the intersection is a meet or overtake:-

- This will affect the value of waiting time. Expressions for waiting times at meets (TDELMT(NO,JT,IT)) and at overtakes (TDELOV(NO,JT,IT)) were given in Table 5.3.
- It will also affect overlap times. As discussed in Section 5.3.4, the overlap time at an overtake must include an expression for minimum headway, not required for overlap time at meets.

(ii) Whether the intersection is at a compulsory stop for either train.

- Waiting time is only included in the expression for an intersection if neither train is at a compulsory stop when the intersection occurs.
- Overlap time is only included if neither train is at a compulsory stop.
- If the train under consideration (train(NO,JT)) is at a compulsory stop when an intersection occurs, or has to wait for a time in addition to a compulsory stop for an intersection to occur, then the additional switching time due to the intersection is given by the difference between switching time at an intersection and switching time at a compulsory stop. Otherwise, it is simply the switching time at an intersection. (see Table 5.4 for switching times).

(iii) Whether the intersection is at a manned or unmanned loop:

- For Paper Order working, additional switching time due to an intersection is affected by whether the loop is manned or unmanned (see Table 5.4).

XVEC(NO,JT,IT)

Elements of XVEC are now discussed with regard to the same considerations (i), (ii), and (iii) as were used in the discussion of TVEC, above. (i) Whether the intersection is a meet or overtake:

- Number of meets and overtakes are derived separately in the model. Table 5.7 gave the equations for:-

XMEET(NO,JT,IT) the average number of meets per journey for a train of type JT travelling in direction NO with a train of type IT travelling in the opposite direction, and:-

XOTAKE(NO,JT,IT) the average number of overtakes per journey for a train of type JT travelling in direction NO with a train of type IT travelling in the same direction.

These equations were derived in Appendix 8.

(ii) Whether the intersection is at a compulsory stop for either train:

- The proportion of times when an intersection occurs at a compulsory stop for a train is obtained by dividing total time per journey spent at compulsory stops by total journey time if no intersections occur. This makes use of the assumption, discussed in Section 5.3.5, that the number of intersections coinciding with compulsory stops is random. The proportion of times when an intersection is not at a compulsory stop can, of course, be obtained by a similar method. The actual numbers used in the elements of XVEC(NO,JT,IT) are then given by these proportions multiplied by total number of intersections, XMEET(NO,JT,IT), and XOTAKE(NO,JT,IT).

(iii) Whether the intersection is at a manned or unmanned loop.

- The proportion of times when an intersection occurs at a manned or unmanned loop is given by the proportion of each type of loop on the line. These proportions are multiplied by total number of intersections to give the numbers in the elements of XVEC(NO,JT,IT).

To summarise the above discussion, the average delay time for a train is calculated as the sum of the uninterrupted journey time, the time spent at compulsory stops, and additional time spent at intersections. Uninterrupted journey time was derived in Chapter 4. Time spent at compulsory stops is given by the average time at compulsory stops multiplied by the number of compulsory stops. For Paper Order and Van Schoor working, compulsory stops are defined separately for manned and unmanned stops. Van Schoor working requires additional compulsory stops to the other methods, since it requires that each train stop at each crossing loop.

Waiting time at intersections varies according to several factors. Waiting times at various types of intersections are therefore calculated as elements of a vector, multiplied by elements of a similar vector for number of intersections, and the results added. The values for number of intersections of each type make use of an equation which is a function of average delay times. An iterative method therefore has to be used, where the calculations for number of intersections are repeated with new values for delay times, which on each occasion have been obtained using the previous iteration's values for number of intersections.

The accuracy of this model is discussed in Section 5.4.

5.4 Accuracy of the Botswana model

As stated during the discussion of a safety allowance in Section 5.3.4, the model has to be run twice:-

- Firstly, without a safety allowance. Journey times obtained from the model are then compared with actual journey times in order to obtain the best value for a safety allowance.
- Secondly, the model is rerun with a safety allowance to check that an accurate value for this parameter has been used.

The fact that the output from the model is used to generate an input to it in this way, means that it is not possible to test the accuracy of the delay predictions from the set of data.

One test was done, however, to give an indication as to whether it was reasonable to assume that a safety allowance should be added to times at each intersection. This test makes use of the fact that number of intersections are calculated as a function of average journey times. By using actual journey times in this calculation, the accuracy of this part of the model can be judged in isolation. If results of such calculations are accurate, it can be assumed that any shortfall in total delay times predicted in the first run of the model is due to average delay times being too short, as the safety allowance assumption implies. Table 5.9 below shows the results of these calculations. The errors produced are all less than 8%, which is regarded as acceptable. This test therefore provides some assurance as to the validity of the safety allowance assumptions.

Table 5.9 A comparison of number of intersections per train journey calculated using average times from the timetable, with actual average numbers of intersections

train type	average no. of intersections	predicted no. of intersections	error (%)
goods up	18.5917	17.241	-7.27
goods down	18.4714	17.078	-7.543
mixed up	17	16.787	-1.254
mixed down	18	16.803	-6.65
pass up	16	16.719	+4.496
pass down	16	16.719	+4.496

Previous discussion shows that inputs to the model are available for all three trains working methods being considered. However, actual delay times are clearly only available from the Working Timetable for the trains working method being used at present; that is, Paper Order. It is therefore the Paper Order method which is discussed here. Results of running the model for other trains working methods are discussed in Chapter 10.

A full set of inputs used for the tests in this chapter are given in Appendix 2, and they are discussed generally here.

The model requires information on number of crossing loops, which for the Botswana line, inside the borders of Botswana, is 52. The number of manned loops - at present 14 - is also required. The switching times are also input, and take the values given in Table 5.4. For the first run of the model, the safety allowance is set to zero.

Information is also required for each type of train, as follows:-

- priorities between train types at meets and overtakes
- number of compulsory stops, and number of manned compulsory stops
- minimum stipulated time at compulsory stops, and deceleration/acceleration time per stop

The priority system between train types used in Botswana can be described as follows. The priority system between train types is fairly obvious, with one type taking total priority over the other, so that RPRMET(NO,JT,IT), RPROV(NO,JT,IT) take the value 0 or 1 for all cases where JT is not equal to IT. The order of priority between train types is:-

passenger

mixed

goods

(NRZ:TWR)

The priority system between trains of the same type, however, is not so clear. It is known that down trains take priority over up trains at unmanned loops with regard to which train enters the loop (i.e. has the longer switching time) (NRZ:TWR). It is not clear whether the same priority system applies to waiting time at unmanned loops, or to switching and waiting time at manned loops. Two values for priorities at meets will be tried in the model. One is RPRMET(1,JT,JT) = 0.73 implying that RPRMET(2,JT,JT) = 0.27. (The 1 signifies the up direction, and the 2 signifies the down direction).

This is based on the assumption that the down train has high priority at both waiting and switching times at unmanned loops, and that this is compensated for by giving them low priority at manned loops. Out of the 52 crossing loops 14 are manned and 38 unmanned; thus RPRMET(1,JT,JT) = 0.73. The other value for RPRMET(NO,JT,JT) tested is 0.5 for NO=1 to 2, and all JT. This is based on the assumption that the high priority for down trains in terms of switching times is compensated for by giving them low priority at waiting times at some unmanned loops, so that effectively trains of the same type in each direction have equal priority.

With regard to average number and length of time at compulsory stops; as stated in Section 5.3.4, these were obtained by analysis of the working timetable. Results are as shown in Table 5.10.

Table 5.10 Number and length of compulsory stops

Direction	Train type	Number of compulsory stops	Number of manned compulsory stops	Average time per compulsory stop (mins)
up	Goods	16.588	11.409	9.799
down	Goods	15.694	11.343	10.390
up	mixed	49.0	14.0	3.319
down	mixed	49.0	14.0	3.255
up	passenger	13.0	13.0	10.462
down	passenger	13.0	13.0	9.077

An acceleration time of 2 minutes per stop for each train type was used, following a convention used in the NRZ timetabling department.

Table 5.11 gives the results for delay times from the first run of the model, using the two alternatives for priorities of two trains of the same type at a meet.

Table 5.11 Delays predicted by the first run of the model (all times in minutes)

train type	Total journey time TIMAV	overall delay time	% error	delay due to meets and overtakes	% error
Actual times taken from working timetable					
goods up	1274.778	428.778		210.224	
goods dn	1196.222	357.222		140.088	
combined	2471.0	786.0		350.332	
mixed up	1020	310		21.379	
mixed dn	1037	313		27.49	
combined	2057	623		48.869	
pass up	850	191		2.994	
pass dn	850	173		2.999	
combined	1700	364		5.993	
With RPRMET (1,JT,JT) = 0.73 for all JT					
goods up	1263.958	417.958	2.59	199.424	5.146
goods dn	1147.878	308.878	13.53	91.744	34.51
combined	2411.836	726.836	7.527	291.178	16.888
mixed up	1018.884	308.884	0.36	20.263	
mixed dn	1020.219	296.219	5.36	10.709	
combined	2039.103	605.103	2.87	30.972	
pass up	850.080	191.08	0.042	3.074	
pass up	848.139	171.139	1.076	1.861	
combined	1698.219	362.219	1.177	4.935	
With RPRMET (1,JT,JT) = 0.5 for all JT					
goods up	1210.535	364.535	14.98	146.001	30.476
goods dn	1201.369	362.369	1.441	145.235	3.674
combined	2411.904	726.904	7.518	291.236	16.888
mixed up	1014.122	304.122	2.836	15.501	
mixed dn	1024.982	300.982	3.84	15.472	
combined	2039.104	605.104	2.873	30.973	
pass up	849.112	190.112	0.465	2.106	
pass dn	849.108	172.108	0.516	2.107	
combined	1698.22	362.22	0.489	4.213	

The following points can be noted about the figures in Table 5.11:-

- Total delay times at compulsory stops show no error because values for average time per compulsory stop were calculated from the working timetable in the first place.

- For mixed and passenger trains, the very small amount of stopping time due to meets and overtakes means that the error in calculating that time is unimportant; it is total delay time that matters, and the percentage error for this is given in Table 5.11. For the goods train, on the other hand, total stopping time at intersections is important, and hence percentage error in calculating this is given in Table 5.11. Since train journey times are used by the model to calculate "round trip" times for use in the assessment of rolling stock requirements, and total train hours for crew costs, the percentage errors in total journey times in both directions are also given.
- As predicted, the model underestimates the effects of delays due to intersections for goods trains, which are the low priority trains.
- As can be predicted from the formulae involved (see Appendix 7) total journey time in both directions is unaffected by whether RPRMET(NO,JT,JT) = 0.73 or 0.5. This is because the formulae for train waiting times for Paper Order and Van Schoor assume these times are proportional to RPRMET(NO,JT,JT). For Colour Light signalling, the formula for train waiting time is a function of the square of RPRMET(NO,JT,IT), so total journey times will be affected by the value of RPRMET(NO,JT,JT).

Experiments showed that the best results were obtained from the model if a safety allowance of 2.5 minutes was assumed. These results are shown in Table 5.12.

Table 5.12 Delays predicted by the model with a safety allowance of 2.5 minutes for low priority trains. All times are in minutes

Train type	Total journey time TIMAV	Overall delay time	% error	Delay time due to intersections	% error
	With RPRMET(1,JT,JT) = 0.73 for all JT				
goods up	1301.341	455.341	4.516	236.807	+12.63
goods dn	1164.856	325.856	8.78	108.722	-22.39
combined	2466.197	781.197	0.611	345.529	1.39
mixed up	1022.546	312.546	0.821	23.925	
mixed dn	1022.218	298.218	4.722	12.708	
combined	2044.764	610.764	1.964	36.633	
pass up	850.697	191.697	1.963	3.691	
pass dn	848.367	171.367	0.804	1.366	
combined	1699.064	363.064	0.257	5.057	
	With RPRMET(1,JT,JT) = 0.5 for all JT				
goods up	1237.758	391.758	8.634	173.224	-17.61
goods dn	1228.507	389.507	9.038	172.373	+23.05
combined	2466.265	781.265	0.602	345.597	1.35
mixed up	1016.947	306.947	9.848	18.326	
mixed dn	1027.817	303.817	2.933	18.307	
combined	2044.764	610.764	1.964	36.633	
pass up	849.534	190.534	0.244	2.528	
pass dn	849.530	172.53	0.272	2.529	
combined	1699.064	363.064	1.413	5.057	

It can be seen that, whereas the results obtained for predicted total delay in both directions due to intersections for goods trains produce errors of less than 1.5%, errors in single directions for goods trains are still fairly large. Errors for mixed and passenger trains are regarded as acceptable for single journeys as well as for the total journey time in both directions.

As stated earlier, results of running the model for all three trains working methods will be discussed in Chapter 10. It is therefore necessary to estimate values for a safety allowance for these methods. It is suggested that 2.5 minutes also be used for the Van Schoor token working method. The higher flexibility of Colour Light signalling with Centralised Traffic Control means that the safety allowance for this method can be smaller, and a value of 1.5 minutes is therefore suggested.

For the purposes of the tests in Chapter 10, a decision has to be made as to which value of RPRMET(NO,JT,JT) to use. RPRMET(NO,JT,JT) = 0.5 is chosen, although RPRMET(NO,JT,JT) = 0.73 would produce a model of similar accuracy.

5.5 Late running

It can be assumed that, even with the "safety allowance" described in previous sections built into the timetable, some late running will occur relative to timetabled times. Allowance has to be made for this in the Botswana model.

With regard to other work on the subject, the World Bank does not address the problem in its model, (IBRD 1970), and the problem is outside the scope of Petersen's paper (Petersen 1974).

It is proposed that a parameter, RLATE, is introduced to the Botswana model, representing the factor by which timetabled train times must be multiplied to obtain actual journey times.

No information at all was available as to the amount of late running in Zimbabwe. It is therefore necessary to guess a value for RLATE. It is not unreasonable to suppose that goods trains, with an average journey time of 1235.5 minutes are on average about two hours late. Thus a value of RLATE = 1.1 will be used in the model.

It should be noted that ratios for late running will be used in two situations; one to define overall train speeds, and one for the definition of line capacity. That used for overall train speeds may be regarded as an average, whereas that for track capacity is a maximum. It is the average value which is discussed here, since the journey time input for track capacity is not overall journey time; it is maximum time between crossing loops for each train type. As such, the ratio of late running used in the definition of track capacity will be discussed in Chapter 6.

5.6 Conclusions

In this chapter, a train delay model has been described which takes account of some of the features of a timetable for a less developed country railway which is concerned with transporting goods at low cost, and does not make fast journey times a high priority. The model allows for large switching times. Waiting times are calculated using the assumption that timetablers make no special attempts to coincide intersections with compulsory stops, or to minimise waiting time at intersections by the arrangement of dispatch times (flighting). Despite these conservative assumptions, a large safety allowance at intersections is required to give delay times of the order of magnitude found in Botswana. Simply looking at the average timetabled delays to trains in Botswana, as given in Table 5.6, shows how large these are, and indicates the perceived unimportance of minimising them. The exceptions to this are the higher priority passenger and mixed trains, which carry a small minority of total traffic.

The model also allows for late running relative to timetabled times. Given the inefficiency of many less developed country railways, this allowance could be important.

No information was available on late running in Botswana; therefore conclusions as to accuracy must be limited to the model of timetabled train delays.

The small number of passenger and mixed trains makes it difficult to judge the results for them. Nevertheless, examination of the Working Timetable shows that their waiting times are almost certainly limited to the minimum requirements at compulsory stops, except on the rare occasions when they meet with trains of the same type or, for the mixed train, when there is an intersection with the higher priority passenger train. The priority system RPRMET(NO,JT,IT) and RPROV(NO,JT,IT) can be said to mirror the actual situation well in these situations where one train type has priority over another train type on all occasions; i.e. RPRMET(NO,JT,IT), = 1, RPROV(NO,JT,IT) = 1, and RPRMET(NO,IT,JT) = 0, RPROV(NO,IT,JT) = 0.

The priority system does not define the situation so well when priorities are fractional, as occurs when trains of the same type meet. Too few such meets occur between mixed and passenger trains for conclusions to be drawn about them, but conclusions can be drawn with respect to the goods trains. Table 5.12 shows that, whereas fairly good results can be obtained predicting total delay to goods trains due to intersections in both directions, the same cannot be said of the predictions of delays due to meets in single directions. This is because such values depend on the value of RPRMET(NO,1,1) which expresses priority at meets between goods trains. Values of RPRMET(NO,1,1) which might be expected to be correct for Botswana were tried; viz RPRMET(NO,1,1) = 0.73 and 0.5. Neither of these produced accurate results. An intermediate value of around 0.6 would be likely to produce better results; but there is no reason to suppose that an operator of the model would choose this value for Botswana. It must therefore be concluded that, in situations where several meets occur between trains of the same type, the value given by the model for total delay in both directions is likely to be more accurate than that in one direction. The conclusion only holds for Paper Order and Van Schoor, however, since for these trains working methods waiting time at meets is proportional to RPRMET(NO,JT,IT). As previously explained, waiting time at meets for colour light signalling is proportional to the square of RPRMET(NO,JT,IT). Thus the value of RPRMET(NO,JT,IT) will affect total delay times in both directions for colour light working, as well as those in one direction.

The overall conclusion to this chapter is that a model of train delays has been constructed which can be used for railways like the Botswana line. Particular attention should be given to the values used when defining the priority system. It may be necessary to do a "dummy run" of the model with a safety allowance of zero, and compare results with known data in order to obtain a value for the safety allowance. This value for the safety allowance can then be used when investigating running the railway in different circumstances. An example of the use of such a dummy run was given in Section 5.4.

PART III - CAPACITY MEASURES AND STATISTICS

CHAPTER 6

LINE CAPACITY

6.1 Introduction

Definitions of, and equations for, line capacity, from various sources, including NRZ, will be discussed in this chapter, and a conclusion reached as to the best ones to use in the Botswana model. Definitions can be grouped into two categories which will here be named as maximum capacity and optimum capacity respectively.

The maximum capacity of a line is the maximum number of trains of the required speed mix which can be carried by the line, and is based on the time taken to traverse the longest section. Some equations for maximum capacity take account of peaks in timetabling; a consideration not relevant in Botswana. Optimum capacity is the maximum number of trains which can be run on the line for other reasons, such as to be within safety limits for certain trains working methods, or to incur delays which are within an acceptable maximum to satisfy demand constraints. All these capacity definitions are in terms of trains per day rather than tonnes of goods and number of passengers per day.

Section 6.2 contains a review of other work on the subject of line capacity. Equations to be used in the model are derived in Section 6.3, and the way in which they are incorporated into the rest of the work in Section 6.4. Running the model for Botswana is discussed in Section 6.5, and a conclusion to the chapter is given in Section 6.6.

6.2 Literature Review

Discussion of the literature will be under the headings maximum capacity and optimum capacity, as defined in Section 6.1.

Maximum capacity

Three approaches to maximum capacity will be discussed here; that of Ove Frank (Ove Frank 1975), the Batelle Institute (Batelle), and NRZ's planning department.

Ove Frank (Ove Frank 1975) assesses maximum capacity for a railway where trains in one direction have priority, all trains travel at the same speed, and trains are not dispatched evenly over time. This approach is not relevant to the situation in Botswana, and is not discussed further here.

The Batelle Institute derive a formula for track capacity with the following characteristics:-

- The model is derived initially for two-track lines, and the original derivation is for a line where trains are dispatched evenly over time. Allowances are then made for flighting and peaking of trains.
- The model is modified to produce an equation for capacity of single track lines. In this model it is assumed that dispatches of trains by direction are random.
- The basis of the derivation is the time required between trains on the slowest section between crossing loops. The derivation of a value for this time is based on the assumption that trains can be divided into two speed groups; fast and slow.

An equation for maximum line capacity based on Batelle's, but modified to make it consistent with the rest of the model, is used in this thesis. Therefore further discussion of Batelle's method is left until Section 6.3.

NRZ's planning department define maximum line capacity in terms of the maximum number of slow trains which could get through the slowest section, according to the timetabled point-to-point time for that section. NRZ's formula is discussed further in Section 6.3.

<u>Optimum capacity</u>

It was pointed out in Chapter 5 on train delays that several simulation models exist which simulate individual train movements to produce a model of a working timetable. The level of detail available in such models allows more sophisticated quantification of track capacity. Australia's Train Working Simulator, for example, defines "capacity as determined by market constraints .... This approach implies that the best railway strategy is to attract traffic by running services according to customers' wishes as currently expressed." (Walker and Jones 1975). Another simulation model, MOST, defines capacity in terms of total weighted delay; that is, the total of delays by train class weighted by the importance of delaying that class. (Walker and Jones 1975). Such definitions of capacity are not relevant to this thesis because of the level of detail required.

NRZ have a definition of optimum capacity which is relevant to this thesis. It is a safety limit for the number of trains which can be run with paper order working, and is set at 12 trains each way per day for all NRZ lines using paper order (NRZ 1982). This safety limit is discussed further in Section 6.3.

6.3 Equations to be used for Botswana

Three definitions of capacity will be used in this thesis:-

(i) maximum capacity.

(ii) optimal capacity in terms of a safety limit for a trains working method.

(iii) optimal capacity in terms of maximum delay to a train.

In this section, equations to be used for these definitions will be discussed in the light of the previous literature review.

Maximum capacity

NRZ's formula for maximum capacity is defined as follows:-

$$XCAP = \frac{1440\ RCAP}{(TSLOIT(1,1) + TSLOIT(2,1) + 6)}$$

Equation 6.1

where:-

XCAP	is maximum capacity in number of trains per day
1440	is the number of minutes in the day.
TSLOIT(NO,1)	is the point to point time in minutes for the goods train in direction NO, over the section between crossing loops which gives the largest value for TSLOIT(1,1) + TSLOIT(2,1)
6	is a time allowance in minutes for stopping and starting at the end of the section, and for overlap time between trains.
RCAP	is a safety factor defining the proportion of capacity which can safely be taken up. NRZ use a "rule of thumb" figure 7/12 for colour light signalling, and 1/2 for paper order.

NRZ's formula is not thought general enough for use in this thesis, because it assumes that the large majority of trains run at the same speed as the slowest train. While this is often the case on railways like Botswana, it is thought desirable to produce a more flexible model, which could be used on railways with various mixes of train type. It can, however, be assumed that results obtained with NRZ's formula are acceptable. The more general Batelle Institute formula (Batelle 1981) is now therefore discussed with a view to:-

- modifying the formula so it reflects the situation in Botswana and is consistent with the rest of the operations model.
- giving values for its inputs which will give roughly the same value for capacity, XCAP, for the Botswana line as it stands, as that using NRZ's formula.

It is the slowest average time between crossing loops, for all train types, weighted by number of trains of each type in both directions, which limits capacity on single track lines (see Equation 6.2). The "slowest" section between crossing loops referred to below is therefore the one on which this slowest average time occurs. It is assumed that there are several sections of line with point-to-point times of the same order of magnitude as those on the "slowest" section. The use of a "slowest" section in this way could be said to contradict the assumption in Chapter 5 of uniform point-to-point times across all sections. It is considered justified, however, because of the way the assumption is used. Calculations of line capacity are affected directly by any differences between average and slowest point-to-point times, whereas the effect of uneven point-to-point times on the calculation of delay times is marginal.

The Batelle calculations assume that the order in which trains are dispatched is random. That is, types of train may follow each other in any order, and from either direction. Calculations are done in 4 stages:-

(i) The mean interval between trains travelling in the same direction is calculated.

(ii) The mean interval between trains travelling in opposite directions on a single track is calculated.

(iii) The mean interval between trains travelling in both directions is calculated, using the formulae derived in stages (i) and (ii).

(iv) The capacity of the line is calculated by dividing the total time for which the line is open by the mean interval calculated in (iii), and reducing the result by a safety allowance, discussed further below.

In this thesis, it is assumed that the mean interval as calculated in (iii) is not the one which limits capacity; it is the mean interval calculated in (ii). The reasoning behind this argument is as follows:-

- Because of the assumption of permissive working (see Chapter 5), the interval described in (ii) is always very much larger than that described in (i). A train following one from the opposite direction must wait until the previous train has completed its journey across the whole section, and must also wait for the relevant overlap time. A train following one from the opposite direction, on the other hand, only has to wait for the overlap time. (Overlap times at meets and overtakes were discussed in Chapter 5. For overtakes they include minimum headway).

- Since, as discussed above, many sections on the line have similar point-to-point times to those on the "slowest" section, and since, as discussed in Chapter 5, trains are dispatched at uniform intervals throughout the day, it can be assumed that there will always be at least one section where one train follows another from the opposite direction.

- While the assumptions used here are more pessimistic than those used by Batelle, they are nevertheless less pessimistic than those used by NRZ, in that average journey times over the slowest section are used in capacity calculations, whereas NRZ use journey times of the slowest train over the slowest section.

The assumptions used in the Botswana model thus make it unnecessary to calculate the interval between trains travelling in the same direction. Batelle's four stages of calculations listed above are therefore reduced to two:-

(i) The mean interval between trains travelling in opposite directions.

(ii) The capacity of the line.

These two stages are discussed in turn below. It should be noted that Batelle's original equations included an allowance for peaks in the timetable; these do not apply for railways like Botswana, and this allowance is not therefore discussed further.

(i) The mean interval between trains travelling in opposite directions on a single track

The average time interval between trains is the sum of the average journey times in each direction, plus overlap time, plus acceleration time. Using notation developed in Chapter 5, the equation for the average time interval between trains, TCAP, is given by:-

$$\mathrm{TCAP} = \frac{\mathrm{TPOINT}}{2} + \frac{\sum_{JT=1}^{NTYPE} \sum_{NO=1}^{2} \mathrm{XTEWPD(JT)} \times (\mathrm{TACC(NO,IT)} + \mathrm{TSLOIT(NO,JT)})}{\sum_{JT=1}^{NTYPE} \mathrm{XTEWPD(JT)}}$$

Equation 6.2

where

XTEWPD(JT)	is the number of trains of type JT per day.
TSLOIT(NO,JT)	is the time taken for train JT to traverse the slowest section in direction NO.
NTYPE	is the total number of types of train JT.
TPOINT	is the time taken to switch the points. TPOINT/2 is the overlap time at a meet, for the low priority train.
TACC(NO,JT)	is acceleration time for train JT travelling in direction NO. All times are in minutes.

It should be noted that the time in excess of running times in Equation 6.2 is given by the overlap time at a meet, plus acceleration time, plus safety allowance. Using the values of these for Botswana discussed in Chapter 5, this gives a time in excess of running times of 2 + 2 + 2 = 6 minutes, which is the value used by NRZ (see Equation 6.1).

(ii) Calculating the capacity of a single track line

The capacity of a single track line is given by:-

$$\mathrm{XCAP} = \frac{(1440 - \mathrm{TCLOSE})\ \mathrm{RCAP}}{\mathrm{TCAP}}$$

Equation 6.3

where:-

XCAP	is the maximum number of trains each way per day
TCLOSE	is the number of minutes per day for which the line is closed for maintenance
TCAP	is the minimum dispatch time in minutes between trains as given by Equation 6.2
RCAP	is the safety allowance

Two points can be made about RCAP:-

- It must account for all safety considerations. Because of this, the safety allowance at an intersection defined in Chapter 5 has not been included in the calculation of the minimum interval between trains, TCAP (see Equation 6.2).

- It can be compared to the ratio for late running RLATE, defined in Chapter 5. As discussed in that chapter, RLATE depicts average late running over the whole line. RCAP must include maximum likely late running over a section, and a safety allowance. RCAP will normally be smaller than the reciprocal of RLATE.

Optimal capacity: Safety limit due to trains working method

As was stated in Section 6.2, NRZ define a safety limit for number of trains which can be run with paper order working. This limit is set at 12 trains each way per day on NRZ lines. However, this safety limit is likely to depend on number of intersections between trains on the line, and number of intersections between trains will change if any investments on the line result in different average journey times. To provide a safety limit which would be applicable in all circumstances, therefore, number of intersections on the line is used in the model, as the safety limit. The initial value for number of intersections is obtained by calculating the number of meets which would occur if 12 goods trains ran on the Botswana line each way per day, and no other trains ran. The equation used for this calculation is Equation 5.1 from Chapter 5:-

$$XMEET(NO,JT,IT) = \frac{(XTEWPD(IT))}{(1440 - TCLOSE)}(TIMAV(NOP,IT) + TIMAV(NO,JT)) \qquad \text{Equation 5.1}$$

where:-

XMEET(NO,JT,IT)	is the number of meets between train JT travelling in direction NO with trains of type IT travelling in the opposite direction.
XTEWPD(IT)	is the number of trains of type IT each way per day.
TCLOSE	is the number of minutes per day for which the line is closed; this is zero for Botswana.
TIMAV(NO,JT)	is the average journey time in minutes for a train of type JT travelling in direction NO.

A problem arises in deciding on a value for average journey time for these calculations. If 12 goods trains each way per day were run on the line, then their average journey time would be longer, because of the extra meets, than it is at present with 8.7143 goods trains, 1 mixed train and 0.2857 passenger trains, i.e. 10 trains each way per day.

A rough idea of the increased journey time can be obtained by assuming that, if number of trains each way per day is increased from 10 to 12, then the number of intersections will increase by a factor of 1.2. (This is a slight underestimate as it assumes that the number of trains encountered is based on the old journey time). If average delay per intersection is assumed the same for each type of intersection, then total delay due to intersections will be increased by a factor of 1.2.

From Table 5.10 in Chapter 5, delays due to meets and overtakes for the goods trains are given by:-

210.244 minutes in the up direction, and
140.088 minutes in the down direction.

Multiplied by a factor of 1.2, these delay times become:-

252.293 minutes in the up direction, and
168.1056 minutes in the down direction.

Present average journey times for goods trains in Botswana are:-

1274.778 minutes in the up direction, and
1196.222 minutes in the down direction.

Figures for average journey times to be used in the capacity calculations therefore become:-

1316.827 minutes in the up direction, and
1224.2396 minutes in the down direction.

(note that these calculations use timetabled journey times, without an allowance for late running).

Substituting these journey times, and the values 12 and 0 for XTEWPD(IT) and TCLOSE respectively in Equation 5.1, a value for maximum number of intersections, XINTMX, which can be allowed for safety reasons can be obtained:-

$$\text{XINTMX} = \frac{12}{1440}\,(1316.827 + 1224.2396)$$

$$= 21.175$$

or 21 to the nearest whole number.

A value of 21 for maximum number of intersections is recommended for the paper order method. The same value is recommended for Van Schoor token working. It is thought unlikely that a maximum need be put on number of intersections with colour light; therefore it is recommended that a negative number be input for this method, indicating that the test need not be done. The operator of the model is, of course, free to use other values for XINTMX as required.

Optimal capacity : delay times

As stated in Section 6.2, some models, such as the Australian ones described there, define a maximum acceptable delay to trains as a measure of capacity.

In railways such as the Botswana line, journey time is not often considered important in its own right, insofar as it is the amount of goods which can be shifted per day, rather than journey time, which matters. (The importance of journey time as it affects number of intersections is very important but is accounted for by the previous test). However, users of the model may sometimes wish to know the effect of certain investments on journey times, particularly for high priority trains. One of the output files produced by the model therefore contains delay times and total journey times for all train types.

6.4 Incorporating equations used to describe capacity into the model

The following operations are performed by the model:-

- Maximum capacity of the line, XCAP, is calculated. The number of trains on the line is compared with this value, and a message output giving the number of trains, and saying what percentage of maximum capacity is used.
- The test for maximum number of intersections is optional. Where it is used, actual number of intersections is output, with the percentage of maximum number of intersections that this represents.
- Delay times for each train type, together with total journey times, are included in one of the output files to the model. An example of this file is given in Chapter 10.

6.5 Running the model for Botswana

Most inputs to the track capacity model are calculated from previous outputs from the model. However, the following inputs are required.

- The allowance for late running and safety used in the calculation of maximum capacity. As stated in Section 6.1, this takes the value 0.5 for Paper Order, as defined by NRZ's planning department.

- The maximum number of intersections. As discussed in Section 6.3, this takes the value 21 for Paper Order.

The results of running the capacity model are given in Table 6.1. (Delay times are given in the output for the model as a whole, in Chapter 10).

<u>Table 6.1 Results of running the model for line capacity</u>

Number of trains		Number of intersections	
maximum	%utilised	maximum	%utilised
11.544	86.627	21.0	88.532

As with some of the calculations described in Chapter 3, a comparison of the results obtained by the model with those obtained by NRZ only allows a check that the figures are of the right order of magnitude since there is no reason for regarding NRZ's formula as more accurate than that of the model.

With regard to maximum number of trains per day as dictated by running times on the slowest section; NRZ's formula would, as expected, give a slightly lower value for this than the one given by the model; their value would be 11.25 as compared with the model's value of 11.544. Figures for capacity of the Botswana line are available in detail for 1980-81 and 1982-83 from an internal NRZ document (NRZ: planning 1981). For 1980-81, actual capacity for the Botswana line was given as being 12.0 trains for all parts of the line except one (Ramatlhabama to Mahalapye) where it is 10.9 trains. For 1982-83, predicted capacity is given as being 12.0 trains for all parts of the line. Since the figure of 11.25 obtained from NRZ's calculation, and 11.544 from the model's calculation is obtained using point-to-point times in the Ramatlhabama to Mahalapye area, these values can be regarded as being of the right order of magnitude.

With regard to the value for optimal capacity; since this was obtained directly from that used by Botswana, it is likely to give the same results, except that it is expressed in number of intersections per train instead of number of trains each way per day.

6.6 Conclusions

In this chapter, measures of capacity have been developed which use three types of limiting factor; run-times on the slowest sections; number of intersections which can safely be handled; and delay times. Of these, the most common measure is likely to be the one based on run-times. The model therefore always calculates this measure, whereas the other two calculations are optional.

The run-time capacity measure includes a safety allowance which must account for all likely operating problems which might affect the use of the line. As discussed in Chapters 1 and 2, less developed countries often have severe operating problems, and therefore for many of them, including Botswana, this safety allowance will be quite large. It could be argued that safety factors of this order of magnitude indicate that the model for track capacity itself could be very rough. This is not the view taken in this thesis, however. It is considered important that optimal running of the railway is accurately represented, so that the effects of varying levels of efficiency can be estimated.

The other two measures of capacity make use of the train delay model described in Chapter 5. The measure for number of intersections does so indirectly, since number of intersections is a function of train journey times, and the one for maximum delay does so directly. It has been pointed out previously that train journey times may not of themselves be important on a less developed country railway. However, for any railway with operating problems, and therefore a good deal of late running, the number of timetabled intersections becomes particularly important, as it is the extra time required at an intersection with a late train which is likely to mean that there is a cumulative effect whereby one late train makes another late. This will particularly be so with a line using low technology trains working methods, where communications do not allow the rescheduling of meets and overtakes to occur at loops other than the ones at which they were timetabled. Therefore, in the runs of the model representing the Botswana line, limits to number of intersections will only be stipulated for the low technology trains working methods. This reflects practice in NRZ, where there is a "safety limit" for the paper order token working method.

CHAPTER SEVEN

OPERATING STATISTICS

7.1 Introduction

This chapter can be seen as a "bridge" between the chapters on the operations model and those on the cost equations. It describes how statistics used in the cost equations are obtained either from the operations model, or directly from railway data. Rolling stock requirements are discussed in Section 7.2, and other statistics in Section 7.3. Explanation of the way these are used in cost equations is left until Chapter 8.

7.2 Rolling stock requirements

7.2.1 Equations for rolling stock requirements

Rolling stock requirements are calculated separately for each type of locomotive used in line haul, and each type of wagon and carriage. Yard locomotive requirements are not calculated by the model; as discussed in Chapter 8, they are included in a general equation for yard costs. Where a locomotive is used both for yard working and for main-line working its representation in the model will therefore be partly as a fractional locomotive requirement for line haul, and partly as a factor affecting the size of parameters in the yard cost equation.

Calculations for rolling stock requirements are discussed as stages (i) to (iv) below, and the equations for each stage given in Table 7.1.

(i) The "block time" is calculated; that is, the time it takes for a car or locomotive to do a "round trip" journey from one end of the line to the other and back. For wagons and carriages, the block time must include yard time as well as journey time. Since journey time depends on train type, block time is calculated separately for each train type.

(ii) Each single train may be regarded as having one "set" of wagons and carriages, and one "set" of locomotives. The total number of "sets" required for each train type is given by the proportion of a total day taken up by a block time, multiplied by the number of trains of that type per day.

(iii) Requirements for each type of rolling stock on each train type are calculated by multiplying the number of vehicles per train by the number of sets of each type of vehicle. This gives numbers for rolling stock which would be required if the stock spent 100% of its time in productive use. The numbers must therefore be increased by ratios which allow for maintenance, overhaul, standby, yard time and unproductive use. In order to identify the best ratios to use in this context, the statistics used in Zimbabwe are discussed below, and compared with the ratios used in the World Bank model of Colombia (IBRD 1970), which makes similar calculations. Locomotives are discussed separately from wagons and carriages.

<u>Locomotives</u>

Using information from NRZ's statistic system, TREND, two ratios can be defined for locomotives:-

RLUF Ratio of unproductive to total locomotive hours. This is the time an available locomotive spends waiting to be used, and depends on train schedules.

RMNLOC Ratio of time spent in maintenance to total locomotive time.

The World Bank uses similar concepts for locomotive utilisation and maintenance, although its ratios are defined slightly differently.

<u>Wagons</u>

NRZ provide figures for the proportion of total wagon time spent in maintenance. This proportion will be used in the model, and defined as RMAINT. The World Bank model defines a similar maintenance ratio.

(iv) Total rolling stock requirements are obtained by summing rolling stock requirements for each train type.

Table 7.1 Calculations for rolling stock requirements

(i) Block time

For locomotives

$$TBLCLC(IKLOC,IT) = TIMAV(1,IT) + TIMAV(2,IT)$$

Equation 7.1

For wagons and carriages

$$TBLCWG(IKMAT,IT) = TIMAV(1,IT) + TIMAV(2,IT) + TYARD(IKMAT)$$

Equation 7.2

(ii) Number of sets per train

For locomotives

$$XSETLC(IKLOC,IT) = (XTEWPD(IT))\frac{(TBLCLC(IKLOC,IT))}{(1440 - TCLOSE)}$$

Equation 7.3

For wagons and carriages

$$XSETWG(IKMAT,IT) = (XTEWPD(IT))\frac{(TBLCWG(IKMAT,IT))}{(1440 - TCLOSE)}$$

Equation 7.4

(iii) Number of vehicles required per train

For locomotives

$$XLOC(IKLOC,IT) = \frac{((XSETLC(IKLOC,IT))(XL(IT)))}{(1 - RLUF - RMNLOC(IKLOC))}$$

Equation 7.5

For wagons and carriages

$$XCAR(IKMAT,IT) = \frac{(XSETWG(IKMAT,IT))(XWGTRN(IKMAT,IT))}{1 - RMAINT(IKMAT)}$$

Equation 7.6

(iv) Number of vehicles required

For locomotives

$$XLOCRQ(IKLOC) = \sum_{IT=1}^{NTYPE} XLOC(IKLOC,IT)$$

Equation 7.7

For wagons and carriages

$$XCARRQ(IKMAT) = \sum_{IT=1}^{NTYPE} XCAR(IKMAT,IT)$$

Equation 7.8

where:-

TBLCLC(IKLOC,IT)	is block time for locomotives of type IKLOC pulling trains of type IT.
TBLCWG(IKMAT,IT)	is block time for wagons of type IKMAT on trains of type IT
TIMAV(NO,IT)	is average journey time for train of type IT travelling in direction NO.
TYARD(IKMAT)	is average yard time per trip for wagons of type IKMAT.

XSETLC(IKLOC,IT)	is number of sets of locomotives of type IKLOC required for trains of type IT.
XSETWG(IKMAT,IT)	is number of sets of wagons of type IKMAT required for trains of type IT.
XTEWPD(IT)	is number of trains of type IT each way per day.
TCLOSE	is number of minutes per day for which the line is closed.
XLOC(IKLOC,IT)	is total number of locomotives of type IKLOC required for train type IT.
XL(IT)	is number of locomotives per train of type IT (note all locomotives on one train are assumed to be the same type)
RMNLOC(IKLOC)	is the ratio of time spent in maintenance and overhaul to total time, for each locomotive of type IKLOC.
RLUF	is the ratio of unproductive to total locomotive hours.
XCAR(IKMAT,IT)	is total number of cars of type IKMAT required for train type IT.
RMAINT(IKMAT)	is the ratio of time spent in maintenance, overhaul and standby to total time for each wagon and car of type IKMAT.
XWGTRN(IKMAT,IT)	is the number of wagons or carriages of type IKMAT in train type IT (obtained from the operations model).
XLOCRQ(IKLOC)	is number of locomotives of type IKLOC required by the railway.
XCARRQ(IKMAT)	is number of wagons or carriages of type IKMAT required by the railway.
NTYPE	is total number of train types.
	All times are in minutes

7.2.2 Running the model using data from Botswana

Locomotives

As stated in Section 7.2.1, NRZ keep figures for ratios of locomotive time spent in maintenance (RMAINT(IKMAT)) and spent idle (RLUF) in a statistics system known as TREND. For reasons of confidentiality the latest statistics available in 1982 were those for July 1975-6 which gave statistics for the preceding five years, as shown in Table 7.2 below.

Table 7.2 Ratios for locomotive utilisation and maintenance

Year (to end June)	Non-Utilisation RLUF	Maintenance RMAINT
1972	0.23	0.15
1973	0.20	0.20
1974	0.18	0.36
1975	0.20	0.36
1976	0.22	0.41

It can be seen that these show a marked progressive increase in time spent in maintenance. Discussion with mechanical engineers made it evident that the increase in maintenance time over this period was due to lack of spares in the 1970's, as a result of sanctions. Although this problem has now been solved it has been replaced by a problem of lack of skilled repair staff. Informal enquiries in the statistical department resulted in the information that there were no major differences between figures for the years 1974-6 and those for the following five years. Taking an average for the years 1974-6 a value of 37.7% can be assumed typical for RMAINT in NRZ. There is no reason to suppose thát the value for RMAINT in Botswana alone would be any different from that on the whole NRZ network, so this figure can be taken as representative for Botswana.

The locomotive utilisation factor, RLUF, on the other hand, depends on scheduling of trains, so might be different for Botswana alone. If anything it would probably be slightly higher as scheduling of locomotives for trains is likely to be less flexible the smaller the network. However, in the absence of further information the average value for RLUF in NRZ for the years 1972-6, i.e. 20.6% will be taken as typical for Botswana.

Wagons and carriages

A member of NRZ planning department stated that when assessing wagon requirements an 8% allowance is made for maintenance cover of wagons and carriages, except for refrigerated wagons, for which an allowance of 12% is made. These will be the figures used for RMAINT for wagons in the Botswana run of the model. This order of magnitude is backed up by a Transmark report on the Botswana takeover (Transmark 1980) which suggested maintenance cover of 10%.

NRZ give a predicted figure of 60 wagon-km per wagon day for 1982 (NRZ Planning 1981(ii)). They considered this to be low, due to lack of locomotive power provision, and expected a progressive increase to 90 wagon-km per wagon day by 1986. Nevertheless, it is the 1982 figure which is used here. It is possible to "work backwards" from this figure to obtain a value for time spent in yards, TYARD. It is 25568 minutes, or 17.76 days per wagon trip, for each wagon type. No figures were available for carriages, but it can be assumed that they will spend less time in yards and terminals than do wagons. An arbitrary yard time of 6000 minutes per carriage will therefore be used in the model.

Results

Locomotive, wagon and carriage requirements for Botswana are given in Table 7.4, below. It is not possible to compare these with actual requirements for Botswana, as these are not assessed separately from the rest of the network. However, Table 7.4 gives figures for NRZ as a whole, and the percentage of that figure given by the Botswana model. The range of acceptable percentages is discussed in Section 7.4; and those of 15.38% for locomotives and 15.5% for wagons are considered acceptable. It should be noted that all actual wagon requirements for NRZ and Botswana are made with reference to wagon-sharing agreements with other countries; a factor outside the scope of the present model.

7.3 Other statistics

Statistics produced by the model for use in the cost equations are listed in Table 7.3, together with the values obtained for them in Botswana. Values available for the same statistics for NRZ as a whole are given in Table 7.4, together with the percentage of these obtained for the Botswana model. A detailed comparison of these figures is not possible, as they will be affected by differences in operating and traffic characteristics found over the NRZ network. However the following points can be made:-

- Gross tonnes and gross tonne-km calculated by the model for Botswana are likely to be reasonably accurate, because they involve fairly simple calculations using directly obtained data. Given that these figures are 17.89% and 24.15% of NRZ's totals respectively, the fact that values for number of vehicles and vehicle-km are within the range 15.38% to 20.8% of NRZ's totals indicates that they are of the right order of magnitude.
- Given that the average length of haul in Botswana is 132.6% of that for NRZ as a whole, the figures of 128.28% for locomotive-km per locomotive, and 138.36% for wagon-km per wagon are of an acceptable order of magnitude. It implies that the number of journeys per vehicle in Botswana are similar to those for NRZ as a whole.

It can be concluded in general that the calculations for statistics to be used in the cost equations produce figures of the right order of magnitude.

Table 7.3 Statistics obtained from the model for Botswana

All statistics per year

Total gross tonnes including locomotives	5095652
Total gross tonnes excluding locomotives	4429813
Total gross tonne-km including locomotives	3270578018
Total gross tonne-km excluding locomotives	2843218007
Total train hours	125400
Total train-km	3722648
Length of line including crossing loops	665

Rolling stock statistics

Vehicle type	Number of Vehicles	Vehicle-km	Vehicle-km per Vehicle	Number of journeys
Wagons				
Gen purpose	1750	36886372	21078	28735
Acid	4	69318	17330	54
Ammonia Anh	15	309365	20624	241
Bitumen (tar)	19	383819	20201	299
Edible oil	3	53914	17971	42
Petrol (std)	71	1498048	21099	1167
Diesel (std)	138	2904954	21050	2263
Avgas (std)	4	69318	17330	54
Paraffin (std)	1	16688	16688	13
LPG	3	46212	15404	36
Tallow	7	137353	19622	107
Refrigerated bunker	0	0	0	0
Refrigerated mechanical	17	342741	20161	267
Resin containers	5	93708	18742	73
Coach	116	8234762	70989	6415
Locomotives				
DE2	36	3722648	103407	

Notes

(i) Gross tonnes, gross tonne-km, train-hours and train-km are for both directions.

(ii) Number of journeys is based on round trip.

(iii) Reasons for differences in vehicle-km per vehicle for wagons taken only on the goods train (all wagons except general purpose and refrigerated mechanical) is that number of vehicles is rounded up to a whole number before the division.

Table 7.4 Statistics for the whole NRZ network for 1981

Statistics are taken from NRZ Facts and Figures (NRZ 1982) unless otherwise stated.

Statistic (and units)	Calculations involved	Figure for NRZ	% obtained by the Botswana model (see Table 7.3)
Gross tonne-km	Directly available	13541000000	24.15
Gross tonnes	Net tonnes x $\frac{\text{gross tonne-km}}{\text{net tonne-km}}$	28489148	17.89
Average length of haul (km)	Directly available	484	132.6
No. of locos for line haul	Total locos x proportion of time spent in line haul (see note 1 below)	234	15.38
No. of wagons	Directly available	13888	15.5
Wagon-km	Two means of calculation:- $\frac{\text{net tonne-km}}{\text{average wagon load}}$	211214060	17.5
	$\frac{\text{net tonnes x average haul length}}{\text{average wagon load}}$	215078470	17.2
Wagon-km per wagon	$\frac{\text{wagon km}}{\text{no. of wagons}}$ (2 values because 2 values for wagon km)	15208 15487	138.36 135.87
Locomotive-km	Directly available	17896000	20.8
Locomotive-km per locomotive	$\frac{\text{Locomotive-km}}{\text{no. of locos for line haul}}$	80613	128.28

notes

(i) ANOP gives hours spent in line-haul and yards respectively, for steam, small diesel, and large diesel locomotives. Steam and small diesels spend about half their time in line-haul, and large diesels 90% of their time. The ratio of large to small diesels is not known. It will be assumed that diesels as a whole spend about 70% of their time in line-haul. Since NRZ Facts and Figures give numbers of steam and diesel locomotives separately, it is possible to assess numbers of each type required for line haul, and add them.

PART IV - COST EQUATIONS

CHAPTER 8

FORM OF COST EQUATIONS TO BE USED IN THE MODEL

8.1 Introduction

The purpose of this chapter is to produce equations for railway costs, divided into the main categories of operations. Within each category cost equations will take the form of functions of the main operating statistics on which they depend. Particular care has been taken to include in these functions those statistics which can be changed by the investments which the model is designed to examine. (This reflects the general problem, discussed in Chapter 2, that cost equations vary according to the purpose for which they were designed).

Ideally, econometric methods would be used on data from NRZ and Botswana to establish the form of each equation. However, this would have required detailed information on the various costs over a long period of time, and such information was not available from NRZ. Some information from NRZ was of use, and will be incorporated into the discussions of individual costs in Section 8.6. This information came from general discussions with NRZ personnel on railway operations, NRZ's costing system, SECT and ANOP, and NRZ's accounting system. These sources are among those discussed in Section 8.2, the literature review. In Section 8.3 some general characteristics of cost equations in the model are listed. Section 8.4 lists categories of costs used in the model, and the relative importance of each of those categories. Section 8.5 deals with the treatment of capital, and Section 8.6 discusses individual costs and the production of cost equations. The chapter ends with a conclusion in Section 8.7.

8.2 Literature Review

The review in this section is limited to a discussion of those costing systems used as sources to derive categories of costs and cost equations for this model. A more general review of railway costing systems has already been given in Chapter 2. The costing systems used in this chapter are:-

- The World Bank model of Colombia (IBRD 1970).

- Frederick Sander's report on Railway Traffic Costing (Sander 1974).
- Majumdar and Blore's comparison of road and rail in Sri Lanka (Majumdar and Blore 1981).
- NRZ's own costing systems, ANOP and SECT.

A general discussion of each of these systems is given in this section. Where they are of use in this thesis, categories of costs used by these cost systems, and the form of their cost functions, are discussed in Sections 8.4 and 8.6 respectively.

<u>The World Bank model of Colombia</u>

The aim of this model is similar to that of the present thesis, viz:- "the model can be used to analyse present conditions along with alternate proposals", in other words, to investigate the effect of various investments. As such, categories of costs are similar to those used by the model in this thesis. However, the work does not discuss the rationale behind its choice of units of variability. The inadequacy of the resultant cost equations has already been discussed in general terms in Chapter2, and will become apparent in terms of specific equations in Section 8.6 of this chapter.

<u>Sander - railway traffic costing</u>

Sander's work consists of a general discussion of railway costing to encompass any or all of the aims for which a railway costing system may be designed. (His list of these aims was reproduced in Chapter 2 of this thesis). As such, his discussion of the factors affecting costs is often useful, particularly as it is based on information from several railways, most of them in developing countries. However, some details he provides, such as his suggestion for treatment of capacity costs which occur when a railway has not made all possible short-run adjustments to a change in operations, are not required for this thesis. Also, because he is concerned with costing systems for rate-making he splits costs, often on the basis of allocation between passenger and freight in a way that is not necessary for this thesis.

Sander's cost categories are formed by breaking costs down in detail, based mainly on the way accounts are kept, and then amalgamating costs under headings according to the parameters with which they vary. For example, freight-car (wagon) costs are divided into distance-related costs, time-related costs, and interest on capital. In this thesis, a categorisation more closely linked with the way costs are incurred in various railway operations will be used. Thus, wagon costs are divided into maintenance costs and depreciation costs, both of these categories having a time-related and distance-related element.

Sander also discusses estimation of changes of inputs to the cost equations, such as gross tonne-km, as part of the costing exercise. In the present thesis such estimation is done by the operations model, as described in Chapters 3, 4, 5 and 7.

Majumdar and Blore

As stated in Chapter2, Majumdar and Blore's study is designed to establish the best modal split between road and rail, and hence the best area for investment. This means that, for the purposes of this thesis, they overemphasize the importance of scale. However, they aim to produce cost equations for investment purposes, applicable to "various situations and various unit prices elsewhere". Their cost categories and equations are, therefore, useful to this thesis. Their study also serves as an illustration of the problems of obtaining data in less developed countries.

NRZ's costing system (ANOP and SECT)

NRZ's costing system is in two parts. ANOP produces cost figures for the whole network, and SECT divides these figures into regions, by allocation on the basis of vehicle-km, crew-km etc. SECT is not therefore useful to this thesis.

ANOP gives predicted annual costs, using the previous year's accounting costs as a basis. As discussed in Chapters 1 and 2, ANOP is designed mainly to aid rate-making, and on the assumption that no major changes in operating characteristics will occur. Thus, both the categorisation of costs and the statistics on which costs are based are unsuitable for this thesis. However, the present model should include all costs which are used in ANOP's total, and it will be seen in Section 8.4 that it has been possible to use ANOP as a "cross-reference" to ensure that cost categories used in this thesis include all railway costs, and that each cost is included only in one category. Also, some of the costs used in ANOP were used in calibrating the equations in the model, as described in the Confidential Annexe attached to Chapter 9.

To conclude, the categorisation of costs will be based on separating out railway operations, and will be similar to the categories used by Majumdar and Blore and the World Bank model of Colombia. In Section 8.4 a "cross-categorisation" will be performed using ANOP to make sure that all costs are included in a category, and that there is no double counting of any costs by their inclusion in more than one category. Within the categories, cost equations will be produced, as functions of the parameters on which they depend. These equations will be based on discussion of operations with NRZ staff, on Sander's generalisation, on the work of Majumdar and Blore, and occasionally on the work of the World Bank. This will be done in Section 8.6.

8.3 General characteristics of cost equations in the model

Cost equations produced for the model exhibit the following features:-

- They are a function of the parameters which will affect them even if the operating characteristics of the line are changed. This means that costing systems devised for different purposes, such as rate-making, with the assumption that operating characteristics remain unchanged, are often irrelevant. This problem was discussed in Section 2.4 of Chapter 2.
- They consist of fixed and long-run variable costs, where long-run variable costs are defined as those that are incurred when a railway has fully adjusted to any change in operating characteristics. Following the convention used by Sander (1974), costs which vary in proportion with a unit are described in the discussion in this chapter as "directly variable" with that unit. Those which vary by a less than proportionate amount are described as "indirectly variable" with that unit. The fact that long-run variable costs are used in the cost equations implies that the model must be used as a "comparative statics" model; no

time-link is assumed between runs of the model, and no facilities are therefore provided to examine dynamic adjustment. Thus, for example, if two runs of the model are done, the second resulting in lower rolling stock requirements than the first, it will not be assumed that, say, the second represents a change over time from the first run. Therefore no indications will be given as to costs of adjustments from the first to the second run, such as the cost of paying rolling stock maintenance staff who cannot be laid off when rolling stock requirements are reduced. Thus, resources such as rolling stock maintenance staff which are variable in the long-run are assumed by the model to be used to capacity. The infrastructure of the railway is not always assumed to be used to capacity. The treatment of line capacity by the model has already been discussed in chapter 6. Yard capacity will not be investigated as it is outside the scope of the model.

- Costs which are fixed for a railway regardless of any changes in operating conditions can, in fact, be set to zero when the model is run if no information is available as to their value. This means that costs produced by running the model several times to investigate different investments will be reduced by the same absolute amount, so that comparisons can still be made between them. In Section 8.6 it is made clear which fixed costs can be set to zero. These include, for example, administrative costs apart from administration of the trains working method, and depreciation costs of the main station buildings.
- Since the model is one of line operations, it is only line costs which are provided in any detail. The equations provided for yard and administration costs are very simple.
- All capital costs are converted to an annual equivalent. Thus capital costs are assumed to be the same in each year of an asset's life.
- Maintenance costs are produced on the assumption that the assets being maintained are a mix of ages, so that age-related maintenance costs even out to an average cost over time. Thus for example it is assumed that at any one time the mix of age of rolling stock will be the same, so that the extra costs of maintaining old stock will be offset by the low costs of maintaining new stock, and "average" rolling stock maintenance

costs can therefore be produced without regard to the age of stock. Such a mix of ages will not, of course, always occur on a railway. However, the assumption is still justified since the output required from the model is average yearly cost, and the average yearly maintenance cost is that which will occur with an average mix of ages of stock.

- For some costs, there is a certain "lumpiness", as for example in track maintenance costs where, once traffic reaches a certain level, a new tamper and new gang to work it is introduced. At first sight, a "stepwise" cost function would seem to reflect such a situation best, with costs going up a "step" for each new tamper introduced. However, this would mean that costs would on occasion increase by large amounts for only small variations in traffic. This makes it difficult for the operator of the model to interpret results. Smooth, continuous functions are therefore preferred for cost equations.
- Since the model is designed to be run with simple input data, the cost equations must be structured in such a way as to reflect the way that costs are likely to be categorised in railway accounts. In order to maintain this simplicity certain details have to be sacrificed. These are listed below, with an indication as to why their exclusion is considered justified.

  (i) Equations will not always be split up into resources required multiplied by unit costs of that resource. For example, total costs of locomotive maintenance will be obtained from an equation which is a function of fixed costs, unit costs per locomotive per year, and unit costs per locomotive-km per year (see Section 8.6.2). It would be possible to break down these unit costs into resources used per unit multiplied by the cost of the resource. Resources used would include staff hours used in each labour grade and materials. Such a breakdown would have both advantages and disadvantages. The advantages are that it would allow the effect of changes in unit costs of resources to be readily incorporated into the model and that it would allow requirements of resources in short supply, such as certain grades of skilled labour, to be estimated. These must be set against the major disadvantage that the information required for such a breakdown would be difficult to obtain. The more simple cost equation is therefore used.

(ii) As discussed in Section 2.4 of Chapter 2, the fact that costs are not broken down into individual resources and unit costs of those resources, means that it is not possible to use shadow pricing techniques for labour and foreign exchange. The model uses one interest rate, as described in Section 8.5 on the treatment of capital. Since this interest rate is input by the operator of the model, a shadow rate of interest can be used if desired.

(iii) No costing is made of externalities to the system, such as pollution. Few externalities are likely to be regarded as significant for most developing countries.

Points (ii) and (iii) combined mean that the model will output market costs, except on those occasions when it is run with a shadow rate of interest.

(iv) Cost equations will be calibrated by the user of the model directly from data available in that country. This precludes making any distinction between costs when the railway is run efficiently, and extra costs due to inefficiency. Unlike the operations model described in earlier chapters, therefore, there are no inefficiency parameters used in the cost equations.

8.4 Categories of costs

The categories of costs used in this thesis are as follows:-

Rolling stock

- Depreciation of locomotives
- Depreciation of wagons and carriages
- Locomotive maintenance
- Wagon and carriage maintenance

Track

- Track renewal
- Track maintenance

Trains working method

Crew

Yards and terminals

Fuel

Administration

All costs will be expressed as annual costs.

ANOP's major cost categories are as stated before, completely different from those given above. Fortunately, ANOP provides a breakdown of these costs into the initial predictions given by the accounting department, and this gives enough information to produce values for costs for NRZ as a whole in categories which roughly correspond to the ones used in this thesis. Table 8.1 shows the relationship between ANOP's cost categories and the ones used in this thesis. Figures are from the fifteenth edition of ANOP and contain predictions for the year 1982. It was not possible to obtain information from any other edition of ANOP, due to the confidentiality of the costing system. Percentages of total costs are given, in order to indicate the relative size of each cost category in ANOP. However, the high level of aggregation of the information available from ANOP means that the categories will not contain exactly the same costs as those contained in the separate equations described in Section 8.5. For example, the administration cost category described in Section 8.5 contains only fixed costs; all variable administration costs should be assigned to other cost categories. The large size of the administration cost produced in Table 8.1 on the other hand implies that it is based on a broader definition of administration than that used by this thesis.

Figures for NRZ will give some indication of relative costs on a railway with similar operating characteristics and unit costs, like Botswana, but should only be taken as a rough guide. Even for NRZ, 1982's figures cannot be taken as average for any year without further investigation. In particular, depreciation costs are likely to have been relatively low in 1982, because NRZ's problems in obtaining new stock during the war years would not have been overcome by then; thus many capital goods were in use for longer than their optimum economic life. Maintenance costs are likely to have been high, both because stock was so old, and because of the scarcity of spares and skilled staff.

From Table 8.1 it can be seen that costs included in categories in the thesis form 99.65% of total costs, provided that the categories overheads (locomotives) and other wagon costs (tarpaulins) are included in one or other of the equations for rolling stock. (Even if they are excluded, this only introduces an error of 0.721% of total costs). Thus, the categorisation described above can include all railway costs, provided a careful examination is made of costs included in each category.

Table 8.1 A "cross-reference" of ANOP's cost categories with those used in the thesis

Categories used in the thesis; percentage of total costs	ANOP's categories; percentage of total costs: Vehicle haulage	Conductors	Track infra-structure	Other general	Vehicle costs	Free haul costs	Total terminal	Mech refridg	Admin	Total
Finance and hire of locos	3.0									3.0
Locomotive maintenance	7.7									7.7
Overheads (locomotives)	0.3									0.3
Finance and hire of wagons and carriages					2.7					2.7
Wagon and carriage maintenance					6.9					6.9
Other wagon costs (tarpaulins)					0.5					0.5
Track renewal			1.7	3.5						5.2
Track maintenance			7.9							7.9
Trains working methods			1.6	5.8						7.4
Crew	5.0	0.4		3.2						8.6
Yards and terminals							21.5			21.5
Fuel	9.5									9.5
Administration									18.5	18.5
Total used in thesis										99.7
Less ballast costs (double counted)	0.2									0.2
Less free haul costs	1.4		0.7	0.7	0.7	total of prev 5 cols				
Plus costs omitted from thesis				0.3				0.3		0.6
ANOP total costs	23.8	0.4	10.6	12.0	9.4	3.5	21.5	0.3	18.5	100.0

note: ballast costs have been double counted because they are difficult to extract from the categories in which they appear, and because their small size means that the error incurred by double counting them is small.

8.5 The treatment of capital costs

For goods requiring a capital outlay, an annual cost, CAN, must be calculated sufficient to cover the cost of this outlay, plus interest. The interest rate may represent interest on a loan, or interest which the railway loses by having to buy equipment with its own capital, rather than investing it. The annual cost, CAN, is calculated assuming equal payments each year; even if this is not the way in which capital is paid back, it is required for the thesis, and indeed for most railway costing systems, that capital costs be "evened out" in this way. It is also assumed that the rate of interest, RINT, is constant over the economic life of the asset. The formula for the annual equivalent cost of capital, CAN, is then given by:-

$$\mathrm{CAN} = \frac{(\mathrm{CPRES} - (\mathrm{CSCRAP}/(1+\mathrm{RINT})^{\mathrm{XLIFE}}))\ \mathrm{RINT}}{1 - (1 + \mathrm{RINT}^{-\mathrm{XLIFE}})}$$

Equation 8.1

where CPRES is the capital cost of the good
CSCRAP is the scrap value of the good
XLIFE is its economic life in years
RINT is the yearly rate of interest, expressed as a fraction

Equation 8.1 can only be used where RINT is greater than zero, as at zero interest rates CAN becomes zero; clearly an incorrect result. In the unusual case of a zero interest rate, therefore, (as might occur if all railway costs were financed by zero interest government loans), the following formula will be used:-

$$\mathrm{CAN} = \frac{\mathrm{CPRES} - \mathrm{CSCRAP}}{\mathrm{XLIFE}}$$

Equation 8.2

where symbols are defined as above.

Railway investments may be paid for from various sources of finance, with different rates of interest. For example World Bank "soft loans" may be available for major new investments. More day to day investments, on the other hand, may be financed from a "sinking fund" of the railways own money - the rate of interest will then be that which the railway could earn if it invested the money instead. However, for simplicity of use, the model has been designed to allow only one value for RINT, the rate of interest, for all investments. This is likely to be of sufficient accuracy to allow comparisons between costs of investments, which is the purpose of this model.

8.6 Cost equations

In this section, costs in each of the categories listed in Section 8.3 will be discussed in turn. For each cost, the approach taken by the authors listed in Section 8.2 will be examined, where relevant. (note that ANOP will rarely be used in this context since its cost equations are usually unsuitable for reasons explained in Section 8.2). Any relevant information on NRZ operating practices will also be discussed. A conclusion as to the best form for the cost equations will then be reached. The cost equations themselves are given in Appendix 11.

8.6.1 Depreciation of rolling stock

The numbers of locomotives required for line-haul, and number of wagons and cars of each type is calculated in the model; this was discussed in Chapter 7. Capital costs are then obtained by multiplying these numbers by unit costs. Discussion in this section can thus be limited to the treatment of depreciation.

Both the World Bank model of Colombia, and Majumdar and Blore, treat rolling stock depreciation costs as being dependent only on age; that is to say, they use an equation similar to Equation 8.1, and assume that the economic life of rolling stock is independent of its use. They do not discuss their reasons for doing this.

By contrast, Sander says the following:-

"The principal causes of depreciation of locomotives and rolling stock are (a) physical wear and tear resulting from use and (b) obsolescence. Equipment that is intensively operated will have a shorter life than that which is underutilized and is less likely to become obsolescent. For costing purposes it is proposed that depreciation as shown in the accounts is based on prescribed lives of the assets in terms of kilometres". He gives an example in which depreciation costs are obtained by dividing capital costs by the number of locomotive-km or car-km. This clearly does not include an allowance for age-related depreciation. He then says "the difference between this and any accounting depreciation may be considered as fixed cost" and separately calculates interest paid assuming a fixed life for rolling stock.

Thus, although he mentions the problem of obsolescence, Sander's equations do not deal with it fully. Consider, for example, a locomotive with an "economic life in km" of 2 million km, which would become obsolescent after 20 years. Using Sander's equations, depreciation costs would be underestimated if the locomotive averaged less than 100,000km per year, since it would become obsolescent before reaching 2 million km, and Sander's equations do not allow for this. Even if the locomotive averaged more than 100,000km, an error would be introduced because in that case the cost of interest should also be dependent on locomotive-km and in Sander's equations it is not.

No information is available from NRZ on the relationship of economic life of rolling stock to use or age. As can be seen from the costing system, ANOP, some rolling stock is hired. There is no reason why hire charges should bear any resemblance to annualised equivalent capital cost, since it depends on the cost of supply to the lending railway, as well as the demand considerations of the borrowing railway. Decisions on the loan of rolling stock may also have a political basis. Hire charges are thus complicated, and will not be dealt with by the model; it will be assumed that a railway owns all the rolling stock it uses.

The formulae for depreciation of rolling stock in this thesis will take into account Sander's point that depreciation comes from two sources; obsolescence, which is age-related, and use. The formulae used will be different from his, in order to overcome the contradictions in his work which have just been discussed.

The following inputs will be required, for each class of locomotive and each type of car:-

Unit capital cost
Number of years until item becomes obsolescent
"Economic life" in terms of locomotive-km or car-km
(Number of locomotive-km or car-km per year will be obtained from the operations model)

The "economic life" in terms of locomotive-km or car-km will be converted by the model into an "economic life" in years by dividing by number of locomotive-km or car-km per year. (note that this is not the same as inputting economic life directly, as it allows depreciation costs to vary with locomotive-km or car-km). This "economic life" will be compared by the model with the number of years until the item becomes obsolescent. The smaller of the two values will be used as the actual life, XLIFE, to be used in Equation 8.1 which converts capital costs to their annualised equivalents.

8.6.2 Locomotive maintenance costs

In discussing locomotive maintenance cost equations, the following must be established:-

- Whether maintenance costs should be calculated separately for running sheds and workshops.
- Whether scheduled and non-scheduled repair costs should be calculated separately.
- Whether there is a fixed element to the equations (i.e. are there any costs involved in using maintenance workshops and running sheds that will be incurred as long as the railway is kept open and regardless of level of usage).
- On what statistics the variable parts of the equation should depend.
- How maintenance costs of mainline locomotives and yard locomotives should be separated.

These questions will now be discussed in turn.

Calculating running shed and workshop costs separately

The World Bank only uses one equation, for both running sheds and workshops. Majumdar and Blore, and Sander, however, both suggest keeping equations for the two separate. ANOP lists running shed and workshop costs separately for locomotives. The maintenance performed in running sheds - running repairs and minor overhauls - is different in nature from that performed in workshops, so the cost equations are likely to be rather different. Also, most railway accounting systems, according to Sander's suggestions, keep figures for running sheds and workshops separate and, indeed, under completely different headings for railway operations. Therefore, in this thesis, separate equations will be used for running shed maintenance costs and workshop maintenance costs.

Scheduled and non-scheduled repairs

Majumdar and Blore are alone in isolating non-scheduled repairs as a separate cost category. Their main reason for doing this is to obtain an equation which explains the increase in locomotive maintenance costs with age. Since this age relationship is not investigated by this thesis, and since, too, it will be difficult to isolate non-scheduled repair costs from scheduled ones in many railway accounts, this thesis does not treat scheduled and nonscheduled repairs separately.

Fixed costs

Of the sources listed in Section 8.2 only Sander and NRZ's costing system ANOP suggest there may be a fixed cost for locomotive maintenance. Sander suggests that depreciation of maintenance of workshops machinery should be made "indirectly variable, that is, having a fixed and variable element", and that "the degree of its variability should be ascertained by study of past trends". ANOP has a heading "overheads" which includes maintenance of shops and sheds, and maintenance and interest on depots and shops. (It also includes accident repairs, which should, strictly, be a variable cost). As can be seen from Table 8.1 the locomotive overheads category is only 3.222% of total mainline locomotive costs. As such, the error introduced by assuming this cost to be wholly fixed, rather than indirectly variable as Sander suggests, is small. They will therefore be taken as fixed in this thesis. Users of the model are warned that where costs of maintenance and interest on workshops are large, they should be examined to see whether part of the cost should be allocated as variable. Overhead costs will be calculated separately for workshops and running sheds. It should be noted that fixed costs refer only to maintenance and depreciation of machinery; because, as discussed earlier, the model is concerned only with long-run variability and labour costs of rolling stock maintenance can be regarded as variable in the long-run.

Calculating costs separately for each type of locomotive

The locomotive maintenance cost equations provided in this thesis will be such as to allow the variable part of these costs, discussed below, to be calculated separately for each type of locomotive. (see equation 8.3 below). Where insufficient information is available to do this it is of course possible to use the same variables for unit costs in equation 8.3 for each locomotive type.

Separating yard and mainline locomotive maintenance costs

Yard operations have not been modelled in the thesis; as will be seen later yard costs are described in very simple cost equations, and not broken down into categories. Hence yard locomotive maintenance costs are not required to be calculated. Care must be taken not to include any cost of yard locomotive maintenance in equation 8.3. In particular the fixed cost, CLOCFX, must be treated with care. Even though it is fixed, it must be assigned in some way between mainline and yard locomotives, and not double-counted. ANOP, for example, assigns locomotive overheads between yard and mainline costs on the basis of locomotive hours run on each operation.

Variability of costs

In all the sources mentioned in Section 8.1, the variable part of cost equations for locomotives maintenance has been made dependent on either the number of locomotives or the number of locomotives-km, or both.

For both workshop maintenance and running shed maintenance Sander suggests that costs should be directly variable with locomotive-km in the long run. This is because "it is normal workshop practice to prescribe the interval between any two scheduled repairs in terms of kilometres run by the locomotive during the relevant period". He does, however, suggest that for workshop costs, though not for running shed costs "the formula for the variability of maintenance with the factor of engine-km may be refined by analysis, as some part of workshop repair expenses may be time-related".

Majumdar and Blore express all locomotive maintenance costs in terms of proportions of total renewal cost of a locomotive. Thus, all locomotive maintenance costs are expressed per locomotive. Calculations are done separately for running repairs (scheduled), minor overhauls and major overhauls, and in each of these cost categories labour and material costs are separately assessed. However, each of these cost equations has the same form; for example, materials costs of running repairs are assessed as 0.17% of the renewal cost of a locomotive, and labour costs of running repairs as 4%. Non-scheduled repair costs are also calculated per locomotive, but are expressed as a function of age. This is not discussed further here, since it is irrelevant to the thesis. Majumdar and Blore do not discuss the use of locomotive-km as a possible variable; nor whether Sri Lankan maintenance routines are defined in terms of locomotive-km as Sander suggests is usual, or in terms of locomotive hours between services. If the latter is true this would explain their preference for number of locomotives as the explanatory variable.

The World Bank have two components to their equation for locomotive maintenance costs. The first component is a cost per locomotive, and the second, added to it, is a cost per locomotive-km.

In the light of the above discussion, the locomotive maintenance cost equations in this thesis are defined separately for running sheds and workshops, but take the same form in each case. They consist of three components; fixed, varying with locomotive-km, and varying with locomotive-hour. It is expected that, when the user calibrates the model, one of the two variable components will often be set to zero. This will leave only one unit of variability; usually, the one used to define the gap between services.

8.6.3 Wagon and car maintenance costs

Many of the conclusions reached in the discussion of locomotive maintenance costs also apply to those for wagon and car maintenance, viz:-

- Running shed and workshop costs are calculated separately.
- Non-scheduled repairs are not separated from scheduled repairs.
- There is a fixed component to the equations, for maintenance and depreciation of workshops.
- Costs are calculated separately for each type of wagon and carriage.

However, variability of wagon and car maintenance costs is regarded as different from that of locomotive maintenance costs, by all sources used in this discussion, apart from the World Bank.

Sander suggests that wagon (i.e. freightcar) workshop maintenance costs should be in terms of car-loadings. This is because "it may be argued that workshops maintenance of freight cars is more a function of the number of times a car is loaded than the kilometres it runs or the days it is in use, and that most damage is caused by rough shunting". Workshop maintenance costs of passenger cars, on the other hand, he suggests should be made "directly variable in relation to car-km". He does not explain why. It suggests that both line maintenance (i.e. running shed maintenance) of freight cars, and of passenger and related cars, should be made directly variable with car-km as this "best explains variability of line maintenance expences".

Majumdar and Blore divide wagon and car maintenance costs into heavy wagon repairs, light wagon repairs, and carriage maintenance costs. For heavy wagon repairs, labour costs are regarded as consisting of a fixed part (irrelevant to this thesis as previously explained), plus a variable part varying with the number of repairs. The number of repairs is found from maintenance schedules, and therefore will depend on either wagon-hours or wagon-km, depending on how the schedule is defined. Materials costs of heavy wagon repairs are expressed per wagon, as a percentage of total renewal costs. Light wagon repairs are expressed per wagon per year, and maintenance costs of carriages are expressed per carriage as a percentage of total renewal costs.

Wagon and carriage maintenance schedules in NRZ are defined per time period, not in terms of kilometres run, hours on the line or number of loadings. It is therefore likely that at least some wagon and carriage maintenance costs can be explained in terms of number of wagons and carriages alone, and this is one parameter on which wagon and carriage maintenance costs will be made to depend. Sander's explanation that the main cause of wagon maintenance costs in workshops is wagon loadings is allowed for in the workshop maintenance cost equations by using wagon journeys as a proxy for wagon loadings. Passenger cars will be treated in the same way as wagons in the equations. Running shed maintenance costs are made to depend on both number of wagons and number of wagon-km.

8.6.4 Track renewal costs

A major difference of opinion between sources shows in the approach taken to variability of track renewal costs. Sander and civil engineers within NRZ take one view, and Majumdar and Blore the opposite.

According to both Sander and civil engineers within NRZ, track renewal costs vary indirectly with traffic in terms of gross tonne-km. Civil engineers in NRZ volunteered the information that the variability of track renewal costs with traffic was larger than the variability of track maintenance costs. Both Sander and NRZ assign ballast costs to track maintenance rather than track renewal, except in cases where the volume of ballast is being increased, and regard ballast costs as having so slight a relationship with traffic as to be virtually fixed. Ballast costs will be discussed further in Section 8.6.5.

Majumdar and Blore, on the other hand, state the following:- "of the three items of track renewal, only ballast replenishment was found to correlate with traffic volume. It showed a linear relationship .... Re-railing and re-sleepering showed little correlation with traffic density or any other relevant parameter". They thus establish annual fixed costs per km for re-railing and re-sleepering, and for labour and minor materials and tools, and use a linear relationship with gross tonnes for ballast replacement.

The World Bank does not calculate track renewal costs separately from routine track maintenance costs. Their equation for track maintenance in general is made up of a component which is fixed per kilometre, and one which varies with gross tonne-km, but they do not discuss the inputs to this equation, nor discuss whether it is track renewals or routine maintenance which will form the fixed part of the equation.

It seems best in this situation to take the approach of NRZ, especially as it is backed up by Sander's approach. The discussion in the rest of this section will therefore be concerned with examining these two sources in order to be able to produce the most suitable equations for Botswana.

Sander discusses the variability of renewal costs of each element of track separately. His conclusions for mainline track are as follows.

Rails, points and crossings may be regarded as variable with traffic, in that their depreciation depends mainly on "physical wear and tear resulting from use". Sander suggests that the economic "life" of these items should be expressed in terms of millions of gross tonnes. Annual equivalent costs of capital are then obtained in a way similar to that described earlier in this section for locomotives. Points and crossings "have a relatively short life" compared with other track.

Depreciation of sleepers should be regarded as arising mainly from "deterioration from exposure to the elements, essentially a function of time rather than use". For steel and concrete sleepers, Sander suggests that time can be regarded as the sole explanatory variable. For wooden sleepers, time is still the most important variable, but "Engineering opinion which has been sought in a number of countries, usually supports the view that variations of about 10 per cent below the all-system average life of wooden sleepers will occur on sections of the lowest and highest train density respectively."

Sander suggests that ballast renewal cost should be regarded as a fixed part of regular track maintenance - as such, this will be discussed in the next section. Only when there is a change in volume of ballast would there be any cost under track renewal. Since the model in this thesis is a "comparative statics" model, this change need not be dealt with.

For both rails and sleepers, Sander suggests that labour costs of renewal should be included in total capital costs of replacement.

With regard to track renewal cost in yards, he says that, with the exception of points and crossings, track depreciation should be made dependent only on time. In this thesis, a global equation, discussed in Section 8.6.7, will be used for yard costs. Sander is quoted here merely to indicate one of the sources of a fixed element to yard cost equations.

NRZ engineers, unlike Sanders, provided estimates for economic life of track as a whole, rather than for its separate inputs. This approach is preferred in this thesis since it allows the model to be run with simpler inputs.

The NRZ engineers suggest that the economic life of track is affected by two main variables; gradient and traffic. They were not, unfortunately, able to provide any quantification of the effect of gradient. They suggested that the effect of traffic on economic life might be as follows. In situations where traffic levels were the same as those in Botswana, the economic life would be about 30 years. Where traffic was heavy, however, it would be 25 years, and where it was light, 35 years. As discussed in Chapter 3, the Botswana line carries approximately 4 million gross tonnes per year in 10 trains each way per day (counting all train types). The lightest train density found on NRZ main lines is about 4 trains each way per day. (although there can be less than one train per day on some branch lines). The heaviest train densities are of the order of 20 trains each way per day. It is suggested, therefore, that traffic levels of less than 2 million gross tonnes per year should be regarded as light, traffic levels between 2 and 6 million gross tonnes should be regarded as medium, and traffic levels above 6 million gross tonnes as heavy.

The above estimates could allow a stepwise function to be calculated for economic life, where it took one of three values, according to traffic levels. However, as discussed in Section 8.4, continuous functions are preferred in this thesis. It is therefore assumed that the economic life of track is reduced from a maximum value in proportion to the amount of traffic it carries.

The calculation of track relaying costs in this thesis can be described as follows. The user of the model will be required to supply the following inputs:-

- Capital costs per kilometre, including labour, to relay track.
- Scrap value per kilometre of track. (It is assumed that the labour costs of scrapping track will be included in the costs of its renewal).
- Values for the parameters required in the equation for economic life of track, described earlier.

The model then calculates the economic life of track. It uses the value for line length, number of crossing loops, and average length of loop, which were inputs to the operations model, to calculate total track length, and thus total capital costs of relaying, and scrap value of track. These costs are converted to an annual equivalent as discussed in Section 8.4, using equation 8.1.

The following points should be noted about this approach:-

- Track renewal costs for crossing loops are calculated under this heading, and should therefore be excluded from calculations of crossing loop costs, described in Section 8.6.6.
- If, as Sander suggests, points have a shorter economic life than the rest of the line, the model is likely to overestimate their economic life in calculating only one value for this variable, for the track as a whole. The number of points is dependent on the number of crossing loops. It is hoped that the overestimation of the life of points will be offset by the underestimation of the life of the rest of the track in the crossing loops, due to the fact that traffic in loops will be less than that on the main line.
- The representation of the effect of gradient is by the economic life input to the model. Lines with high average gradient can be expected to have a shorter life for any given traffic level than lines, like Botswana, with low average gradient. It was not possible, from the information available, to provide guidelines to quantify this effect, so estimation is left up to the user. Economic life of track will anyway be different for different railways due to many factors such as type of soil, and level of maintenance of track.
- Clearly, type of track in terms of weight of rail, type of sleepers and fastenings, and volume of ballast, will affect capital costs. It may also affect economic life of track, and maintenance costs. Operating parameters such as maximum axle load, and hence type of wagon used, may also be affected. The model does not link all these effects to type of track, however, they are left as separate inputs for the user.
- Track renewals do not include costs of earthworks, since these are regarded as new works, outside the scope of the model.

8.6.5 Track maintenance costs

Sander examines the variability of each of the main components of track maintenance costs. He concludes that some costs are fixed per km, some vary indirectly with traffic, and some directly with traffic. He suggests that the best measure of traffic is gross tonne-km. With regard to indirectly variable costs, he suggests that the main cost is labour for "on-track" repairs. This is as distinct from "off-track" labour costs of maintaining road bed and earthworks, which he suggests are fixed per kilometre per year. He points out that many railways keep records of "off-track" and "on-track" labour costs separately, but that where this does not occur, costs should be allocated between off-track and on-track labour according to estimated proportion of time spent at each task.

Sander discusses the variability of on-track labour costs for railways in Mexico, Korea, and Canada, and finds "approximately 40 per cent variability relative to the average traffic volume" for Mexico, 33.33 per cent for Korea, and 34 per cent for Canada. It is only in the case of Korea that he gives enough information (three costs at three different traffic volumes) to show how he obtained the variability figure. For Korea he has implicitly defined a stepwise function, but the size of step is defined in terms of the dependent variable (cost) rather than the independent one (traffic). This is theoretically unjustifiable. Also, as stated earlier, stepwise functions are avoided in this thesis. The Korean figures do, however, allow a continuous function to be defined, in the form:-

$$\text{variable annual labour cost} = B \times (\text{annual gross tonne-km})^K$$

$$\text{where, for Korea } B = 1.083 \text{ and } K = 0.4425$$

K describes the fact that costs vary less than proportionately as traffic increases. As such, it will vary from railway to railway according to the state and weight of track, but there will be some similarity between its values on different railways. B, on the other hand, will vary according to the cost of labour and unit of currency in a country, and so its value as calibrated for one railway will bear no resemblance to that on another.

Sander then suggests that other indirectly variable costs (such as that for track machines) should be assumed to vary in the same way as "on-track" labour costs. He also examines which track costs apply only to the maintenance of the main line, and which apply to both the main line and yards. He points out that yard and main line costs should be separately assessed, but that if this is not possible, costs should be allocated between the two in proportion to gross tonne-km carried.

The variability of the components of track maintenance costs as suggested by Sander is summarised in Table 8.2. With reference to this table, it should be noted that only "spot replacement" of rails, sleepers and other track material is included in track maintenance, since the main cost of replacement will be included under track renewal. Sander suggests that this spot replacement will occur "on curves and in other localities where the wearing-out rate is substantially higher than the normal rate assumed for depreciation purposes." He also points out that such spot replacement is included under track renewal costs by some costing systems. This will be the approach taken in this thesis, so that track maintenance costs only consist of fixed and indirectly variable costs, as listed in the first four columns of Table 8.2.

Table 8.2 Sander's definition of variability of track maintenance costs per kilometre with gross tonnes

Fixed		Indirectly variable		Directly variable (not included as maintenance costs in this thesis)	
mainline only	Yard and mainline	mainline only	yard and mainline	mainline only	yard and mainline
	labour costs of maintenance of roadbed and earthwork	maintenance of track machines	labour costs of track repairs and surfacing	spot replacement of rails, sleepers and other track	
	Ballast		Small tools and supplies		

It should be noted that Sander only includes maintenance costs of track machines under the heading of track maintenance costs. This is because he has a different set of cost categories from that used by the thesis; in the thesis, depreciation of track machines should also be included under the heading of track maintenance. It will be assumed to be an indirectly variable cost.

Both the World Bank's model of Colombia and Majumdar and Blore describe track maintenance costs by an equation with a component which is fixed per track-km per year, and one which varies directly with gross tonne-km. The World Bank's Colombia equation is for all track costs. That used by Majumdar and Blore is for labour input only since, they say, "labour input constitutes a large proportion of the routine track maintenance". They say that their equation "is valid between 2500 and 8000 gross tonnes per day. It was observed that the labour man-hours are fixed, for low and high traffic volumes, beyond the limits mentioned above."

Majumdar and Blore also have a component of their equation which varies with average gradient. It should be noted, however, that they did not use average gradient as an explanatory variable for track renewal. In this thesis, following discussions with NRZ engineers, the view is taken that the main effect of average gradient on track costs is through its effect on rate of renewal of track. This was discussed in Section 8.6.4. Gradient will not, therefore, be represented in track maintenance cost equations in this thesis.

The conclusions that can be drawn from the sources described so far are as follows. Track maintenance costs per kilometre will have a fixed component plus components which vary with gross tonnes. This variability may be direct or indirect, may be stepwise or continuous, and may only apply between certain upper and lower limits of gross tonnes. The situation in Botswana will now be described, with a view to establishing whether these general conclusions apply there.

In Botswana, routine maintenance is done:-

(i) by using a tamping machine, which corrects the top and alignment, and

(ii) by "handwork"; checking fastenings, and doing off-track work, such as weed-killing.

Separate gangs of men are employed for tamping and for hand work.

The following information was available on the variability of each of these costs.

Depreciation of tampers

The economic life of tampers can be regarded as fixed.

Ballast costs

Ballast wastage will normally be about 2% of total volume per year. A civil engineer on NRZ stated that this is not much affected by traffic levels, but that perhaps 0.5% more ballast per year might be lost on a more heavily used line.

General variability of track maintenance costs with gross tonne-km

It was not possible to obtain enough data to investigate the variability of track maintenance costs directly, so the opinion of a civil engineer in NRZ was sought on this subject. He was at pains to stress that there was not much variability of costs with traffic. Like Sander, he pointed out that off-track maintenance, such as firepath cleaning and weed-killing would not be affected by traffic. There is an added problem that tampers are obviously a "lumpy" cost. As an indication of variability, the civil engineer estimated the following:-

If traffic increased or decreased by 10% he would not alter the regime. If it decreased by 20% he might remove one tamper, and if it decreased by 50% he would remove one tamper and decrease the strength of each gang from 16 to 12 men, although keeping the same number of gangs.

In concentrating on the costs of labour and tampers, this civil engineer's comments imply that he agrees with Majumdar and Blore that materials costs are unimportant, except for ballast.

Thus, information from NRZ backs up the theory of other authors that track costs are in part fixed and in part vary with gross tonne-km. It also suggests that there is a certain "lumpiness" to track costs which might mean that they would best be expressed as a discontinuous function. However, as with the rest of this thesis, a continuous function will be preferred.

Sander's approach will be used in this thesis in preference to that in the World Bank's model of Colombia, or Majumdar and Blore's work. This is because his conclusions are based on research into three different railways, where he found the same sort of function applying in each case, albeit by using a vague definition of variability. Majumdar and Blore's function is by contrast too specific, and that of the World Bank's model of Colombia not based on any detailed research. Also, information from NRZ confirms the validity of Sander's approach.

Total track maintenance costs will therefore be expressed as two components; one component varying with track-km, and the other with gross tonne-km. Variability with gross tonne-km will be regarded as indirect, and this will be expressed by raising gross tonne-km to the power K, where K takes a fractional value. The option will be given of allowing the user to define upper and lower limits to gross tonne-km outside of which costs remain constant.

8.6.6 Trains working method and station costs

There are problems in separating station costs from trains working method costs. The number of manned stations, and, by implication, unmanned crossing loops, on a line is influenced by the trains working method. As discussed in Chapter 5, both the Paper Order and Van Schoor token working methods require some crossing loops to be manned for the purposes of operating them. In the case of Van Schoor every other loop must be manned, and thus the introduction of this method may cause some unmanned loops to be closed. Colour light signalling makes no demands with regard to the number of loops, manned or unmanned.

Where the existence of a crossing loop, or whether it is manned, depends on the trains working method, its full cost should be part of the trains working method cost. There will also be some major stations which will remain open regardless of the trains working method employed, as they are points at which a significant amount of goods traffic is loaded and unloaded, or at which many passengers begin and end their journey. For a simple line like that in Botswana, the costs of installing and operating the trains working method at such stations is likely to be of the same order of magnitude as at the smaller stations, whose manning depends on the trains working method. However, their other costs such as depreciation and traffic handling, are likely to be much larger than at the smaller stations.

In this thesis costs will be defined per station, and divided between trains working method costs and station costs as follows:-

- all costs at each unmanned loop and minor manned station will be regarded as trains working method costs.
- costs at each major station will be divided into two parts. A cost equivalent to that at a minor manned station will be regarded as the trains working method cost. Extra costs will be regarded as the station cost.

This division means that no distinction need be made between major and minor stations when calculating the trains working method cost per manned loop. It should be noted that costs of maintaining crossing loop track are included in general track maintenance costs, as discussed in Section 8.6.5, and should not therefore be included in the costs discussed in this section.

In addition to costs per crossing loop, there will be administrative costs. Those for stations can be included in the general administrative costs discussed in Section 8.6.8. Administrative costs of the trains working method, on the other hand, should be isolated and quantified, since they may change for each trains working method.

Variability of all the components of station and trains working method costs is now discussed, in turn.

<u>Trains working method costs at unmanned loops</u>

Costs will consist of depreciation and maintenance costs of buildings and equipment. Depreciation costs are clearly fixed per loop, and NRZ regard all maintenance costs as labour costs which "would only vary marginally with a large increase or decrease in traffic" (NRZ 1983).

Trains working method costs at manned loops

In addition to depreciation and maintenance costs, there will be a labour cost of operation. Labour costs are also likely to be fixed, for reasons explained by Sander:-

For purposes of "clearance and crossing of trains and related operational duties ... staff is normally provided in sufficient numbers to man the station throughout the 24 hours of each day. They should therefore be capable of handling traffic up to the maximum capacity of the line in terms of train paths. Within that limitation, therefore, staff expenses at wayside stations may be taken as fixed costs." Sanders approach is backed up by the 1978 report by a committee on the takeover of the Botswana line (NRZ:JWC 1978). The committee discussed the number of train dispatchers (also known as station foremen) involved in operating Van Schoor token working at various traffic levels and with various numbers of crossing loops. From this it is possible to calculate the average number of train dispatchers required in each case and it is consistent at 3.6 per manned loop regardless of traffic levels. The fraction in the calculation represents relief cover.

Extra costs at large stations

As previously explained, these are the costs incurred at main stations in addition to those for the trains working method. Costs incurred will be due to staff employed separately from those working the trains working method, any materials costs (probably small), and extra depreciation costs due to larger buildings. The functions performed at large stations may include passenger and freight booking, freight handling, catering, and maintenance of the buildings and equipment. Passenger and freight booking and freight handling costs may vary to some degree with the amount of traffic handled. However, most freight booking and handling is likely to take part in major yards, and is discussed under yard costs. Also, passenger booking is likely to be relatively small on a railway like the one being modelled, which is predominantly for freight. Other recurrent costs can be assumed to be fixed. Therefore, a fixed recurrent cost per main station will be defined. Thus, both the extra cost per main station and the number of main stations will remain constant for all runs of the model. It was explained in Section 8.3 that costs that remain constant in this way can, if the user requires, be set to zero.

Administrative costs of the trains working method

The sources on cost equations being used in this chapter (listed in Section 8.2) include supervisory costs of trains working methods and stations with general administrative cost equations, and do not discuss them separately. It will be assumed, therefore that trains working method administrative costs have the same variability as all other administrative costs, as discussed below in Section 8.6.8; that is, fixed unless there are very large changes in traffic levels. The administrative costs should include the following:-

- Depreciation costs of any administrative or control centres.
- Maintenance costs (if any) of administrative and control centres.
- Costs of maintenance staff.
- Materials costs of administration.

It should be stressed that only those trains working method administrative costs that cannot be divided into a cost per crossing loop should be included in the above list.

Summary

The discussion of trains working method and station costs can be summarised as follows:-

- None of the costs varies with traffic levels. The fact that there may be a link between number of loops and traffic levels is already accounted for in the operations model described in Chapters 3 to 6.
- Trains working method costs are made up of administrative costs, costs at manned loops and costs at unmanned loops.
- Station costs are defined as extra to the trains working method costs and will remain fixed for all runs of the model. They include only costs which vary with the number of stations, as station administrative costs are included in the general administrative costs of the railway.

8.6.7 Yard costs

The model developed in this thesis is designed to examine the effects of changes in line operations. Yards are not studied in detail, and therefore yard costs are represented by a single, simple equation. Yard costs are incurred by the following:-

Maintenance and depreciation of buildings
Locomotive maintenance and depreciation
Fuel
Crew
Yard masters and other yard staff
Track maintenance and depreciation

Costs in each of these categories must be isolated from their main-line equivalents, in order to avoid double counting. In cases where railway accounts do not provide separate costs for yards and lines, the division between the two must be made by apportioning them according to some statistic. For example, in NRZ's costing system, ANOP, tractive effort costs are allocated between yards and lines according to the proportion of tractive-effort hours spent at each operation.

With regard to the variability of yard costs, all costs of building may be regarded as fixed if no change is made to yard structure. Sander also suggests that track renewal costs in yards may be regarded as fixed. As for labour costs, Sander states the following. "With the exception of yard masters, their assistants, and clerical staff, the number of men in yards will be governed by the number of yard locomotive shifts operated. In the very long run the number of yard locomotive shifts will be adjusted to traffic volume so as to produce a cost variability of close to 100%." Majumdar and Blore back this up by their discussion of a six-month sample of a yard in Colombia, which produced an equation for man-hours as a proportion of gross tonnes. (The definition of the variables in their formula, implies that labour varies with the square of gross tonnes; in the light of their discussion, however, this must be regarded as a misprint).

Locomotive depreciation and maintenance, and track maintenance costs might be expected to vary in the same way as their counterparts in the line cost equations. For the cruder level of approximation used here, however, simpler relationships are assumed. It is assumed that locomotive depreciation and maintenance costs depend only on the number of locomotives in use, and that this number is directly variable with gross tonnes. It is assumed that track maintenance costs are made up of a fixed cost representing off-track maintenance (since length of track is invariant), plus part of on-track maintenance, and a variable part representing on-track maintenance directly variable with traffic.

The above assumptions allow a yard cost to be formed from two components; one which is fixed, and one which varies with gross tonnes passing through the yard.

The fixed part consists of:-

Costs of buildings
Track renewal costs
Fixed staff costs (e.g. yard masters salary)
Part of track maintenance costs.

The variable part consists of:-

Variable labour costs (e.g. crew, traffic recorders)
Locomotive depreciation and maintenance costs
Part of track maintenance costs.

The unit of variability, gross tonnes passing through the yards, is the same as gross tonnes on the line. This is because the model assumes that a train is made up in a yard at the beginning of a line, and stays the same until it reaches a yard at the end of a line.

<u>8.6.8 Administration costs</u>

Sander points out that the variability of administrative costs, which he calls superintendence, depends on "the range of officer grades encompassed within the meaning of "superintendence", which varies widely as between one railway and another. Where the accounting rules follow the Uniform System of Accounts presented by the Interstate Commerce Commission (ICC) of the US, superintendence includes all officers from the grade of departmental chief to general foreman and inspector, together with their clerks and other office employees. Other railways consider superintendence to comprise only the departmental head, his immediate assistants in charge of the overall activities of the department, and officers in headquarters, such as architects, draftsmen, and research and personnel officers, together with the clerks and other employees directly supervised by such officers. In the latter case, foremen, inspectors, shop clerks, timekeepers, etc, are excluded from "superintendence", and their salaries are charged to the respective direct heads of expense .... Under this more restrictive concept of superintendence it is reasonable to assume that, within the limits of possible traffic increases over a comparatively short period of time, cost will not significantly increase."

In this thesis the administrative cost category will be the more restrictive one defined by Sander. Cost equations in every other category defined in this thesis have been designed in such a way as to include superintendence costs directly attributable to the category, and the user should be aware of this when calibrating each equation. Sander is quoted in full above in order to make clear which costs should be considered as administrative in this thesis. They will be represented by a fixed cost. As Sander implies, the size of this cost may vary in the long term if there are large increases or decreases of traffic. Therefore, if the model in this thesis is being used to compare costs of operating the railway at two traffic levels, one much higher than the other, a separate value for administrative costs may have to be used for each run.

If the user decides that administrative costs are likely to be fixed for all runs of the model which he or she wants to do, then, for reasons discussed in Section 8.3, these costs may be set to zero.

As discussed in Section 8.6.6, administrative costs of the trains working method must not be included in the general administrative costs discussed here.

8.6.9 Crew costs

Sander suggests that crew costs should be divided "between those which are time-related (salaries, overtime, allowances etc) and those which are distance-related (e.g. mileage or kilometrate allowances). He then suggests locomotive-hours as the best explanatory variable for time-related crew costs, and locomotive-km as the best explanatory variable for distance-related crew costs. He points out that locomotive-hours and locomotive-km must be "reduced as necessary for multiple-heading of trains with a single locomotive crew."

Majumdar and Blore do not study the variability of crew costs. Instead, they found an average value for number of crew per train, and divided this by the average gross train weight multiplied by the average train speed to give a value for crew costs per gross tonne-km.

The World Bank define crew costs per train-mile, and give no discussion of their reason for using this explanatory variable.

Sander provides the best rationale for use of explanatory variables. Number of crew will clearly not depend directly on gross tonne-km as Majumdar and Blore suggest; they are using this value as a proxy for more suitable ones, such as locomotive-hours, train-hours, locomotive-km or train-km which may be difficult to identify in their model. It is clear that some crew costs will be time-related, so the World Bank model must also be rejected.

If it is assumed that the number of crew on a train will be unaffected by the number of locomotives on that train, then train-hours and train-km can be used in the place of locomotive-hours and locomotive-km respectively, thus obviating the need to modify statistics to allow for double-headed working. Crew costs are therefore represented in this thesis in terms of two components, one varying with train-hours and the other with train-km. The second component may be set to zero in some cases, where there are no distance-related costs.

8.6.10 Fuel, lubricant and water costs

Fuel costs

The amount of fuel used by a train will depend upon the amount of energy it expends, plus an amount for loss of fuel due to wastage and theft when filling tanks. The energy expended by a moving object is equal to the force it exerts multiplied by the distance it travels. Forces exerted on a train were discussed in Chapters 3 and 4. They consist of the tractive effort of the locomotive, and train resistance. It was established there that both these forces are functions of train speed. As discussed in Chapter 4, detailed information on train speeds, including periods of acceleration and deceleration, is not obtained by the model. This means that the equations for tractive effort and train resistance cannot be used directly to obtain a value for fuel costs. However, they can be used to indicate which variables are likely to affect fuel costs. These are as follows:-

From the equation for tractive effort:-
locomotive power

From the equation for train resistance:-
gross weight of train
gradient

From both equations
train speed

Sander, Majumdar and Blore, and NRZ's engineering department, all discuss the variability of fuel costs with some, though not all of these variables. Their arguments are reproduced below.

Sander says; " ... special studies can be undertaken to determine comparative levels of fuel consumption, in opposing directions, on different sections on the line, and by various classes of train ... however, on all railways except those constructed in exceptionally mountaineous country, it is generally found that fuel consumption per 1000 gross trailing ton-km is a reasonably consistent measure, both as an all-line average, and by regions or sections. For example, on a railway of over 3000 route-km, with an undulating line rising no more than 700 meters above sea level at any point, fuel consumption per 1000 gross trailing ton-km in any district of the system did not vary from the all line average by more than 2 per cent. On the other hand, in Peru, for example, where the line rises to almost 5000 meters above sea level in a relatively short distance, it is obvious that there will be considerable directional variation in fuel consumption."

Majumdar and Blore tested diesel consumption "in relation to gradient and indirectly to train size through traffic density". They found little variation with traffic density, and there is no a priori reason to suppose there will be significant economies of scale for fuel. This part of their work is not therefore considered further by this thesis. Their conclusions as to the effect of gradient are considered important. The gradients varied with -2.0% to +2.2% on the routes they examined, and they found that fuel varied more than proportionably with the modulus average gradient; this variable was raised to the power 1.6 in their equation.

Majumdar and Blore's work thus contradicts Sander's and NRZ's conclusions that gradient is unimportant. Since their work, unlike that of Sander and NRZ, is based on a quantified survey, it is considered necessary to provide an equation which can allow for the effects of gradient. Total fuel costs are expressed in terms of gross tonne-km, and fuel cost per gross tonne-km as proportional to the modulus average gradient raised to a power. On the occasions when it is impossible to assess the effects of gradient the value of this power can be set to zero.

Lubricant costs

Majumdar and Blore studied oil consumption and came to the following conclusion, "Oil consumption differed widely between locomotive types and neither showed any relationship to class, age, nor could be, with the information available, correlated with running parameters. A mean consumption rate of a locomotive class whose performance was both extensive and reasonable is taken as representative." They then suggested a figure of 0.15 litres per train-km. This implies that there are a fixed number of locomotives per train, and that lubricant consumption can be expressed per locomotive-km. This is the explanatory variable suggested by Sander, and the one used in this thesis.

Water costs

Sander mentions these separately, and suggests that they should be assumed to vary in the same way as fuel costs. They are likely to be small, and in this thesis will be included in the equation for fuel costs.

8.7 Conclusion

Cost equations have been derived in this chapter which express costs as a function of the most important factors affecting variability, and are simple enough to be easily calibrated. The equations themselves are given in Appendix 11. An example of how the cost equations were calibrated using data from Botswana is given in the Confidential Annexe, and discussed in Chapter 9.

There was not enough information available to examine variability of costs using statistical methods. Therefore this was estimated partly by examining operating practices in NRZ, partly by considering the opinions of NRZ staff, and partly from secondary sources.

As discussed in Chapter 2, general information on railway costing from secondary sources is poor, even in developed countries, and is worse in less developed countries. Therefore, the cost equations in this chapter may be described as contributing to knowledge on railway costing in less developed countries, since they are derived by combining information from NRZ with that from several other sources.

CHAPTER NINE

CALIBRATING THE COST EQUATIONS USING INFORMATION FROM BOTSWANA

9.1 Introduction

The cost model was calibrated using information from Zimbabwe and Botswana. Since much of this information is confidential, it has been placed in a Confidential Annexe. In this chapter, the calibration is discussed in general terms.

In Section 9.2 some general points are made about the costs being calibrated. Section 9.3 explains the structure of the Confidential Annexe. Data sources are discussed in Section 9.4, and methods of calibration in Section 9.5. Results of calibrating the model so as to replicate the existing situation in Botswana are discussed in Section 9.6, and Section 9.7 contains a conclusion to the chapter.

9.2 General considerations

9.2.1 Zimbabwean and Batswana costs

In most cases, cost data was collected from Zimbabwe. For consistency, therefore, all cost equations will be calibrated using Zimbabwean data. Batswana costs may differ, particularly in respect of wage rates, which are lower on average than in Zimbabwe, and possibly the rate of interest. The results of the model as calibrated in the Confidential Annexe therefore give the costs of running the Botswana line as a separate railway, but as if it were run entirely from Zimbabwe. While this does not completely reflect the situation in Botswana, it provides adequate information to give indicators of the cost effects of changes in operating practices on the Botswana line.

9.2.2 A base year for costs

For consistency, all costs must be calculated for the same year. The year chosen is that for which the most data is available, which is 1981. All other costs were adjusted to their equivalent value in 1981, using the relevant values for the rate of inflation, as given in the Confidential Annexe.

9.2.3 Currency

Cost equations are calibrated in Zimbabwean dollars. Where relevant, costs have been converted from the Batswana unit of currency, the pula, to the Zimbabwean dollar using an exchange rate of 1.4 pula to the dollar. In 1981 there were approximately 1.3 Zimbabwean dollars to one pound sterling.

9.3 Structure of the Confidential Annexe

The Confidential Annexe is in two sections; CA1 and CA2. In the first section, general information, required in several of the cost equations, is given as follows:-

- Rates of interest for use in converting capital costs to their annualised equivalents.
- The rates of inflation required to convert costs to their 1981 equivalent.
- Unit labour costs. Although these were not used directly in any of the cost equations derived in Chapter 8, they were often required indirectly, in calculating parameters. The unit cost required includes all costs incurred by the railway, and not simply the wage rate.

In section CA2 each of the cost equations, as outlined in Chapter 8 and listed in Appendix 11, is discussed in turn.

9.4 Data sources

The full set of references used for the cost equations is given in the Confidential Annexe. These data sources are summarised below:-

9.4.1 Internal, unpublished documents from NRZ

The following information came from internal written sources within NRZ:-

- Job descriptions; the authorised complement of staff in Botswana; and NRZ and Botswana staff grading systems were obtained from the Personnel department, as were some of the unit costs of employing staff.
- Costs of fuel were obtained from the fuel ledgers kept by NRZ's Accounting department, as were the economic lives of railway equipment.

- Fuel consumption figures were obtained from the Mechanical Engineering department.
- Figures for total costs of locomotive maintenance, wagon maintenance, yards and crew were obtained from NRZ's costing system, ANOP. Some of the statistics used to convert these to the unit costs required in the equations also came from ANOP.
- Capital costs of rolling stock and number of station foremen per crossing loop were obtained from an internal document on the change of ownership of the line from NRZ to the Batswana government.

9.4.2 Verbal communication with NRZ staff

Much of the information relating to track maintenance costs was obtained from verbal interviews with members of the Civil Engineering department. This information included the structure of gangs used in track maintenance and renewal; variability of different types of work; ballast replacement rates; and tamper prices.

9.4.3 Written communication with NRZ staff

Information obtained during the 1982 visit to NRZ was supplemented by a written reply received early in 1983, to a series of questions. This document was not signed or dated. It contained the following information:-

- Some unit costs for staff (those not already obtained in 1982).
- Average non-wage costs per employee.
- Capital costs and economic lives of Paper Order trains working equipment, and numbers of staff required to operate and maintain it.
- Costs of relaying track.

9.4.4 Published NRZ documents

The following information came from published NRZ documents:-

- Figures for the average gross trailing load of trains were taken from the Working Timetable.
- Some statistics used in calculating unit costs were taken from a small published booklet containing miscellaneous figures on NRZ's operations.

9.4.5 Other documents

The following documents were also used:-

- An unpublished consultant's report evaluating various trains working methods for Botswana was used to obtain costs for the control centres for CTC; for equipment for Van Schoor token working; and for converting an unmanned crossing loop to a manned station.
- The publications of a Zimbabwean bank were used to obtain values for the rate of inflation.
- Majumdar and Blore's work on Sri Lankan Railways was used to obtain values for some minor costs, where no information was available from elsewhere. These included the repair costs of tampers, and the rate of oil consumption. Scrap values of rolling stock were set to zero in the model, as were materials costs of track maintenance, excluding ballast, following Majumdar and Blore's example.

9.4.6 Conclusions on data sources

In general, then, enough information was available to allow cost equations to be calculated almost entirely from NRZ sources. However, most of these sources were unofficial and unpublished, and most of the information could not be cross-checked. Also, data often had to be obtained from several different sources for one equation, as was the case, for example, with the trains working method costs, some of which were obtained from NRZ's 1983 written reply, some from a consultant's report, and some from an internal NRZ document on the change of ownership of the line from NRZ to the Botswana government. The exact nature of costs defined in each of these sources may have been different, leading to some inconsistencies in the final equations, and it was not possible to check or quantify this.

9.5 Method of calibration

9.5.1 Introduction

Calibration of the cost equations in the model involved the following stages:-

- Unit costs were obtained from Batswana and Zimbabwean information

- The entire model (including the operations model, the calibration of which was described in the chapters in Part II) was run with these values for unit costs

- The resultant costs were compared with data available from NRZ.

General methods used to obtain unit costs are described in Section 9.5.2, the detail being contained in the Confidential Annexe. The results of running the model, and comparisons of these results with NRZ data, are discussed in Section 9.6.

9.5.2 Method of obtaining unit costs

In general, the data from which unit costs were obtained was so aggregated, and available for so few years, that it was only possible to produce simple averages for parameters; no figures were obtained for standard deviations from those averages.

The problem of data being obtained from several sources was discussed in the previous section. Wherever possible, data from a single source was used to maintain consistency within each cost equation. For example, when costs from NRZ's costing system, ANOP, are used, these are divided by statistics as given in ANOP wherever possible, even when alternative values for those statistics are available. This means that the Confidential Annexe sometimes refers to more than one value for a single statistic, or refers to a value different from that used elsewhere in the thesis.

9.6 Results

9.6.1 Introduction

The results of running the model using the unit costs derived in the Confidential Annexe are given in Table 9.1. These are the costs for the Paper Order working method only; cost equations for the other trains working methods are used in Chapter 10 to simulate changes from the present operating characteristics of the Botswana line.

Table 9.1 Costs output from running the model to simulate present operations on the Botswana line

ANNUAL COSTS IN Z$

ROLLING STOCK	
LOCOMOTIVE DEPRECIATION	1749140
WAGON DEPRECIATION	5187426
LOCOMOTIVE MAINTENANCE	3633889
WAGON MAINTENANCE	1419777
TRACK	
TRACK RENEWAL	4673393
TRACK MAINTENANCE	1084547
TRAINS WORKING METHOD (PAPER ORDER)	
TWM ADMINISTRATION	83424
TWM DEPRECIATION: EQUIPMENT	3823
TWM DEPRECIATION: BUILDINGS	165795
TWM OPERATION AND MAINTENANCE	1600420
STATION	
EXTRA MAIN STATION COSTS	0
OTHER TRAIN OPERATION	
CREW	3894302
FUEL	6064047
OIL	219450
YARDS AND ADMINISTRATION	
YARDS	6412155
ADMINISTRATION	0
TOTAL	
TOTAL	36191588

To complete the calibration these results must be compared with data from Botswana. Unfortunately, these results cannot be compared directly with the actual costs for the Botswana line since this is not at present costed separately from NRZ as a whole. However, the following tests can be done to check that figures of the right order of magnitude are being obtained.

- Total costs for Botswana can be compared with those for NRZ. The ratio between the two can be compared with ratios for gross tonne-km and gross tonnes on the line, as these indicate the relative sizes of operations.

- The proportions of total cost taken up by each cost category for Botswana can be compared with those for NRZ as a whole.

These tests imply that the Botswana line can be treated as an "average" NRZ line. The justifications for this assumption are discussed in Section 9.6.2. In order to do these tests, the total costs for NRZ must be commensurate with those for Botswana, in that any fixed costs set to zero for Botswana must also be omitted from NRZ's costs. This is discussed further in Section 9.6.3. Results of the comparison are discussed in Section 9.6.4

9.6.2 Justification for treating the Botswana line as a branch of the NRZ line

Similarities and differences between the Botswana line, and NRZ lines in general, are listed in this section, together with an indication of the effect these are likely to have on relative costs.

- Unit costs used in the model were obtained from Zimbabwean, not Batswana data, and are therefore similar to those that would be obtained on any other section of the NRZ network.

- Traffic is lighter than average for NRZ. This is likely to lead to a higher proportion of fixed costs compared with costs varying with traffic. Thus, where fixed costs are included in the model, the resultant average cost per unit of traffic is likely to be higher than that for NRZ as a whole.

- Average length of haul in Botswana is 133% of that in Zimbabwe (see Chapter 7). As discussed in Chapter 7, this means that wagon-km per wagon, and locomotive-km per locomotive are of the order of 130% of those in NRZ. This is likely to decrease costs which vary with the number of wagons or locomotives.

- Costs for the trains working method in ANOP include Colour Light as well as Paper Order. However, total Colour Light signalling costs obtained by running the model with statistics representing present operations on the Botswana line are of a similar order of magnitude to those for Paper Order (although divided differently between depreciation, operation, and maintenance). Therefore, the ANOP trains working method costs can serve as an indicator of the correctness of the order of magnitude of these costs obtained by the Botswana model.

9.6.3 Making total costs for NRZ commensurate with those from Botswana

The fixed costs which were set to zero when running the model for the Botswana line were:-

Extra costs at main stations
Fixed yard costs
Administrative costs, apart from trains working method administrative costs.

With regard to subtracting these costs from total costs for NRZ given in ANOP:-

- It was not possible to separate extra costs at main stations from other yard and terminal costs. These are thus still included.

- As discussed in the Confidential Annexe, fixed yard costs are underrepresented in ANOP due to the fact that depreciation costs for infrastructure have largely been paid off already. These are therefore included since the error incurred in doing so is small.

- Administrative costs are excluded. As discussed in Chapter 8, the large size of these costs in ANOP (see Table 8.1) suggests a broader definition of administration than the one used in this thesis. This will therefore cause an inaccuracy by making total costs too small, which may be offset to some extent by the inclusion of the other two costs mentioned above. It was not possible to separate general administrative costs from those of the trains working method.

9.6.4 Discussion of results of comparing the models output with NRZ information

Omitting administration costs (together with other minor costs, listed in Table 8.1, which must be omitted for consistency with this thesis), ANOP's total costs are Z$171792000. This compares with a value of Z$36191590 for Botswana which is 21% of NRZ's total. As stated in Table 7.4 of Chapter 7, the Botswana line carries approximately 17.89% of the gross tonnes carried on NRZ as a whole, and 24.15% of the gross tonne-km. Thus, the percentage of total costs obtained by the model is within the limits which might be expected, given the differences between the Botswana line and the NRZ network, as discussed in section 9.6.2. It should be noted that ANOP tends to understate true depreciation costs, for reasons discussed below, and so will underestimate total costs.

Table 9.2 compares percentages of total costs obtained from the Botswana model with those obtained from ANOP. The following points can be noted about these:-

- Costs involving depreciation (locomotive and wagon depreciation, and track renewal) form a higher proportion for the total produced by the model than for ANOP. This is to be expected because, for reasons explained in Chapter 8, capital goods used by NRZ in 1981 are likely to have been kept for longer than their optimum economic life, and thus their depreciation costs are likely to be lower than those predicted by the model, which assumes replacement at the optimal time. Also ANOP's estimates for depreciation costs are not based on replacement costs, unlike those in the model.

- The fact that stock is so old on NRZ also means that maintenance costs are higher than those predicted by the model.

- With regard to yard costs, the variable part of these is dependent on gross tonnes in the model. The fact that gross tonnes per annum on Botswana are lower than the average for a line on the NRZ network helps explain why the model predicts low yard costs. The fact that the model does not include extra fixed costs at main stations, whereas they are included in ANOP's terminal and yard costs, for reasons discussed in Section 9.6.3, is also likely to make the model's value for yard costs lower than ANOP's.

Table 9.2 A comparison of percentages of total costs obtained for ANOP with those obtained from the Botswana line

Cost category	per cent for Botswana	per cent for NRZ (ANOP)
Rolling Stock		
Locomotive depreciation	4.833	3.717
Wagon depreciation	14.333	3.345
Locomotive maintenance	10.041	9.891
Wagon maintenance	3.923	9.130
Track		
Track renewal	12.913	6.496
Track maintenance	2.997	9.807
Trains Working Method (Paper Order)		
Total trains working method costs	5.121	9.204
Other train operation		
Crew	10.760	10.614
Fuel and oil	17.362	11.778
Yards and terminals		
Yards and terminals	17.717	26.637

9.7 Conclusions

It can be concluded that the calibration for the model was successful as far as it could be tested. Differences in proportions of costs as shown in Table 9.2 are acceptable, when it is considered that the definitions of cost categories in the model vary from those in ANOP, and that there will always be differences between the cost structures of two different railways. However, the control data used for testing the model must be regarded as weak in that no separate costs were available from Botswana, and comparisons had therefore to be made instead with the NRZ network as a whole.

General conclusions can be made with regard to the problems likely to be encountered in obtaining values for unit costs. This chapter illustrates the fact that the information required for the cost equations will not usually be available from official statistical documents produced by the railway. The user may find that the following factors affect the quality of data and, indeed, whether data is available at all in some cases.

- Records kept by developing countries can be expected to be poor. They may also not be kept for very long.
- Information may be confidential.

- Information may be patchy since its acquisition may be dependent on the goodwill of different members of railway staff.
- Information will often come from verbal interviews, and from unsigned, undated, untitled, written documents.
- It is rarely possible to double-check information.
- There may be problems in obtaining exact definitions of units costed.
- The quality of data obtained will depend not only on what is available, but on the relationship between the user of the model and the railway; and hence on the motivation of the railway to provide the information.

Earlier work in less developed countries (eg Sander 1974, IBRD 1970, Majumdar and Blore 1981) illustrates the problems listed above. Detail obtained from NRZ can be regarded as good compared with that which is often obtained from less developed countries.

The general conclusions to this chapter must therefore be that enough information was obtained from a short stay with NRZ to allow the cost equations in Chapter 8 to be calibrated, and that the results of running the model with those equations are of the right order of magnitude. There was not enough information available to rigorously test the accuracy of the equations, and this is likely to be the situation whenever the model is used in a less developed country. However, if the model is used elsewhere, the user will have a double advantage. Firstly, the only information required is that to run the model; information was also required from NRZ to build the model. Secondly, the order of magnitude of the figures obtained for NRZ can serve as a check on the order of magnitude of figures obtained elsewhere.

PART V - RUNNING THE MODEL, AND CONCLUSIONS

CHAPTER TEN

RUNNING THE MODEL

10.1 Introduction

The purpose of this chapter is to demonstrate the way in which the model might be used. As stated in Chapter 1, and as listed in Section 10.2 below, five main areas of change in operating conditions can be investigated by the model. Within each area of change, many parameters can be altered. Therefore the number of combinations of operating conditions which can be represented is very large; and all can be investigated at several traffic levels, and with several values for unit costs and economic lives of resources.

However, it is likely that most users of the model would be interested only in specific combinations of changes, with many operating conditions being left in their present state. While there are interactions between all of the operating conditions listed above, links between some of them are particularly strong. Therefore, certain combinations of operating conditions are likely to be investigated together. These are discussed in Section 10.2.

The model would normally be run using inputs representing the "present state", and then again several times with new sets of inputs representing the changes. Outputs from each run can then be compared. As stated in Chapter 1, output is split between four files:-

(i) A general file, giving capacity measures, percentage utilisation of capacity, and total annual cost.
(ii) Journey times, including non-stop journey times, and delay times due to various factors, for each type of train in each direction.
(iii) Rolling stock requirements.
(iv) Annual costs, broken down into categories, such as locomotive depreciation, locomotive maintenance, track renewal, track replacement, etc.

There is also a fifth file available, giving journey times on each section between crossing loops, and stating which section is the one which limits line capacity. This is a utility file for investigations into changes in the number of crossing loops. (The number of crossing loops in the model is reduced by closing specific loops, and increased by opening loops at points midway between existent loops). Examples of each output file, when run for the model in its "present state", are given in Tables 10.1 to 10.5 below.

Table 10.1 The general output file from running the model for present operations on the Botswana line

CAPACITY MEASURES				TOTAL COSTS
NO OF TRAINS		NO OF INTERSECTIONS		Z$
MAXIMUM	% UTILISED	MAXIMUM	% UTILISED	
13.304	62.279	21.000	66.393	36191590

Table 10.2 The journey times output file from running the model for present operations on the Botswana line

	TRAIN TYPE					
	GOODS		MIXED		PASSENGER	
	UP	DOWN	UP	DOWN	UP	DOWN
NUMBER OF TRAINS	7.000	7.000	1.000	1.000	0.286	0.286
TIMETABLED TIMES (minutes):						
NON-STOP JOURNEY TIME	838.081	860.758	718.949	735.826	692.337	706.011
DELAY TIME AT INTERSECTIONS	144.887	145.323	18.750	18.793	2.715	2.716
DELAY TIME AT COMPULSORY STOPS	218.540	217.135	288.621	285.510	188.006	170.001
TOTAL JOURNEY TIME (minutes) (INCL LATE RUNNING)	1321.659	1345.537	1128.953	1144.142	971.364	966.600
NO OF INTERSECTIONS	13.921	13.942	13.611	13.619	13.555	13.555

Table 10.3 The rolling stock output file from running the model for present operations on the Botswana line

WAGON REQUIREMENTS	
General purpose	1750
Acid	4
Ammonia Anhydrous	15
Bitumen(tar)	19
Edible oil	3
Petrol(std)	71
Diesel(std)	138
Avgas(std)	4
Paraffin(std)	1
LPG	3
Tallow	7
Refrigerated bunker	0
Refrigerated mech	17
Resin containers	5
Coach	116
LOCOMOTIVE REQUIREMENTS	
DE2	36

Table 10.4 The costs output file from running the model for present operations on the Botswana line

ANNUAL COSTS IN Z$

ROLLING STOCK	
LOCOMOTIVE DEPRECIATION	1749140
WAGON DEPRECIATION	5187426
LOCOMOTIVE MAINTENANCE	3633889
WAGON MAINTENANCE	1419777
TRACK	
TRACK RENEWAL	4673393
TRACK MAINTENANCE	1084547
TRAINS WORKING METHOD (PAPER ORDER)	
TWM ADMINISTRATION	83424
TWM DEPRECIATION: EQUIPMENT	3823
TWM DEPRECIATION: BUILDINGS	165795
TWM OPERATION AND MAINTENANCE	1600420
STATION	
EXTRA MAIN STATION COSTS	0
OTHER TRAIN OPERATION	
CREW	3894302
FUEL	6064047
OIL	219450
YARDS AND ADMINISTRATION	
YARDS	6412155
ADMINISTRATION	0
TOTAL	
TOTAL	36191588

Table 10.5 The secton times output file from running the model for present operations on the Botswana line

File of section times in minutes

SECT	GOODS		MIXED		PASSENGER	
NO	UP	DOWN	UP	DOWN	UP	DOWN
1	12.891	12.891	11.793	11.793	11.793	11.793
2	16.979	24.545	15.533	21.573	15.533	19.448
3	21.674	27.539	19.828	22.848	19.828	20.508
4	18.642	23.686	15.791	18.737	15.791	16.869
5	14.568	16.971	12.340	13.482	12.340	12.340
6	14.919	15.792	11.935	12.756	11.189	11.621
7	17.746	21.426	14.197	16.924	13.309	15.292
8	17.995	17.995	15.243	15.243	15.243	15.243
9	14.267	15.140	12.085	12.223	12.085	12.085
10	23.467	23.467	19.168	19.168	19.168	19.168
11	16.317	20.733	14.927	16.363	14.927	14.927
12	14.199	14.199	12.027	12.027	12.027	12.027
13	23.507	23.507	23.507	23.507	23.507	23.507
14	21.430	17.136	16.837	13.709	15.182	12.852
15	21.035	17.484	16.624	13.987	15.024	13.113
16	10.393	10.393	8.314	8.314	7.794	7.794
17	14.507	21.709	11.606	18.433	10.881	17.129
18	12.577	15.619	10.061	12.284	9.432	11.081
19	19.825	19.825	15.860	15.860	14.869	14.869
20	16.551	13.954	13.110	12.275	12.275	12.275
21	13.280	12.737	10.757	10.190	9.809	9.553
22	16.559	13.019	14.956	11.910	13.358	11.910
23	13.915	13.080	11.230	10.464	10.227	9.810
24	11.353	11.353	9.082	9.082	8.515	8.515
25	7.012	7.289	5.610	5.907	5.259	5.388
26	17.409	20.353	15.926	16.159	15.926	15.926
27	13.537	13.537	10.830	10.830	10.153	10.153
28	10.220	12.985	8.176	11.236	7.665	10.060
29	23.562	23.562	18.849	18.849	17.671	17.671
30	19.101	19.101	16.180	16.180	16.180	16.180
31	18.332	18.332	14.666	14.666	13.749	13.749
32	16.286	16.286	13.029	13.029	12.215	12.215
33	14.046	17.846	11.237	15.065	10.534	13.508
34	13.537	13.537	10.830	10.885	10.153	10.153
35	12.963	12.963	10.370	10.370	9.722	9.722
36	23.402	23.402	18.722	18.722	17.552	17.552
37	19.340	19.340	17.692	17.692	17.692	17.692
38	17.135	13.374	15.464	11.329	13.808	11.329
39	7.603	11.705	7.603	9.293	7.603	9.168
40	23.295	23.295	22.199	22.199	22.199	22.199
41	4.233	4.233	3.873	3.873	3.873	3.873
42	15.728	15.728	15.728	15.728	15.728	15.728
43	8.835	8.835	8.082	8.082	8.082	8.082
44	11.573	11.573	11.573	11.573	11.573	11.573
45	10.890	10.890	9.963	9.963	9.963	9.963
46	21.197	20.280	20.280	20.280	20.280	20.280
47	14.881	14.881	13.614	13.614	13.614	13.614
48	7.125	7.125	6.518	6.518	6.518	6.518
49	26.289	20.690	22.608	19.716	20.249	19.716
50	15.025	14.709	14.709	14.709	14.709	14.709
51	18.079	11.856	13.458	11.856	11.856	11.856
52	15.949	15.949	14.030	14.030	14.030	14.030
53	12.902	12.902	10.322	10.322	9.677	9.677

CRITICAL SECTION 3

Results from the general file from each run will normally be compared first. Information in the other three output files may then be used. Often, the "best" few runs, where "best" may be in terms of capacity, cost, or a combination of the two, will be investigated further. For example, the run with the lowest rolling stock requirements may also be considered, as this is a resource often in short supply. Also, the breakdown of costs will often be of interest, and gives a rough indication of how costs are split between capital and other costs. Journey times may be of interest in their own right, or as an indication of how they affect the capacity of the line. The "utility file" for crossing loops may be used if investigations are made into opening or closing loops as it indicates the best sections for doing this.

Some examples of running the model to investigate possible changes on the Botswana line are given in Section 10.3, and this provides an opportunity to show how each output file might be used. In Section 10.4 results obtained from the runs are discussed, and Section 10.5 provides a conclusion to the chapter.

10.2 Combinations of operating conditions

The most important operating conditions which can be represented by the model are:-

(i) Type of trains working method

(ii) Number of crossing loops on the line, and/or their minimum length

(iii) Gradient and curvature of the track and/or track weight, type of fastening and sleeper materials

(iv) Size and/or speed of trains, and train types

(v) Types of rolling stock

The most common combinations which will be investigated are as follows:-

(i) and (ii): Choice of trains working method and number of crossing loops on the line

As discussed in Chapter 5, the number of crossing loops open on the line is affected by the choice of trains working method. There is an obvious link between the total costs of the trains working method and the number of loops that have to be equipped and operated. Also, the Van Schoor token working method requires every other loop to be manned, and this may influence the total number of loops remaining open.

(iii) Gradient and curvature of the track

This could be investigated on its own.

(iii) and (iv) Track weight and vehicle type

Maximum allowable axle load is dependent on track weight; hence track weight can affect the choice of vehicles.

(ii) and (iv) Minimum length of crossing loops and size of train

As discussed in Chapter 3, one of the factors influencing maximum train weight is the length of crossing loops.

(iv) Train types

The introduction of new train types (for example, one-commodity "liner" trains, or express passenger trains) will often be investigated on its own.

In most cases, investigation of any of the above combinations of operating conditions will be done for several possible levels of demand input. It may also be done using more than one set of values for unit costs and other parameters in the cost equations, if the user is doubtful as to the accuracy of their calibration.

10.3 Running the model using data from Botswana

As discussed in Chapter 5, a change in trains working method is envisaged when Botswana take over the line from NRZ. This is because there is debate as to whether the present Paper Order method is sufficiently safe when operated by newly trained crew. Two alternative trains working methods; the Van Schoor token working method and Colour Light signalling with CTC, have been discussed throughout this thesis. The investigation in this section is therefore based on an examination of the consequences of introducing new trains working methods.

If the Van Schoor method is introduced, this may mean closing some unmanned crossing loops, as well as manning some others. This will decrease the capacity of the line. One possibility being mooted in Botswana to compensate for this is the running of larger trains, by increasing the number of locomotives per train from one to two, and the minimum length of crossing loop from 414 metres to 762 metres. The runs of the model discussed in this section, therefore, include some with trains of the present size, and some with larger trains.

The model was also run for two demand levels; the present level, and double the present level.

The runs were done in the following order:-

1. Present traffic levels and train size; changing the number of crossing loops

For each trains working method, runs were done with:-

- 52 crossing loops. This is the present number in Botswana, and for the Van Schoor method necessitated increasing the number of manned loops from the present number of 14 to 26.
- 29 crossing loops. For Van Schoor, this is the maximum number of loops that there can be on the line without increasing the number of manned loops.
- 42 crossing loops (and 21 manned loops for Van Schoor)

2. Present traffic levels: increasing train size

Runs were done for each trains working method, and for each of the three numbers of crossing loops listed under 1. Train size was increased by increasing the minimum size of crossing loops from 414 metres to 762 metres, and the number of locomotives per train from one to two.

3. Doubling traffic levels

All the runs under 1 and 2 were then redone with a doubling of the goods traffic input. Results were above maximum capacity for all runs using the present train size, regardless of the number of crossing loops, except for with 52 loops and colour light signalling, when the line was at 98.5% of full capacity. All runs with the increased train size were below capacity. Further runs were therefore done to see the effect on capacity of increasing the number of crossing loops to 78, for both the present and larger train size.

Although all five output files were produced for each run (see Tables 10.1 to 10.5 for examples of these files) and information from them will be used in the ensuing discussion, only the results in the general files are reproduced in full here, in Table 10.6.

Table 10.6 Results produced by the general file for all runs of the model

Runs				Capacity measures				Total costs
				No of trains		Intersections		Z$
Run no	Locos per train	No of loops	Twm	maximum	utilised (%)	maximum	utilised (%)	
1. Present traffic levels and train size; changing no of crossing loops								
1	1	52	PO	13.304	62.279	21.000	66.393	36191590
2	1	52	VS	13.304	62.279	21.000	85.157	38968144
3	1	52	CL	15.666	52.891	-	-	35984449
4	1	29	PO	8.795	94.205	21.000	70.420	36381854
5	1	29	VS	8.795	94.205	21.000	79.119	37015829
6	1	29	CL	10.324	80.258	-	-	35621387
7	1	42	PO	11.103	74.626	21.000	67.583	36247165
8	1	42	VS	11.103	74.626	21.000	81.503	38084954
9	1	42	CL	13.053	63.475	-	-	35798698
2. Present traffic levels: increasing train size								
10	2	52	PO	13.341	31.054	21.000	31.086	33318718
11	2	52	VS	13.341	31.054	21.000	44.972	35957616
12	2	52	CL	15.709	26.373	-	-	33301388
13	2	29	PO	8.813	47.006	21.000	31.884	33235427
14	2	29	VS	8.813	47.006	21.000	38.897	33849876
15	2	29	CL	10.345	40.047	-	-	32748143
16	2	42	PO	11.133	37.213	21.000	31.327	33265931
17	2	42	VS	11.133	37.213	21.000	42.151	35019946
18	2	42	CL	13.089	31.652	-	-	33056510
3. Doubling traffic levels								
19	1	52	PO	13.182	115.958	21.000	135.111	61838662
20	1	52	VS	13.182	115.958	21.000	170.012	65974200
21	1	52	CL	15.520	98.488	-	-	60862441
22	1	29	PO	8.754	174.620	21.000	153.150	63052732
23	1	29	VS	8.754	174.620	21.000	165.674	64091564
24	1	29	CL	10.275	148.773	-	-	60917601
25	1	42	PO	11.039	138.470	21.000	139.544	62161147
26	1	42	VS	11.039	138.470	21.000	165.240	64938543
27	1	42	CL	12.978	117.785	-	-	60801033
28	2	52	PO	13.203	57.346	21.000	59.779	55539127
29	2	52	VS	13.203	57.346	21.000	84.486	59391363
30	2	52	CL	15.545	48.706	-	-	55272312
31	2	29	PO	8.767	86.367	21.000	62.927	55643722
32	2	29	VS	8.767	86.367	21.000	74.960	56782378
33	2	29	CL	10.290	73.582	-	-	54814461
34	2	42	PO	11.063	68.442	21.000	60.709	55546596
35	2	42	VS	11.063	68.442	21.000	79.540	58210555
36	2	42	CL	13.005	58.217	-	-	55045497
37	1	78	PO	19.161	79.774	21.000	129.125	61492802
38	1	78	VS	19.161	79.774	21.000	187.427	69084273
39	1	78	CL	22.655	67.472	-	-	61224460
40	2	78	PO	19.181	39.473	21.000	58.872	55679305
41	2	78	VS	19.181	39.473	21.000	98.202	62610862
42	2	78	CL	22.679	33.385	-	-	55884069

10.4 Discussion of results

Choice of trains working method

For each combination of traffic inputs, train size and number of crossing loops, the run with Colour Light signalling is cheapest, followed by that with Paper Order, the Van Schoor run being the most expensive of the three. The only exception to this is the run with 78 loops and the large train size, where the Paper Order method is slightly cheaper than the Colour Light method.

It could be expected, therefore, that Colour Light signalling would be chosen as the best trains working method for all combinations of circumstances represented in Table 10.6, apart from the one exception mentioned above.

However, there are several reasons why this cannot be regarded as a fundamental choice, valid on all occasions. These are as follows:-

- Total trains working method costs are split differently between capital and operating and maintenance costs for each method; capital costs of Colour Light signalling being much higher than those for the other methods. For example, for those runs of the model with present traffic levels, train size, and number of crossing loops (runs 1 to 3 in Table 10.6), depreciation costs make up 9.15% of the total for Paper Order, 10.66% for Van Schoor, and 53.27% for Colour Light. (For the purposes of this comparison, administrative costs for Paper Order and Van Schoor were taken to be an operating cost, since, as discussed in the Confidential Annexe, they consist of staff costs. Colour Light administrative costs were split such that they had the same operating costs as Paper Order and Van Schoor, the remainder representing depreciation of buildings). Shortages of capital on some railways may mean that the Paper Order method could be preferred over the Colour Light method unless the difference in costs between the two reached a certain level.
- On railways such as the Botswana line, where there is doubt as to the safety of the Paper Order method, Van Schoor may be chosen over Paper Order despite the difference in cost.

- Since operating and maintenance costs are largely staff costs, these will be lower on railways with lower wage rates or manning levels. The fact that a large proportion of Paper Order and Van Schoor costs are due to operating and maintenance costs means that the total costs of such methods will be reduced in a larger proportion, and may become cheaper in absolute terms, than those for Colour Light.
- If there are shortages of skilled staff, Paper Order or Van Schoor working may be preferred to Colour Light because these methods are easier to maintain.
- The accuracy of the calibration of the cost equations for trains working methods in this thesis (see the Confidential Annexe) cannot be estimated.
- Although not relevant to these runs of the model, it is worth pointing out that, as White suggests, (White 1983), Colour Light signalling may sometimes be preferred even on those occasions when it is more expensive than other methods. This will be true when other methods require manning of crossing loops in remote places, where few people want to live, and to which it is difficult to provide services such as water.

Thus Colour Light cannot be expected to be the cheapest method in all circumstances on all railways; and anyway other factors may influence the final choice of method. Therefore, in the ensuing discussion, runs for all three trains working method will be considered further. The discussion is broken into two parts; one on the effect of increasing train size, and one on the effect of varying the number of crossing loops. This section ends by picking out the lowest cost combinations which can be chosen from the runs in Table 10.6 at each traffic level; and by summarising those runs which must be rejected as being above the capacity of the line.

<u>Train size</u>

For any of the runs listed in Table 10.6; that is, for any trains working method, number of crossing loops, and traffic level; increasing the train size as described in Section 10.3 has the effect of roughly doubling capacity, while decreasing the total cost to the railway. The way in which each category of cost is affected is discussed here with reference to two runs; that representing the present operations in Botswana (Run 1 of Table 10.6), and that representing the same situation, but with larger trains (run 10). Table 10.7 provides the rolling stock requirements and cost breakdowns for run 10; those for run 1 have already been given in Tables 10.3 and 10.4.

Table 10.7 Rolling stock requirements and costs of increasing train size, leaving all other parameters the same (run 10 of Table 10.6)

Rolling stock file

WAGON REQUIREMENTS

General purpose	1740
Acid	4
Ammonia Anhydrous	15
Bitumen(tar)	19
Edible oil	3
Petrol(std)	71
Diesel(std)	137
Avgas(std)	4
Paraffin(std)	1
LPG	3
Tallow	7
Refrigerated bunker	0
Refrigerated mech	17
Resin containers	5
Coach	89
LOCOMOTIVE REQUIREMENTS	
DE2	34
DE3	0
DE4	0
DE6	0

Costs file

ANNUAL COSTS IN Z$

ROLLING STOCK	
LOCOMOTIVE DEPRECIATION	1702557
WAGON DEPRECIATION	4713718
LOCOMOTIVE MAINTENANCE	3633889
WAGON MAINTENANCE	1394160
TRACK	
TRACK RENEWAL	4773724
TRACK MAINTENANCE	1100141
TRAINS WORKING METHOD (PAPER ORDER)	
TWM ADMINISTRATION	83424
TWM DEPRECIATION: EQUIPMENT	3823
TWM DEPRECIATION: BUILDINGS	165795
TWM OPERATION AND MAINTENANCE	1600420
STATION	
EXTRA MAIN STATION COSTS	0
OTHER TRAIN OPERATION	
CREW	1837741
FUEL	5876273
OIL	219450
YARDS AND ADMINISTRATION	
YARDS	6213602
ADMINISTRATION	0
TOTAL	
TOTAL	33318718

The following points can be noted with regard to how costs change between the two runs.

- 11 less wagons, 27 less coaches, and 2 less locomotives are required for the larger trains. (The large drop in coach requirements is due to the fact that service vehicles are defined as coaches in this thesis, and depend on the number of trains). This means that locomotive and wagon depreciation costs, and, to a lesser extent, wagon maintenance costs, are reduced.
- Track renewal and maintenance costs are increased, due to the extra length of track required for crossing loops to accomodate the longer trains. The point made in Chapter 8, that the costs of earthwork involved in increasing crossing loop length are not included, and therefore track costs may be underestimated, is reiterated here.
- Trains working method costs are unaffected by train size.
- There is a very large saving of crew costs, which are more than halved with the longer train lenths. In fact, 71.6% of the difference between runs 1 and 10 comes from the difference between crew costs in the two runs. In situations where it is not considered possible or desirable to reduce the number of crew employed, it may not be possible to incur the financial benefits represented in the model, and it may in some circumstances therefore be considered preferable to retain the smaller trains. Also, the size of total differences in costs between running the smaller and larger trains will be heavily influenced by wage rates.
- There are some savings on fuel and yard costs with the larger trains.

The above discussion was conducted with regard to runs 1 and 10, for the Paper Order method. Other runs, for other trains working methods, show similar differences between the smaller and larger trains, except that, for Van Schoor, rolling stock requirements, and therefore costs, can be higher for the larger trains. This is because switching times at unmanned loops are longer, because the guard has to walk further with the longer crossing loops. Therefore turnaround times are longer for the larger trains with this trains working method. Journey times with other trains working methods are not affected in this way; although the occasional switching time at an unmanned loop may be longer for Paper Order, this is offset by the fact that there is less waiting time at meets and overtakes for a line with fewer, larger trains. For Colour Light, delay times are unaffected by loop lengths, but overall delay time is reduced when there are less meets and overtakes. (The decrease in delay time due to there being less meets and overtakes also occurs for Van Schoor but is not offset by the increased delay time due to longer crossing loops).

It can be concluded that the increase in train size will be preferred, except where:-

- It is not possible to recover the saving in crew costs by making some crew members redundant.
- Wage rates are very much lower than in Zimbabwe, so that the cost savings incurred by increasing the train size are small.
- The cost of earthworks to increase crossing loop size is unacceptably high.
- The smaller trains are preferred because they allow a higher frequency of service. However, as discussed in Chapter one of this thesis, this is not usually a priority for railways like the Botswana line.

Number of crossing loops

For all trains working methods, the smaller the number of crossing loops the lower the cost compared with other runs at the same traffic level and for the same train size. Therefore, the run with the lowest number of crossing loops which fulfils the requirement for maximum capacity will normally be chosen.

The effect of number of crossing loops on capacity varies according to the trains working method, and is now therefore discussed separately for each method.

For Colour Light, only one capacity measure is used. This is the one which is a function of the longest journey time between loops (see Chapter 6). Clearly, the more crossing loops the shorter the journey between them. Therefore, capacity for the Colour Light method always increases as the number of loops is increased.

Paper Order has two capacity measures. One is a function of journey time between loops, which always increases as the number of crossing loops increase, as described for Colour Light above. The other is based on the maximum number of intersections between trains, and was described in Chapter 6. For any given number of trains, the number of intersections between trains decrease as total journey times decrease (formulae for number of intersections were given in Table 5.6 of Chapter 5). Delay times at intersections decrease as number of crossing loops increase, because a train involved in an intersection at a loop does not have to wait so long, on average, for the other train to arrive at the loop. This effect is quite marked; for example, delay time due to intersections when modelling the Botswana line at present (run 1) is 144.887 minutes for the goods train in the up direction, whereas when the number of loops is reduced to 29 (run 4) it is 221.527 minutes. All other elements of journey time are unaffected by the number of loops for Paper Order, and so an increase in the number of loops will always increase capacity in terms of intersections.

Thus, for Paper Order, both measures of capacity increase as the number of crossing loops increase, but the measure which is critical in defining capacity varies according to the run. For all runs in Table 10.6 which are within capacity, number of intersections is critical at 78 and 52 loops, whereas section times are critical for 42 and 29 loops. This implies that the "number of intersections" measure of capacity becomes critical compared with the "section time" one as the number of loops increases.

The Van Schoor token working method has the same two measures of capacity as Paper Order. The measure defined by section times will always increase, as it does for the other trains working methods. The situation with number of intersections, however, is different. The Van Schoor method requires every train to stop at every loop. Therefore, delay times at compulsory stops increase as the number of loops increases. Even though delay time at intersections decreases for reasons explained in the discussion of capacity for Paper Order, the net result of an increase in the number of loops is to increase journey times, and thus to decrease capacity as defined by number of intersections.

Thus, one measure of capacity increases with the number of loops for Van Schoor, while the other decreases. The optimum number of loops in terms of maximum capacity for Van Schoor cannot be defined for all possible runs of the model, but for all runs defined in Table 10.6 which are within capacity it is 42.

Lowest cost combination

The lowest cost combination which can be chosen from the 42 runs in Table 10.6 is that with Colour Light signalling, larger train size, and 29 loops on the line. If lowest cost were the only factor considered, however, further runs would be done with less than 29 loops, since with this number of loops the line only uses 40.047% of capacity at present traffic levels, and 73.582% of capacity if traffic levels are doubled. Other factors influencing choice of combination of investments have been discussed above, and are more important in the case of trains working method than of train size.

Runs above capacity

When traffic levels are doubled, all runs with the present train size must be rejected, except for that with Colour Light signalling and 52 or 78 loops, on the grounds that they are above the capacity of the line.

10.5 Conclusion

The runs of the model discussed in this chapter illustrate the model's capability of quickly providing measures of capacity and cost, and thus allowing a very large number of combinations of investments to be investigated. This general information can be used to provide pointers as to the best areas for further investigation; for example the discovery that if train size is increased the line is well below capacity at present traffic levels for all trains working methods may lead to further investigations into shutting loops or increasing train size.

Information in the supplementary files is useful in allowing investments to be investigated on a less crude basis, once the most preferred general runs have been isolated, by indicating how costs are incurred, and showing the effect on journey times.

Obtaining the information in Table 10.6, and the information from the suggested further runs, without the model, would be painstaking in the extreme. Normally, only a very few combinations of investments could be investigated, as has been the case in Botswana. Use of a model such as the one described in this thesis is therefore important if an optimum investment strategy is to be formed.

CHAPTER ELEVEN

CONCLUSIONS

11.1 Introduction

In this thesis, a need has been identified for an investment model for a broad group of less developed country railways of which the Botswana line is a typical example, and a suitable model built and tested. This chapter provides an overview of how the model was developed and tested in Section 11.2. An account of how it can be used is given in Section 11.3. Conclusions reached from using the model in Botswana are discussed in Section 11.4. Implications for further work on the subject are discussed in Section 11.5. A final conclusion is reached in Section 11.6.

11.2 Development of the model

11.2.1 Identifying the type of model required

When a railway is being upgraded, several alternative investment proposals are usually available as to how this should be done. It is not possible to consider many combinations of such proposals without a computerised model, partly because of the interconnections between all areas of railway operations, and partly because of the number of combinations which should be considered for even a fairly simple investment package.

An investment model which could represent all the important effects of changing a railway's operating conditions, and produce quick, easily interpreted results using a simple data input was therefore considered necessary. The model was designed for railways like the Botswana line, and as such it was necessary to identify the type of operations which should be represented, and the most important measures of success of an investment proposal, on such lines. It was established in Chapter 2 that the lines of the Southern African region can be typified as predominantly goods lines, carrying traffic in slow-moving trains, often with severe operating problems, and a lack of resources. The main aims of such lines are to provide sufficient capacity at lowest possible cost; quality of service indicators such as speed and frequency of service are not often considered to be of importance.

Particular attention has been paid in this thesis, therefore, to building a model of the type of operations found on southern African railways, and to allowing for the problems of inefficiency. Care has been taken to develop suitable measures of capacity for such lines, as discussed in Chapter 6, based on the maximum amount of traffic that can be carried through a section, and safety considerations. The cost information produced by the model reflects the main effects of operating changes, and includes a breakdown of costs into the main areas of operations in which they occur. Final output from the model is presented in separate files. This allows a quick initial comparison of all investment alternatives using the "general" output file from each run to be followed up by more thorough investigation as required, using information from the other output files.

11.2.2 Developing the model from previous work on the subject

There was no model which, overall, satisfied the requirements in Section 11.2.1. Therefore one had to be built, and took the form of an operations model, capacity measures, and a cost model. Previous work was referred to at the construction of each stage of the model, but in all cases had to be developed further before it could be used.

The train speeds model described in Chapter 4 drew on some of the theory used in the World Bank model of Colombia (IBRD 1970). However, the World Bank had not tested their own model, and had it been used on the Botswana line it would have produced very inaccurate results. A model was developed for Botswana which allowed speeds to be calculated using user-defined sections, rather than the line as a whole, thus allowing the effects of gradients to be better represented. It also allowed speed limits to be defined on each section, due to curvature and other factors, as well as for the line as a whole. Extra factors likely to reduce speeds were identified and discussed, and a function derived to represent them.

A train delay model was also developed. This drew on E.R. Petersen's work (Petersen 1974) but made many alterations. Some of these were due to the fact that the trains working methods considered in this thesis had far longer switching times than those considered by Petersen. This meant that more care needed to be taken in defining the components of switching time. Also, the way in which different types of train delay could coincide was considered important; for example if one train is waiting for another, some of the operations performed in switching time can be performed during this waiting time. The model in this thesis was developed to allow for this. Furthermore, the possibility that train timetablers do not minimise delays to trains, as Petersen suggests, but rather build a safety allowance for trains to recover from late running was discussed. Such a safety allowance was defined, and tests on the Botswana line showed it to be of significant size. In addition to timetabled delays to trains, the model also defined an allowance for late running.

Several capacity measures were discussed in Chapter 6. Some of those used in developed country railways are defined in terms of fulfilling market constraints, such as timing and speed of delivery, and were considered inappropriate for the Botswana model. Two direct measures of capacity were defined. One was in terms of slowest section times, and adapted the work of the Batelle Institute. The other was a safety limit on the number of meets and overtakes between trains, developed from a NRZ limit on number of trains, in a way which would make it generally applicable to several lines. An indirect measure of capacity - train journey times - is also made available by the model.

Cost equations also had to be developed, as none suitable existed. This is partly due to the fact that little work has been done on the subject, and partly because some work which has been done is irrelevant because it is for costing systems designed for a purpose different from that in this thesis. Equations were produced using information on the variability of costs obtained from NRZ directly, and from other general sources.

11.2.3 Use of Botswana as a case study

The Botswana line provided a suitable case study as its operations are similar to those of the other railways in the Cape Gauge network, and thus a model built using data from Botswana could be used on several other southern African railways.

The choice of investments for study in the model was influenced by those being considered in Botswana; the model can represent three different trains working methods, and concentrates on single track running. The model can also represent some investments not being considered in Botswana, however, such as realignment of track.

Data was collected mainly from NRZ, as they run the Botswana line, with some supplementary data from Botswana. NRZ staff were helpful, and records kept at NRZ are probably better than those available on many other railways in the southern African region, many of which have severe operating problems. The data for the operations model was usually available from official sources within the railway, or from general literature on railway operations, and so collection of this data presented few problems.

Data for the cost equations was less easy to obtain, and often came from verbal interviews, or unsigned, undated, untitled written documents. Other work on the subject of railway costing shows this to be a general problem, and the information from NRZ can be regarded as helpful both in developing ideas on the variability of costs, and in providing a calibration of the model's cost equations for Botswana; albeit one whose accuracy cannot be thoroughly tested.

11.2.4 Accuracy of the model

Each stage of the operations model was tested against data available from NRZ and Botswana. Stages of the operations model can be divided into two groups. Firstly, there are those using the same sort of calculations as the Planning department at NRZ would use, such as the conversion of net tonnes to gross tonnes, calculation of number of trains each way per day, and calculation of capacity. In such cases, the model's output is as valid as the figures produced by NRZ, and comparison between the two was only done to check that results were of the right order of magnitude. Secondly, there are those for which tests were important in establishing their validity. These were maximum train weight, point to point speeds, and delay times.

While tests done on these parts of the model represent a development from previous work on the subject, they must be regarded as incomplete in the case of the point to point speeds and delay times sub-models, due to lack of data. This is because, for both these sub-models, time allowances are built in (for unknown factors reducing speed, and for a safety allowance at intersections, respectively), the values for which were obtained by comparing the outputs from the model run with these allowances set to zero, with the actual values for speeds and delay times in Botswana. The allowances were then set to a value which made the model's output as near as possible to actual results. Strictly, the calibrated model should have been tested on new data, in situations where these time allowances can be expected to be unchanged. This was not possible, and indeed, is unlikely to be possible on most railways. It is not considered to be a serious problem, however, as values for the time allowances would be similarly obtained wherever the model was used (see Section 11.3.1) and, once calibrated, would not be expected to change much with the sort of changes of operations subsequently examined by the model.

The accuracy of the cost equations, and the statistics they use such as gross tonne-km, and train-hours, could not be tested directly, as NRZ does not produce figures for Batswana costs and statistics separately from its own totals. However, the model's results were compared with those for the NRZ network as a whole, as a rough indication that orders of magnitude were correct. It was found that the model's statistics and costs were of the order of 15%-25% of NRZ's total, which is considered reasonable. Moreover, the breakdown of costs for Botswana is in proportions similar to those for NRZ as a whole.

11.3 Using the model

11.3.1 Preparation

Before the model can be used it has to be calibrated. A full set of input requirements, together with the values used in Botswana, is given in Appendix 2. Most of the inputs to the operations model, such as power of locomotives and weight of vehicles, will be easily and directly obtainable from railway data. The exceptions to this rule are the two time allowances, mentioned in Section 11.2.4, associated with point-to-point speeds and delay times. Ideally, these would both be obtained by running the point-to-point speeds and delay times sub-models separately, and comparing results with actual results until the best value for these allowances is found.

Calibration of the cost equations is more complicated, and the ease with which it can be done will depend on the quality of data available. The Confidential Annexe to this thesis gives an example of the activities involved in producing the required figures.

11.3.2 Running the model

Usually, an initial run of the model will be done, representing present operations on the line, and the resultant output compared with available information to check that the model is producing valid results. Once this has been done, it is a quick, simple task to run the model several times with the relevant inputs changed to represent the investments being investigated. As discussed in Chapter 1 and illustrated in Appendix 2, inputs are grouped into files according to the investments which affect them, so that only a few files will have to be changed for each run. Output is in four files, and normally the general file from each run will be examined first. This file contains measures of line capacity and total cost and will be used:-

- to identify a small number of runs of the model which have produced the "best" outcomes, where "best" is defined by the user, and will normally be the lowest cost outcomes which produce the required capacity. These runs can, if required, be examined further, in terms of rolling stock requirements, journey times, and breakdown of costs, using information from the other three output files.
- To provide pointers for further runs of the model. For example, if all runs were well below capacity, further runs could be done with less resources. Alternatively, changing one parameter may have resulted in decreasing costs, and therefore lead to investigating further changes in that parameter.

By repeatedly following pointers to further runs, and identifying the best of those runs, the user may easily produce hundreds of runs. Even the simple illustration of the model's use in Chapter 10 produced 42 runs. The amount of information thus available to the user of this model is very much greater than that which would be available using normal appraisal methods, and there is therefore a far greater likelihood of the optimum investment package being identified if the model is used.

11.4 Information obtained by running the model for Botswana

The runs of the model discussed in Chapter 10 merely served as an illustration of the way the model could be used. Information from them cannot therefore be taken as conclusive evidence as to the best investment package to use on the Botswana line. However, the information from these runs did show that the model was able to provide a more comprehensive analysis of the different options available to Botswana than had been made in the original documents examining them. The options considered were changing the trains working method and number of crossing loops, changing the train size, and changing the traffic levels.

The model was able to show:-

- That increasing the train size by using two locomotives per train instead of one, and increasing the crossing loop length, had the effect both of increasing capacity and decreasing cost. The cost saving came mainly from a decrease in crew requirements. The accuracy of the cost equations used in Botswana is unknown, but, even if very large changes in unit labour costs were observed, some cost saving would occur by increasing train size.
- That colour light signalling was the cheapest trains working method, with the present calibration of costs. However, this conclusion is not as robust to cost changes as was the conclusion on train size; changing unit costs could well make another trains working method cheaper than Colour Light. The difference in breakdown of costs for the three trains working methods is important, Colour Light having a far larger proportion of capital costs than the other methods, and this may influence the final choice of trains working method, as discussed in Chapter 10.
- As is to be expected, a decrease in the number of crossing loops on the line decreases total costs, all other things being equal. However, the effect of the number of loops on capacity varies in ways which might not at first be obvious. This was discussed in detail in Chapter 10 where it was stated that, all other things being equal, increasing the number of crossing loops increased the capacity for Colour Light signalling and Paper Order working. However, for Van Schoor working, increasing the number of loops

increases journey times, and hence number of intersections between trains, which is one of the measures of line capacity. Therefore, for Van Schoor there is an optimum number of loops below which capacity will fall as journey times between loops increase, and above which capacity will fall as number of intersections increase.

- The model's results provide the following pointers for further investigation:-

  (i) Increasing train size has the effect that, at present traffic levels, less than half the capacity of the line is used, even when the number of crossing loops is reduced to the lowest level tested (29). Provided no increase in traffic levels is expected, therefore, it is possible to reduce resources, and therefore costs, by reducing the capacity of the line further. This could be done, for example, by reducing the number of crossing loops below the lowest number tested.

  (ii) If the Van Schoor trains working method is investigated, the optimum number of loops from the point of view of capacity should be established. Above this number, capacity falls and costs rise so it is never rational to have more loops unless these are essential because they are required as compulsory stops on the line. Below this number there will be a trade-off between total costs and capacity, as observed for the other trains working methods.

11.5 Implications for further work

11.5.1 Introduction

Further work on the model can be divided into four areas. Firstly the accuracy of the operations model could be further tested. Secondly, further work could be done on costing. Thirdly, the model as it stands could be used for other investigations than those discussed in Chapter 10. Fourthly, the model could be developed further so that it could investigate other investments. These are discussed in turn.

11.5.2 Further tests on the operations model

As partly discussed in earlier sections of this chapter, further testing would be welcome to establish the accuracy of the sub-models on point-to-point speeds and train delays. In the case of point-to-point speeds it would be particularly useful to test the model on a line with more variation in gradients than that in Botswana. In the case of the train delay model, tests for trains working methods other than Paper Order would be desirable.

11.5.3 Developing the cost equations

As was made clear in the literature reviews in Chapters 2 and 8 of this thesis, general information on the factors affecting railway costs is poor, and any work done in this area would be beneficial to the development of cost equations for the model.

With regard to calibration of the cost equations; their accuracy could be much improved if enough information was available from a railway to allow a time-series econometric analysis to be used to establish the size of parameters. Also, such an analysis could be used to include in equations some variables which are known to be important, but which are excluded at present due to lack of data on the subject. These variables include the effect of gradient and track weight on track maintenance equations, and the effect of crew working methods on crew costs.

When the model is run, it may be found that one cost is particularly affected by the investment being investigated. In the case of the runs described in Chapter 10, for example, crew costs were found to be crucially affected by train size. Where this is the case, the user of the model might pay particular attention to developing the cost equation shown to be of importance.

11.5.4 Using the present model for further investigations

As the model stands, investigations into changes in unit costs and economic lives; gradient and curvature of track; and train types could be performed. Also, further investigation into changes in trains working method, number of crossing loops and train size could be done using the pointers to new runs provided in chapter 10. This was discussed earlier in this chapter in Section 11.4. Other parameters could be altered within the runs used in Chapter 10 - for example, a change in minimum switching time for each trains working method could be investigated. Furthermore, the model could investigate changes in track weight and vehicle type, although, as discussed in Section 11.5.3, track maintenance equations do not include track weight as an explanatory variable.

11.5.5 New areas of development of the model

The areas of development of the model most likely to be required are to allow it to represent double track working, and different types of traction (electric and steam).

Introduction of double track would necessitate changes in the train delay model, so that the only intersections were overtakes, and switching times were changed. Representation of changes in traction would require different equations for tractive effort.

A further, less likely area of development would be to allow for train speeds greater than 75kph. In this case alternative tractive effort and train resistance equations would have to be provided which were accurate over the higher speed ranges.

11.6 Conclusion

A model has been built which fulfils the objective of the thesis. That is, it produces information on a railway's capacity and costs with sufficient accuracy and detail to facilitate investment decisions. The inputs required for the model are simple enough to allow it to be easily calibrated even under circumstances where data collection is difficult, as is often the case in less developed countries. Once calibrated for the railway being investigated, the model can quickly and easily be run many times, to produce figures showing the effects of many different investment alternatives.

The model could usefully be further tested and extended in several ways, as indicated in Section 11.5. It can nevertheless be regarded in its present form as an adequate basis for an investment model for a less developed country railway.

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Mr Frank Butler	Planning
Mr Howard Butson	Rail Priority Committee
Mr Don Chapman	Mechanical Engineering
Mr Cameron	Planning
Mr deYong	Mpopoma running sheds and yards
Mr Digby-Jones	Personnel
Mr Evans	Planning
Mr Len Garland	Planning
Mr Ken Jackson	Planning
Mr Keefe	Planning
Mr Keene - Young	Bulawayo Workshops
Mr C. Langoire	Accounts
Mr McCarthy	Estates
Ms Ann Moody	Personnel
Mr O'Connell-Jones	Personnel
Mr Keith Pardoe	Statistics
Mr Bob Parker	Working Timetable
Mr Bill Richards	Wagon Control
Mr Sawyer	Signals
Mr Swindells	Planning
Mr Ventura	Accounts
Mr Gavin Viljoen	Planning

Other unnamed persons were also interviewed within NRZ

Other Organisations

Mr John Bumphrey	Independent Consultant, Otley 1982
Mr O.P. Nayar	Ministry of Works and Communications, Botswana 1982
Mr John Sutton	GEC Traction 1981 and 1982

APPENDIX TWO

Input files used in testing the model with Botswana data

The general structure of input files was discussed in Sections 1.1 and 1.5 of Chapter 1. It was pointed out there that inputs are grouped into files according to certain criteria. These criteria are listed below, together with the symbols used to represent them.

x	trains working methods and crossing loops
t	train types
g	track profile
w	track weight and type of fastenings and sleepers
c	traffic levels
e	parameters describing efficiency of railway operations, and general railway operating characteristics
p	unit costs
l	economic life of capital goods

Eleven input files are used, representing different combinations of the above criteria. Their names are as follows:-

CATWw
WEIGCcTt
PAYLDWw
TRANTt
LINEGg
XLOOPXx
EFFIEe
COSTPp
LIFELl
COSTPpXx
LIFELlXx

Whenever a change in one of the eight criteria listed above is being investigated, those input files whose names contain the symbol representing that criterion will require changes. Other input files can remain the same.

The contents of each input file are discussed below, and the example file used when testing the model with Botswana data is given. For one file affected by the trains working method, XLOOPXx, three examples are given, one for each trains working method being considered in Botswana. For the other files affected by the trains working method, COSTPpXx and LIFELlXx, information is given for all three trains working methods in the Confidential Annexe. For all other files only one example is given.

As stated in Chapter 1, parts of the model cna be run separately for testing purposes. When this is done, subsets of each input file are used, as required for that part. In addition, an input file COMMONKk is used, which contains all the information which would be passed across from other subroutines when the model is run as a whole. No examples of the file COMMONKk are given in this Appendix.

CATWw

Information on wagons and locomotives.
For Botswana this is as follows:-

Wagons

Wagon name	Ref no	Tare weight (tonnes)	X-sect area (sq m)	Length (metres)	No of axles
General purpose	1	18.5	7.90	12.89	4.00
Acid	2	18.1	9.50	13.00	4.00
Ammonia Anhydrous	3	26.2	10.38	13.51	4.00
Bitumen(tar)	4	30.2	10.38	13.51	4.00
Edible oil	5	21.4	2.39	14.37	4.00
Petrol(std)	6	20.9	9.50	13.00	4.00
Diesel(std)	7	20.9	9.50	13.00	4.00
Avgas(std)	8	20.8	9.50	13.00	4.00
Paraffin(std)	9	20.9	9.50	13.00	4.00
LPG	10	29.4	10.38	13.51	4.00
Tallow	11	19.8	7.19	12.69	4.00
Refrigerated bunker	12	30.0	9.50	13.15	4.00
Refrigerated mech	13	23.0	9.60	14.22	4.00

Resin containers	14	23.0	2.39	14.37	4.00
Coach	15	30.0	10.00	15.0	4.00

number of passengers per coach 173
average weight per passenger 0.1 tonne

Locomotives

Loco name	Weight (tonnes)	X-sect area (sq m)	Length (metres)	no of axles	no of powered axles	elec-mech eff	min cont sp(kph)
DE2	114.8	11.5	18.060	8.0	6.0	0.886	21.8

WeigCcTt

Number of train types, and then, for each train type, number of commodities, number of passengers, name and amount of each commodity to be carried.

For Botswana these are as follows:-

Number of train types 3

First train type

train type name	GOODS
number of commodities	81
number of passengers	0

names of commodities carried, and annual gross tonnages

AMMONIUM ANHYDROUS	7200.0000
AMMONIUM SOLUTION	200.0000
AMMONIUM SULPHATE	1520.0000
ASBESTOS	600.0000
BEER	200.0000
BITUMEN	7460.0000
BORATE	800.0000
BRICK, FIREBRICKS	13940.0000
CAUSTIC SODA LYE	3120.0000
CEMENT	22880.0000
CLAY	1100.0000
COAL	26280.0000
COBALT	0.0000
COKE	23340.0000
COPPER CONCENTRATES	0.0000
COPPER METAL	0.0000
COTTON	0.0000
EDIBLE OIL	1260.0000
EXPLOSIVES	13820.0000
FERRO ALLOYS	40.0000
FERTILISERS	19300.0000
FIRE CLAY	1440.0000
FLOUR	8500.0000
FLUOISPAR	80.0000
FRUIT CITRUS	0.0000
FRUIT FRESH	840.0000
GLYCERINE	140.0000
GYPSUM	1440.0000
HESSIAN	1040.0000
HIDES	0.0000
KAOLIN	400.0000
LEAD	360.0000
LIME	22460.0000
LIMSTONE	80.0000
LIVESTOCK	0.0000
MACHINERY	4820.0000
MAIZE	178600.0000
MAIZE MEAL	23400.0000
MALT	2800.0000
MANGANESE	2400.0000
MINERALS(OTHER)	460.0000
MOTOR VEHICLES	1820.0000
NITRATE OF SODA	2480.0000
OIL SEED CAKE	0.0000
ORS GENERAL	6320.0000
OTHER GOODS	193020.0000
PAPER	3920.0000
PIG IRON	200.0000
LPG	900.0000
PETROL	34300.0000
DIESEL	60660.0000
DIESEL (RAILWAY)	8800.0000
KEROSENE	7000.0000
POWER PARAFFIN	400.0000

AVGAS	1500.0000
LUBRICANT(TANK CAR)	3020.0000
LUBRICANT(DRUMS)	0.0000
POTASH	11200.0000
REFRIGERATED TRAFFIC	0.0000
BEEF	0.0000
MISCELLANEOUS	0.0000
RESIN	2320.0000
SALT	38180.0000
SCRAP IRON,STEEL	0.0000
SILICON	480.0000
SORGHUM	16400.0000
STEEL	36240.0000
STOCK	15280.0000
STONE	6000.0000
SULPHUR	22600.0000
SULPHURIC ACID	1920.0000
SUGAR	0.0000
TALLOW	3080.0000
TEA	700.0000
TIMBER (PROCESSED)	5040.0000
TIMBER (ROUGH)	26320.0000
TIN	0.0000
UREA	3000.0000
WAX	960.0000
WHEAT	54400.0000
ZINC	280.0000

Second train type

train type name	MIXED	
number of commodities	2	
number of passengers	482298	
LIVESTOCK		500.0000
BEEF		4000.0000

Third train type

train type name	PASSENGER
number of commodities	0
number of passengers	125673

PAYLDWw

For each commodity the payload in tonnes is given, together with the reference number for the wagon which carries it. (Reference numbers for wagons are also listed in CATWw)
For Botswana the information is as follows:-

Commodity	payload	wagon ref no
AMMONIUM ANHYDROUS	32.0	3
AMMONIUM SOLUTION	27.0	1
AMMONIUM SULPHATE	34.0	1
ASBESTOS	39.0	3
BEER	35.0	1
BITUMEN	25.0	4
BORATE	30.0	1
BRICKS, FIREBRICKS	38.0	1
CAUSTIC SODA LYE	35.0	1
CEMENT	39.0	1
CLAY	37.0	1
COAL	39.0	1
COBALT	41.0	1
COKE	28.0	1
COPPER CONCENTRATES	41.0	1
COPPER METAL	38.0	1
COTTON	19.0	1
EDIBLE OIL	30.0	5
EXPLOSIVES	26.0	1
FERRO ALLOYS	39.0	1
FERTILISER	39.0	1
FIRE CLAY	38.0	1
FLOUR	36.0	1
FLUOISPAR	38.0	1
FRUIT CITRUS	22.0	1
FRUIT FRESH	14.0	1
GLYCERINE	35.0	1
GYPSUM	37.0	1
HESSIAN	20.0	1
HIDES	18.0	1
KAOLIN	40.0	1
LEAD	39.0	1

LIME	38.0	1
LIMSTONE	42.0	1
LIVESTOCK	9.0	1
MACHINERY	12.0	1
MAIZE	39.0	1
MAIZE MEAL	35.0	1
MALT	32.0	1
MANGANESE	39.0	1
MINERALS(OTHER)	34.0	1
MOTOR VEHICLES	6.0	1
NITRATE OF SODA	31.0	1
OIL SEED CAKE	32.0	1
ORS GENERAL	31.0	1
OTHER GOODS	18.0	1
PAPER	22.0	1
PIG IRON	33.0	1
LPG	25.0	10
PETROL	32.0	6
DIESEL	34.0	7
DIESEL (RAILWAY)	34.0	7
KEROSENE	32.0	7
POWER PARAFFIN	33.0	9
AVGAS	28.0	8
LUBRICANT(TANK CAR)	32.0	6
LUBRICANT(DRUMS)	19.0	1
POTASH	37.0	1
REFRIGERATED TRAFFIC	12.0	12
BEEF	15.0	13
MISCELLANEOUS	12.0	12
RESIN	32.0	14
SALT	37.0	1
SCRAP IRON,STEEL	35.0	1
SILICON	42.0	1
SORGHUM	39.0	1
STEEL	40.0	1
STOCK	30.0	1
STONE	38.0	1
SULPHUR	36.0	1
SULPHURIC ACID	36.0	2
SUGAR	37.0	1
TALLOW	29.0	11
TEA	17.0	1
TIMBER (PROCESSED)	30.0	1
TIMBER (ROUGH)	29.0	1
TIN	29.0	1
UREA	29.0	1
WAX	35.0	1
WHEAT	39.0	1
ZINC	37.0	1

TRANTt

Information on each train type.
For Botswana this is as follows:-

	Goods		Trains Mixed		Passenger	
Number of locos per train	1		1		1	
Type of locomotive	DE2		DE2		DE2	
Max no of axles over which brakes will work	200		200		200	
Ratio of allowed to max weight (RMAXWT)	1.0		0.7		0.595	
Number of guards vans per train	1		1		1	
Speed limit (kph)	60.0		75.0		80.0	
	Directions					
	Up	Down	Up	Down	Up	Down
Ave no of comp stops per journey	16.558	15.694	49.0	49.0	13.0	13.0
Ave time per comp stop (mins)	9.779	10.39	3.319	3.255	10.462	9.07
Ave deceleration time per stop (mins)	2.0	2.0	2.0	2.0	2.0	2.0
Ave no of comp stops at manned loops	11.409	11.343	14.0	14.0	13.0	13.0

Priorities between train types at meets and overtakes:-
RPRMET(NO,JT,IT) proportion of times that a train of type JT travelling in direction NO takes low priority in a

	meet with a train of type IT travelling in the opposite direction
RPROV(NO,JT,IT)	proportion of times that a train of type JT travelling in direction NO takes low priority in an overtake with a train of type IT travelling in the same direction

```
0.5   rprmet(1,1,1)
1.0   rprmet(1,1,2)
1.0   rprmet(1,1,3)
0.0   rprmet(1,2,1)
0.5   rprmet(1,2,2)
1.0   rprmet(1,2,3)
0.0   rprmet(1,3,1)
0.0   rprmet(1,3,2)
0.5   rprmet(1,3,3)
1.0   rprov(1,1,2)
1.0   rprov(1,1,3)
1.0   rprov(1,2,3)
1.0   rprov(2,1,2)
1.0   rprov(2,1,3)
1.0   rprov(2,2,3)
```

<u>LINEGg</u>

Information on the track profile
For Botswana this is as follows:-

ruling gradient (%) 1.25
number of sections (user defined with no major gradient changes) 53

For each section:-

average gradient (%)	speed limit (kph) (1000.0 = no section limit)	length (metres)
-0.115	62.5	10442
-0.698	62.5	13753
-0.478	62.5	17556
-0.429	67.5	15100
-0.346	67.5	11800
-0.268	77.5	12084
-0.376	77.5	14374
0.0	67.5	14576
-0.270	67 5	11556
0.1136	70.0	19008
-0.4267	62.5	13217
0.146	67.5	11501
-0.0197	55.0	18316
0.406	77.5	13880
0.373	1000.0	14162
0.0413	1000.0	8418
-0.735	77.5	11751
-0.400	1000.0	10187
-0.045	77.5	16058
0.361	65.0	11303
0.2559	1000.0	10317
0.569	62.5	10545
0.272	1000.0	10595
-0.00522	77.5	9196
-0.2535	77.5	5680
-0.349	62.5	14101
-0.0876	1000.0	10965
-0.522	1000.0	8278
-0.0503	77.5	19085
0.155	67.5	15472
0.178	77.5	14849
0.0728	1000.0	13192
-0.496	77.5	11377
-0.208	1000.0	10965
0.183	1000.0	10500
0.0	1000.0	18956
0.0153	62.5	15665
0.576	67.5	10833
-0.810	55.0	5924
0.146	60.0	18869
0.0	62.5	3429
0.245	55.0	12255
-0.067	62.5	7156
0.0976	42.5	7378
-0.0272	62.5	8821

0.5687	47.0	13503	
0.0199	62.5	12054	
0.0832	62.5	5771	
0.5155	60.0	16759	
0.5886	45.0	9377	
1.0479	42.5	7558	
0.167	65.0	12919	
-0.1837	1000.0	10451	
ave gradient of whole line (nb can be anything since pgav 0.0)			2.0

XLOOPXx

Information on crossing loops and trains working methods. Three versions of this file are given here; XLOOPX1 for paper order working, XLOOPX2 for Van Schoor token working, and XLOOPX3 for colour light.

	XLOOPX1	XLOOPX2	XLOOPX3
Min length of crossing loop (metres)	414.0	414.0	414.0
For each section of the line in turn, number of crossing loops on the section (for the Botswana line there is one crossing loop per section, thus 52 1's and one 0 are input; not repeated here.			
Time to exchange paper orders (mins)	2.0	-	-
Time to exchange tokens (mins)	-	2.0	2.0
Ave length of crossing loop (metres)	440.0	440.0	440.0
Number of manned loops	14.0	26.0	14.0
Switching time at points (mins)	4.0	4.0	3.0
Headway allowance (mins)	1.0	1.0	1.5
Safety allowance (mins)	2.5	3.0	1.5

EFFIEe

Parameters expressing the operating characteristics and efficiency of the railway.
For Botswana these are:-

Ratio of empty to full wagons	0.424
Ratio of average to allowed train weight	0.82
No of days p.a. for which line is open	350.0
No of days over which timetable completes	7.0
VACPRE speed in kph below which predicted speeds are multiplied by RACLOW	45.0
RACLOW ratio of actual to predicted speeds at low speeds	1.0
RACBAL ratio of actual to predicted speeds at speeds between VACPRE and the sp limit	0.85
RACPRE ratio of actual to predicted speeds at the speed limit	0.81
Time per day for which the line closed (mins)	0.0
RLATE ratio of actual to timetabled speeds	1.1

For each wagon type
yard time (TYARD) and ratio of time spent in maintenance
TYARD = 25568.0 mins for all wagons; 6000.0 mins for coaches
RMAINT = 0.08 for all wagons and coaches apart from refrigerated vehicles, for which it is 0.12
For each locomotive type
ratio of time spent in maintenance (RMAINT)
For the DE2 RMAINT = 0.377
Locomotive utilisation factor, RLUF 0.206

COSTP1

Cost information not varying with trains working method
Information contained in Confidential Annexe

COSTP1X1, COSTP1X2, COSTP1X3

Cost information varying with trains working method
Information contained in Confidential Annexe

LIFEL1

Information on economic lives of capital goods
not varying with trains working method
Information contained in Confidential Annexe

<u>LIFEL1X1</u>, <u>LIFEL1X2</u>, <u>LIFEL1X3</u>

Information on economic lives of capital goods
varying with trains working method
Information contained in Confidential Annexe

APPENDIX THREE

A comparison of actual and computed values for NRZ's DE2 locomotive

Since NRZ's values for tractive effort are in kg, and the formula quoted in the text (Equation 4.1) was in KN, the formula must be converted as follows.

$$TE = \frac{3600(PL)(EL)}{9.81\ V}$$

for the DE2, PL = 1095kW

therefore if EL = 0.822, $TE = \frac{330308.2568}{V}$

if EL = 0.886, $TE = \frac{356025.688}{V}$

Speed (kph)	Actual tractive effort (kg)	Predicted tractive effort		Percentage error	
		EL=0.822	EL=0.886	EL=0.822	EL=0.886
0.0	27800				
5.0	25800	66061.65	71205.15	156.05	176.00
10.0	23800	33030.83	35602.57	38.79	49.59
15.0	21750	22020.55	23725.05	1.24	9.13
20.0	17200	16515.41	17801.28	-3.98	3.50
25.0	14000	13212.33	14241.03	-5.63	1.72
30.0	11800	11010.28	11867.52	-6.69	0.57
35.0	10200	9437.38	10172.16	-7.48	-0.27
40.0	9200	8257.71	8900.64	-10.24	-3.25
45.0	7700	7340.18	7911.68	-4.68	2.75
50.0	7020	6606.16	7120.51	-5.90	1.43
55.0	6500	6005.60	6473.19	-7.61	-0.41
60.0	6030	5505.14	5933.76	-8.70	-1.60
65.0	5450	5081.67	5477.31	-6.76	5.06
70.0	4400	4718.69	5086.08	7.24	15.59
75.0	3740	4404.11	4747.01	17.76	26.93
80.0	3260	4128.85	4450.32	26.65	36.51

APPENDIX FOUR

Comparison of initial computed goods speeds with actual speeds, plotted against average gradient

Comparison of initial computed mixed speeds with actual speeds, plotted against average gradient

APPENDIX FIVE

Regression of goods speeds on average gradient for sections where speed limit=60kph

Data set & regress form	R^2	s.d of V	mean of V	para-meters	Estimate of para-meters	s.e of est. of para-meters	df	t for R^2	t>2	para est >2SE
GAV>0.25 quadratic	0.382	5.205	43.37	I	53.8877	11.566	19	2.7	yes	yes
				G	-20.9257	51.7824				no
				S	-8.0107	54.2958				no
GAV>0.25 linear	0.381	5.076	43.37	I	55.5037	3.622	20		yes	yes
				G	-28.4664	8.1099				yes
GAV=<0.25 linear	0.170	5.278	48.692	I	47.325	0.729	69	3.416	yes	yes
				G	-10.192	2.736				yes
GAV>0.16 quadratic	0.416		44.275	I	50.0684	5.9293	24	3.156	yes	yes
				G	-4.286	30.2654				no
				S	-24.6305	35.1636				no
GAV>0.16 linear	0.404	4.834	44.275	I	53.826	2.499	25		yes	yes
				G	-25.044	6.082				yes
GAV=<0.16 linear	0.197	5.332	48.725	I	46.862	0.814	64	2.22	yes	yes
				G	-11.755	2.991				yes
GAV>0.07 quadratic	0.272	5.281	44.095	I	42.749	3.289	32	2.95	yes	yes
				G	28.008	20.275				no
				S	-57.170	26.801				yes
GAV>0.07 linear	0.169	5.558	44.095	I	48.535	1.9567	33	2.36	yes	yes
				G	-13.855	5.356				yes
GAV=<0.07 linear	0.132	5.237	49.460	I	47.571	0.953	55	2.69	yes	yes
				G	-9.600	3.320				yes
GAV>0.0 quadratic	0.224	5.672	44.743	I	46.0247	2.0134	40	2.993	yes	yes
				G	10.0203	14.8119				no
				S	-36.344	22.0379				no
GAV>0.0 linear	0.1715	5.79	44.743	I	48.288	1.504	41	2.649	yes	yes
				G	-13.271	4.556				yes
GAV=<0.0 linear	0.146	4.953	49.767	I	47.431	1.0855	47	2.62	yes	yes
				G	-9.965	3.5109				yes
all GAV quadratic	0.299	5.317	47.419	I	47.836	0.707	89	5.154	yes	yes
				G	-10.567	1.737				yes
				S	-4.095	4.305				yes
all GAV linear	0.2915	5.315	47.419	I	47.419	0.554	90		yes	yes
				G	-10.567	1.736				yes

Parameters:-

I intercept
G coeffient of Gav
S coefficient of the square of GAV

Regression of mixed speeds on average gradient for sections where speed limit=75kph

Data set & regress form	R^2	s.d of V	mean of V	para-meters	Estimate of para-meters	s.e of est. of para-meters	df	t for R^2	t>2	para est >2SE
GAV>0.25 quadratic	0.692	4.918	50.531	I	80.819	13.476	8	2.35	yes	yes
				G	-105.653	61.685				no
				S	65.607	64.409				no
GAV>0.25 linear	0.652	4.928	50.531	I	67.87	4.48	9		yes	yes
				G	-43.764	10.669				yes
GAV=<0.25 linear	0.317	6.246	61.138	I	58.727	1.259	31		yes	yes
				G	-18.251	4.808				yes
GAV>0.16 quadratic	0.5407	5.459	51.691	I	62.033	8.301	12	2.54	yes	yes
				G	-25.919	43.789				no
				S	-10.881	50.725				no
GAV>0.16 linear	0.539	5.255	51.691	I	63.650	3.354	13		yes	yes
				G	-35.095	9.002				yes
GAV=<0.16 linear	0.258	6.415	62.001	I	58.863	37.47	27		yes	no
				G	-17.797	-3.06				yes
GAV>0.07 quadratic	0.3503	6.699	51.212	I	50.086	6.147	14	6.086	yes	yes
				G	32.254	35.890				no
				S	-72.014	45.631				no
GAV>0.07 linear	0.2347	7.024	51.212	I	58.098	3.634	15	1.876	no	yes
				G	-22.203	10.352				yes
GAV=<0.07 linear	0.193	5.372	63.066	I	60.595	1.446	25			yes
				G	-12.655	5.173				yes
GAV>0.0 quadratic	0.378	6.635	52.845	I	57.076	3.378	18	2.608	yes	yes
				G	-3.541	23.457				no
				S	-33.152	34.174				no
GAV>0.0 linear	0.346	6.625	52.845	I	59.281	2.494	19	2.564	yes	yes
				G	-24.969	7.883				yes
GAV=<0.0 linear	0.166	5.546	63.637	I	60.703	1.843	21		yes	yes
				G	-12.464	6.098				yes
all gradients quadratic	0.5607	5.971	58.486	I	59.585	1.134	41	4.792	yes	yes
				G	-20.546	2.912				yes
				S	-11.512	7.217				yes
all gradients linear	0.533	6.080	58.486	I	58.485	0.917	42		yes	yes
				G	-20.546	2.965				yes

Parameters:-

I intercept
G coeffient of Gav
S coefficient of the square of GAV

APPENDIX SIX

Combinations of delay times

In this Appendix, ways in which the different delay times described in Section 5.3.4 can combine are discussed. To repeat the list given in that section, delay times are:-

- Waiting time
- Switching time
- Overlap time
- Compulsory stops
- Acceleration time
- Safety allowance

The incorporation of acceleration time into waiting time is discussed in Section 5.3.4 and Appendix 7. For all other types of delay acceleration time is simply added to other times, since it clearly cannot occur while the train is stationary. The safety allowance is always added to other delay times; the point of it would be lost if it was combined with them.

Combinations of delay times are discussed as follows:-

- Compulsory stop and waiting time
- Compulsory stop, switching time and overlap time
- Waiting time, switching time and overlap time

Compulsory stop and waiting time

If a train already delayed at a compulsory stop is also waiting for another train to arrive for a meet or overtake, then the two times can be combined. That is, waiting time will only have to be defined in addition to a compulsory stop if the other train has not arrived by the time the compulsory stop would normally have finished.

It might be expected that timetablers would try to minimise delay times by making waiting time coincide with compulsory stops wherever possible. However, the following analysis of the Botswana timetable shows that this is not the case. The number of compulsory stops which would coincide with meets and overtakes by chance will be dictated by the proportion of time spent at compulsory stops compared with time spent on the line. If this number is calculated it is found to be slightly more than the number of meets and overtakes actually coinciding with compulsory stops in the Working Timetable. The Botswana model therefore assumes that the coincidence of compulsory stops and waiting time is random.

It will be seen in Section 5.3.6 that a train's total journey time is defined as its uninterrupted journey time, plus delay time at compulsory stops if no intersections occur, plus delay time due to intersections. Where a train is involved in a delay time which includes both a compulsory stop and waiting time this is therefore represented in the model by two stops; one due to the compulsory stop and one for the extra time incurred for the meet or overtake. This extra time must include consideration of the differences in switching time for and addition of overlap time and acceleration time to a compulsory stop which is combined with an intersection. The discussion below of combining switching time and overlap time with compulsory stop, and with waiting time respectively addresses this problem.

<u>Compulsory stop, switching time and overlap time</u>

Compulsory stopping time and switching time are always added to each other. That is because it is assumed that the operations occurring during a compulsory stop are not, in general, performed at the same time as the operations occurring during switching time. At an unmanned loop for the Paper Order or Van Schoor trains working method this is almost certain to be true, since a large part of the switching time is taken up with the guard walking the line. Operations required because of compulsory stops (such as loading and unloading) are likely to be performed by the guard, and therefore to take time in addition to switching time.

At manned stops for Paper Order and Van Schoor, and at all stops for Colour light signalling, switching time includes the setting up of new routes, and point changes. While some of the operations at a compulsory stop might be performed during this time it seems reasonable to assume that many will not. The relatively short switching time at manned loops, and all loops for colour light signalling, means that the error incurred by this assumption will be small.

Where an intersection is in common with a compulsory stop there may, in a few cases, be an extra waiting time required so that an overlap time can occur between the arrival and departure of trains. However, in most cases the overlap time will be absorbed in the compulsory stop time, because one train will arrive, and depart, while the other is still at the compulsory stop. Therefore, in the Botswana model, overlap time is not included in expressions for delays at intersections which occur at compulsory stops.

Waiting time, switching time and overlap time

When one train is waiting for another at a loop, it can perform all the operations required during switching time. Overlap time, however has to be added.

As stated earlier, waiting time can occur at a crossing loop where a train may or may not already have been at a compulsory stop, and this affects the total switching time involved, as follows.

Where the waiting time is at a loop which is not a compulsory stop, total delay time will be given by:-

The larger of waiting time and switching time
(since these times are combined)
Plus overlap time
Plus acceleration time.

Where the waiting time is at a loop which is also a compulsory stop, the delay time at a compulsory stop will already be included in the model. This is made up of the compulsory stopping time, plus switching time, plus acceleration time. Additional delay time is therefore given by:-

The larger of the extra time a train has to wait in excess of a compulsory stop, and the extra switching time, over and above that at a compulsory stop.
Plus overlap time.

(Table 5.4, previously referred to, showed the difference between switching times at intersections and at compulsory stops with no intersections).

APPENDIX SEVEN

Derivation of expressions for waiting times

Expressions for delays at meets and overtakes are derived separately, thus two definitions of waiting time are given:-

TDELMT(NO,JT,IT) is the average delay to a train of type (NO,JT) caused by it waiting for a train of type (NOP,IT) to arrive at a loop for a meet (NOP depicts the opposite direction to NO).

TDELOV(NO,JT,IT) is the average delay to a train of type (NO,JT) caused by it waiting for a train of type (NO,IT) to arrive at a loop for an overtake.

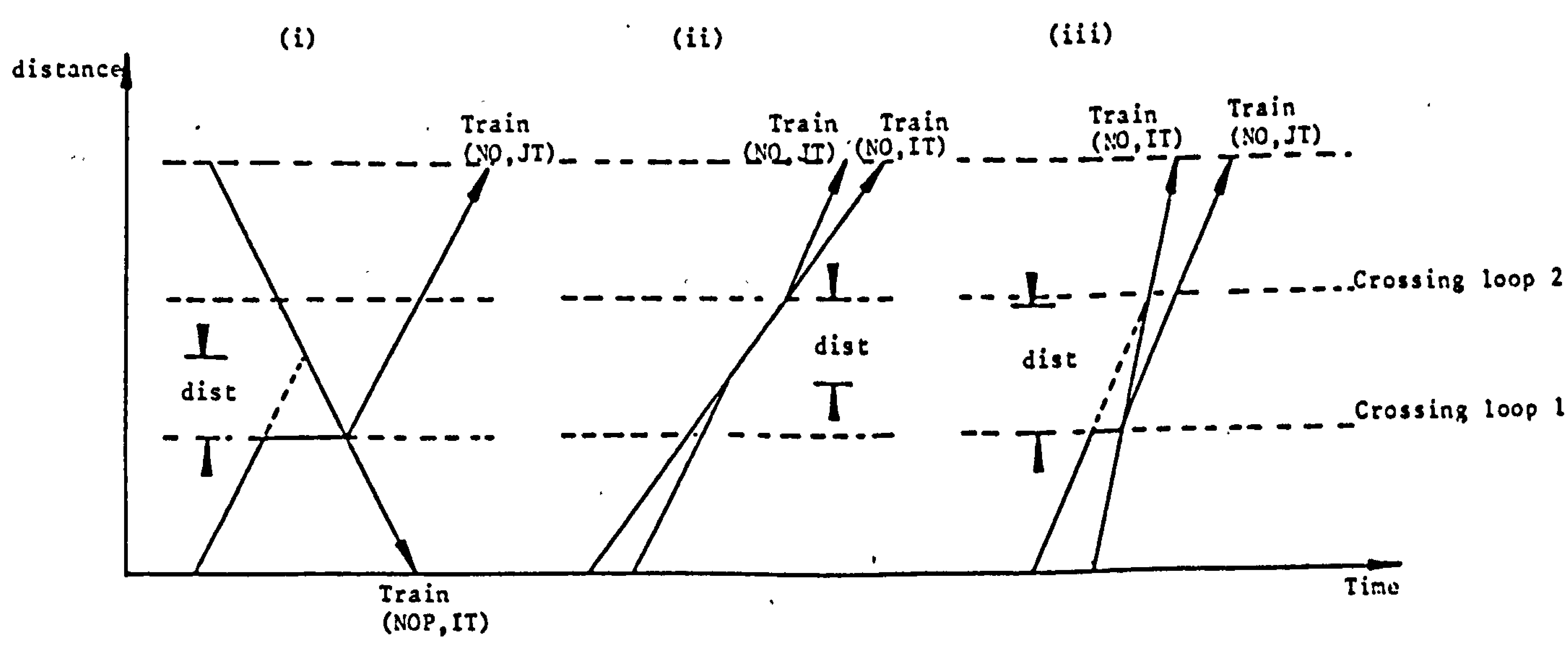
Figure A7.1 gives diagrams of the occasions on which a train of type (NO,JT) may have to wait for another train:-

i) at a meet

ii) when overtaking another train

iii) when it is overtaken by another train

Figure A7.1 Delays to a train of type (NO,JT)



In Figure A7.1 the projected intersection is shown as occurring at a distance dist from the crossing loop where train (NO,JT) waits. Taking only those intersections where both trains would be on the line, the proportion of times when train (NO,JT) waits for train (NOP,IT) at a meet is RPRMET (NO,JT,IT), and the proportion of times when train (NO,JT) waits for train (NO,IT) at an overtake is RPROV(NO,JT,IT).

Note that Figure A7.1 illustrates the situation where neither train (NO,JT) nor train (NOP,IT) have a compulsory stop at the loop where the intersections takes place.

The range of values for dist over which train (NO,JT) can be expected to wait will depend on the way in which waits for that train are assumed to be selected . If it is assumed, in accordance with Petersen's work, that the occasions when train (NO,JT) waits are not selected at random, but are those which cause it least delay, then it can be assumed that the train (NO,JT) waits at all those intersections where:-

0<dist=<(RPRMET(NO,JT,IT)) D for a meet
0<dist=<(RPROV(NO,JT,IT)) D for an overtake

Expression A7.1

If however, the occasions when train (NO,JT) waits at an intersection are assumed to be random, then the range of values of dist becomes:

0<dist<D for a meet or overtake

Expression A7.2

While Petesen's assumption can be assumed valid for colour light signalling, it is more difficult to justify for Paper Order & Van Schoor working. That is because, for these methods, priorities at intersections at unmanned loops are fixed. Even if it is assumed as discussed in Appendix 6, that there is some attempt to compensate by giving different priorities for switching and waiting time, it is still unlikely that there will be enough freedom in timetabling to allow train (NO,JT) to wait at those intersections causing it least delay.

Thus, the range over which train (NO,JT) stops will be assumed to be described by Expression A7.1 for colour light, and by A7.2 for Paper Order and Van Schoor.

Note that for RPRMET(NO,JT,IT),RPROV(NO,JT,IT)=1.0 or 0.0, Expressions A7.1 and A7.2 are identical.

The delay to train (NO,JT) due to waiting at any individual meet with a train of type (NOP,IT) is thus given by:-

<u>For Colour Light</u>

$$\text{dist} \times \left\{\frac{1}{\text{SPEED(NO,JT)}} + \frac{1}{\text{SPEED(NOP,IT)}}\right\} \text{ for } 0 =< \text{dist} =< \text{RPRMET(NO,JT,IT) D}$$

$$\text{or } 0 \qquad \text{for dist} > (\text{RPRMET(NO,JT,IT)) D}$$

<u>For Paper Order & Van Schoor</u>

$$\text{dist} \times \left\{\frac{1}{\text{SPEED(NO,JT)}} + \frac{1}{\text{SPEED(NOP,IT)}}\right\} \text{ for } 0 =< \text{dist} =< \text{D}$$

where SPEED(NO,JT) is the speed of the train (NO,JT).

Expression A7.3

Since train departures are assumed to be evenly spaced, projected train intersections are equally likely to occur at any point between two crossing loops. Since point-to-point timings between any two loops are assumed to be the same for any one train type, average delay over one section between crossing loops will be the same as average delay over all sections.

Average delay to train (NO,JT) on those occasions where a meet occurs with train (NOP,IT) at a crossing loop where neither train is already at a compulsory stop is obtained by the following steps.

- Average delay to a train type which is at low priority at a meet will be given by substituting half of the range of total distance for dist in equation A7.3 (since a random distribution of distances from the crossing loop within this range can be assumed).
- Average delay to a train type will in general be its priority multiplied by its average delay when it is at low priority.

This gives the following results:-

<u>For Colour Light</u>

$$\frac{\text{RPRMET(NO,JT,IT))}^2}{2} \times \left\{\frac{1}{\text{SPEED(NO,JT)}} + \frac{1}{\text{SPEED(NOP,IT)}}\right\} \times \text{D}$$

<u>For Paper Order & Van Schoor</u>

$$\frac{\text{RPRMET(NO,JT,IT))}}{2} \times \left\{\frac{1}{\text{SPEED(NO,JT)}} + \frac{1}{\text{SPEED(NOP,IT)}}\right\} \times \text{D}$$

But, if the time taken by a train type is uniform between any two crossing loops, then:-

$$\frac{D}{SPEED(NO,JT)} = \frac{TOTTIM(NO,JT)}{(XCROSS+1)}$$

Where:-
TOTTIM(NO,JT) is the uninterrupted journey time, and
XCROSS is the number of loops; hence (XCROSS+1) is the number of sections on the line.

Thus average delay at crossing loops where neither train has had a compulsory stop is given by:-

For Colour Light

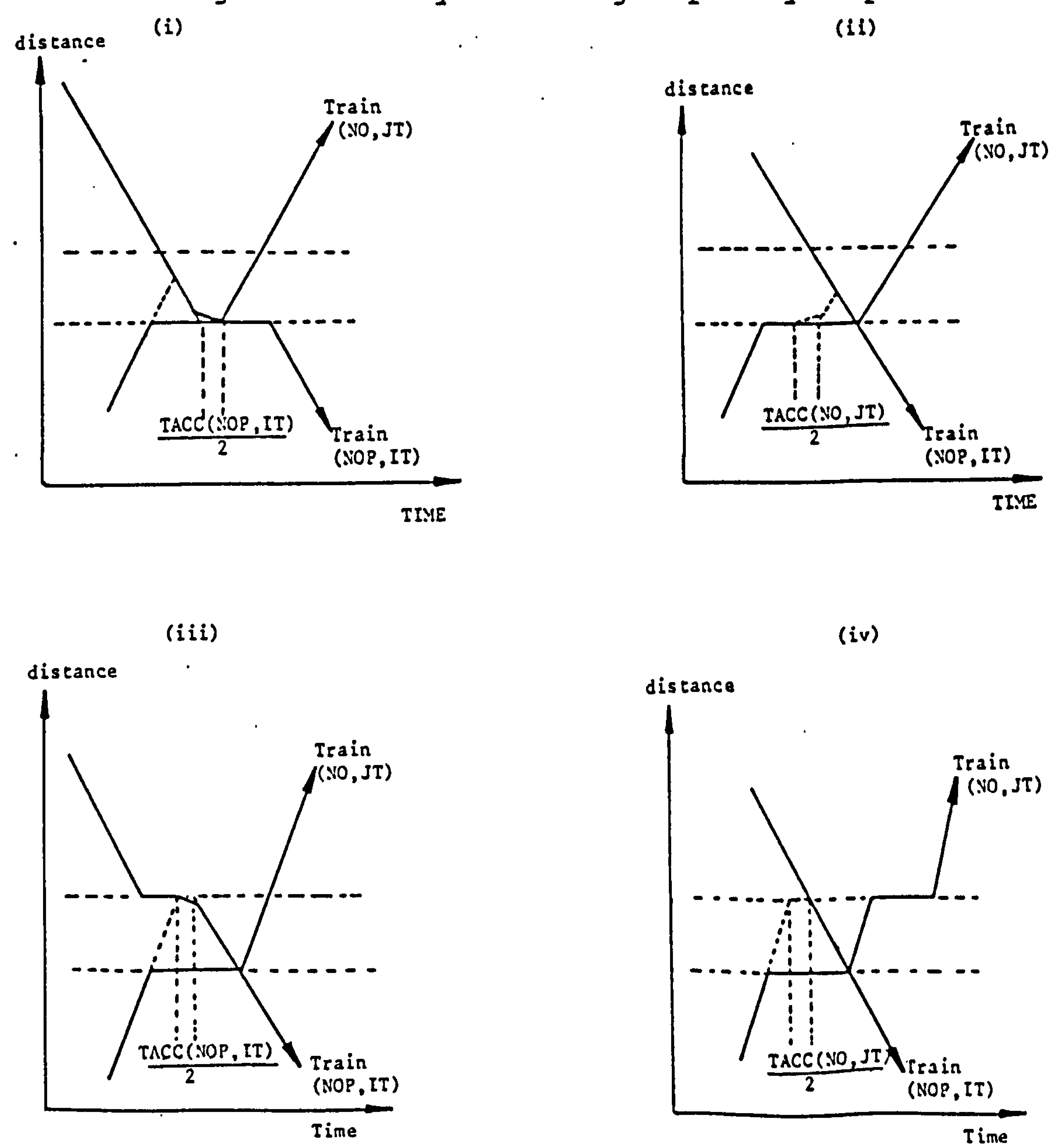
$$\frac{(RPRMET(NO,JT,IT))^2}{2 \times (XCROSS+1)} (TOTTIM(NO,JT) + TOTTIM(NOP,IT))$$

For Paper Order & Van Schoor

$$\frac{RPRMET(NO,JT,IT)}{2 \times (XCROSS+1)} \times (TOTTIM(NO,JT) + TOTTIM(NOP,IT))$$

The situation where either train (NO,JT) or train (NOP,IT) has a compulsory stop at the crossing loop must now be addressed. Figure A7.2 shows meets occuring at loops where compulsory stops also occur.

Figure A7.2 Delays involving compulsory stops



Diagrams (i) and (ii) in Figure A7.2 show the situation where train (NOP,IT) and train (NO,JT) respectively would have stopped at the loop anyway, for a compulsory stop . (Note that this is the case where a projected intersection with both trains on the line is followed by a compulsory stop; in those situations where the intersection occurs where one or other train is already at a compulsory stop no waiting time is involved).

In a few cases, if train (NO,JT) has low priority at all meets with train (NOP,IT) (RPRMET(NO,JT,IT)=0), there may be some projected intersections which occur almost at the crossing loop next to, or previous from (depending on the direction of the train), the crossing loop where the intersection actually occurs. In this situation if there is a compulsory stop for train (NOP,IT) at this previous stop, as shown in diagram (iii) of Figure A7.2 for meets; or a compulsory stop for train (NO,JT) at the next stop, as shown in diagram (iv) of Figure A7.2 for meets, there will also be extra waiting time for train (NO,JT).

Diagrams in Figure A7.2 depart from the convention used in the rest of this chapter that acceleration time is not shown as time on the line, being an "add-on" to other waiting times. Moreover, in these diagrams only the acceleration and deceleration times relevant to this discussion have been shown; the others are not shown to avoid cluttering the diagrams.

TACC(NO,JT) is total deceleration and acceleration time to and from a stop for train (NO,JT). Deceleration and acceleration are assumed to take the same amount of time; hence deceleration time is $\frac{TACC(NO,JT)}{2}$

The following simplifying assumptions will be made:-

- Each time there is a compulsory stop for train (NOP,IT) at a meet where train (NO,JT) has to wait, as shown in diagram (i) of Figure A7.2 a time $\frac{\text{TACC(NOP,IT)}}{2}$ will be added to TDELMT(NO,JT,IT). Since this analysis deals only with the times when trains are on the line, the proportion of meets at which this will happen is:-

$\frac{\text{XCOMP(NOP,IT)}}{\text{XCROSS}}$ x RPRMET(NO,JT,IT) for Paper Order & Colour Light

RPRMET(NO,JT,IT) for Van Schoor

Where:-

XCOMP(NOP,IT)	is the number of compulsory stops for train (NOP,IT).
XCROSS	is the number of crossing loops on the line.

- Each time there is a compulsory stop for train (NO,JT) at a meet where train (NO,JT) has to wait, as shown in diagram (ii) of Figure A7.2 a time $\frac{\text{TACC(NO,JT)}}{2}$ will be added to TDELMT(NO,JT,IT)).

The proportion of meets at which this will happen is:-

$\frac{\text{XCOMP(NO,JT)}}{\text{XCROSS}}$ x RPRMET(NO,JT,IT) for Paper Order & Colour Light

RPRMET(NO,JT,IT) for Van Schoor

- The situations depicted in Diagrams (iii) & (iv) will be assumed to occur so infrequently that they can be ignored.

Therefore average additional waiting time per meet for train (NO,JT) due to acceleration and deceleration is given by:-

$\frac{\text{RPRMET(NO,JT,IT)}}{2 \text{ x XCROSS}}$ x {XCOMP(NOP,IT)xTACC(NOP,IT)+XCOMP(NO,JT) x TACC(NO,JT)}

for Paper Order & Colour Light, and

$\frac{\text{RPRMET(NO,JT,IT)}}{2}$ x (TACC(NOP,IT)+TACC(NO,JT)) for Van Schoor

Adding the above expression to that for average delay to train (NO,JT) waiting for train (NOP,IT) when neither of the trains involved has a compulsory stop gives expressions for TDELMT(NO,JT,IT) as follows:-

For Colour Light

$$TDELMT(NO,JT,IT) =$$

$$\frac{RPRMET(NO,JT,IT)}{2} \times \left\{ (XCOMP(NOP,IT) \times TACC(NOP,IT) + XCOMP(NO,JT) \times TACC(NO,JT)) \times \frac{1}{XCROSS} + (TOTTIM(NO,JT) + TOTTIM(NOP,IT)) \times \frac{RPRMET(NO,JT,IT)}{(XCROSS+1)} \right\}$$

For Paper Order

$$TDELMT(NO,JT,IT) =$$

$$\frac{RPRMET(NO,JT,IT)}{2} \times \left\{ \frac{XCOMP(NOP,IT) \times TACC(NOP,IT)}{XCROSS} + \frac{XCOMP(NO,JT) \times TACC(NO,JT)}{XCROSS} + \frac{TOTTIM(NO,JT) + TOTTIM(NOP,IT)}{(XCROSS+1)} \right\}$$

For Van Schoor

$$TDELMT(NO,JT,IT) =$$

$$\frac{RPRMET(NO,JT,IT)}{2} \times \left\{ TACC(NOP,IT) + TACC(NO,JT) + \frac{TOTTIM(NO,JT) + TOTTIM(NOP,IT))}{(XCROSS+1)} \right\}$$

Equation A7.4

TDELOV(NO,JT,IT) the average delay to a train of type (NO,JT) caused by it waiting for a train of type (NO,IT) to arrive at a loop for an overtake, is derived in a similar manner to that described above, for TDELMT(NO,JT,IT).

From diagrams (i) and (ii) of Figure A7.1, the delay to a train (NO,JT) at any individual overtake with a train of type (NO,IT) is given by:-

For Colour Light

$$dist \left| \left\{ \frac{1}{SPEED(NO,JT)} - \frac{1}{SPEED(NO,IT)} \right\} \right| \begin{cases} \text{for } 0=<dist=<RPROV(NO,JT,IT) \times D \\ \text{or} \\ \text{for } dist>RPROV(NO<JT,IT) \times D \end{cases}$$

For Paper Order & Van Schoor

$$dist \left| \left(\frac{1}{SPEED(NO,JT)} - \frac{1}{SPEED(NO,IT)} \right) \right| \text{ for } 0=<dist=<D$$

Expression A7.5

where the vertical bars denote that the absolute value of the expression is taken.

The average waiting time per overtake for all trains (NO,JT) at overtakes with trains of type (NO,IT) is given by an equation analagous to Equation A7.4 for meets:-

<u>For Colour Light</u>

$$\mathrm{TDELOV(NO,JT,IT)} = \frac{\mathrm{RPROV(NO,JT,IT)}}{2} \times \left\{ \left(\mathrm{XCOMP(NO,IT)} \times \mathrm{TACC(NO,IT)} + \mathrm{XCOMP(NO,JT)} \times \mathrm{TACC(NO,JT)}\right) \times \frac{1}{\mathrm{XCROSS}} + \left|\left(\mathrm{TOTTIM(NO,JT)} - \mathrm{TOTTIM(NOP,IT)}\right)\right| \times \frac{\mathrm{RPROV(NO,JT,IT)}}{(\mathrm{XCROSS}+1)} \right\}$$

<u>For Paper Order</u>

$$\mathrm{TDELOV(NO,JT,IT)} = \frac{\mathrm{RPROV(NO,JT,IT)}}{2} \times \left\{ \frac{\left(\mathrm{XCOMP(NOP,IT)} \times \mathrm{TACC(NOP,IT)}\right.}{\mathrm{XCROSS}} + \frac{\left.\mathrm{XCOMP(NO,JT)} \times \mathrm{TACC(NO,JT)}\right)}{\mathrm{XCROSS}} + \left| \frac{\left(\mathrm{TOTTIM(NO,JT)} - \mathrm{TOTTIM(NO,IT)}\right)}{(\mathrm{XCROSS}+1)} \right| \right\}$$

<u>For Van Schoor</u>

$$\mathrm{TDELOV(NO,JT,IT)} = \frac{\mathrm{RPROV(NO,JT,IT)}}{2} \times \left\{ \mathrm{TACC(NOP,IT)} + \mathrm{TACC(NO,JT)} + \frac{\left|\left(\mathrm{TOTTIM(NO,JT)} - \mathrm{TOTTIM(NO,IT)}\right)\right|}{(\mathrm{XCROSS}+1)} \right\}$$

Equation A7.6 .

APPENDIX EIGHT

Derivation of expressions for number of meets and overtakes

A train of type JT travelling in direction NO is illustrated in diagram (i) of Figure A8.1. This train has a journey time along the whole line, including delays, of TIMAV(NO,JT) minutes, and starts its journey at time TSTART.

Train (NO,JT) will meet all trains of type IT travelling in direction NOP = (3-NO) which start from the other end of the line during the period {TSTART - TIMAV(NOP,IT)} to {TSTART + TIMAV(NO,JT)} as illustrated in diagram (ii) of Figure A8.1. The assumption of regular dispatch of trains discussed in Section 5.3.2 means that, for each train type, the number of trains per minute (obviously fractional) is simply the number of trains per day divided by (1440 - TCLOSE) where TCLOSE is the average time, in minutes per day for which the line is planned to be closed. The introduction of TCLOSE produces another error in the train delay model, insofar as train departures cannot be evenly distributed throughout the time period for which the line is open, since the last train in the time period must depart at a time equal to its own journey time before the line closes. Since TCLOSE in Botswana, and on many lines, is zero, the errors introduced by its inclusion are not directly addressed. It is included to increase the generality of the model, with a warning that its use may introduce an unknown error.

Thus:-

$$\text{XMEET(NO,JT,IT)} = \frac{\text{XTEWPD(IT)}}{(1440 - \text{TCLOSE})} \times (\text{TIMAV(NOP,IT)} + \text{TIMAV(NO,JT)})$$

Equation A8.1

Train (NO,JT) will encounter overtakes with all trains of type (NO,IT) which start at the same end of the line during the period {TSTART + TIMAV(NO,IT) - TIMAV(NO,JT)} to TSTART if train (NO,IT) is slower than train (NO,JT); or during the period TSTART to {TSTART + TIMAV(NO,JT) - TIMAV(NO,IT) } if train (NO,IT) is faster than train (NO,JT). The situation where train (NO,IT) is slower than train (NO,JT) is illustrated in diagram (iii) of Figure A8.1, and the situation where train (NO,IT) is faster than train (NO,JT) is illustrated in diagram (iv) of the same table. In both cases, the time period during which train (NO,JT) is involved in overtakes with train (NO,IT) is:-

$$|(\mathrm{TIMAV(NO,IT)} - \mathrm{TIMAV(NO,JT)})|$$

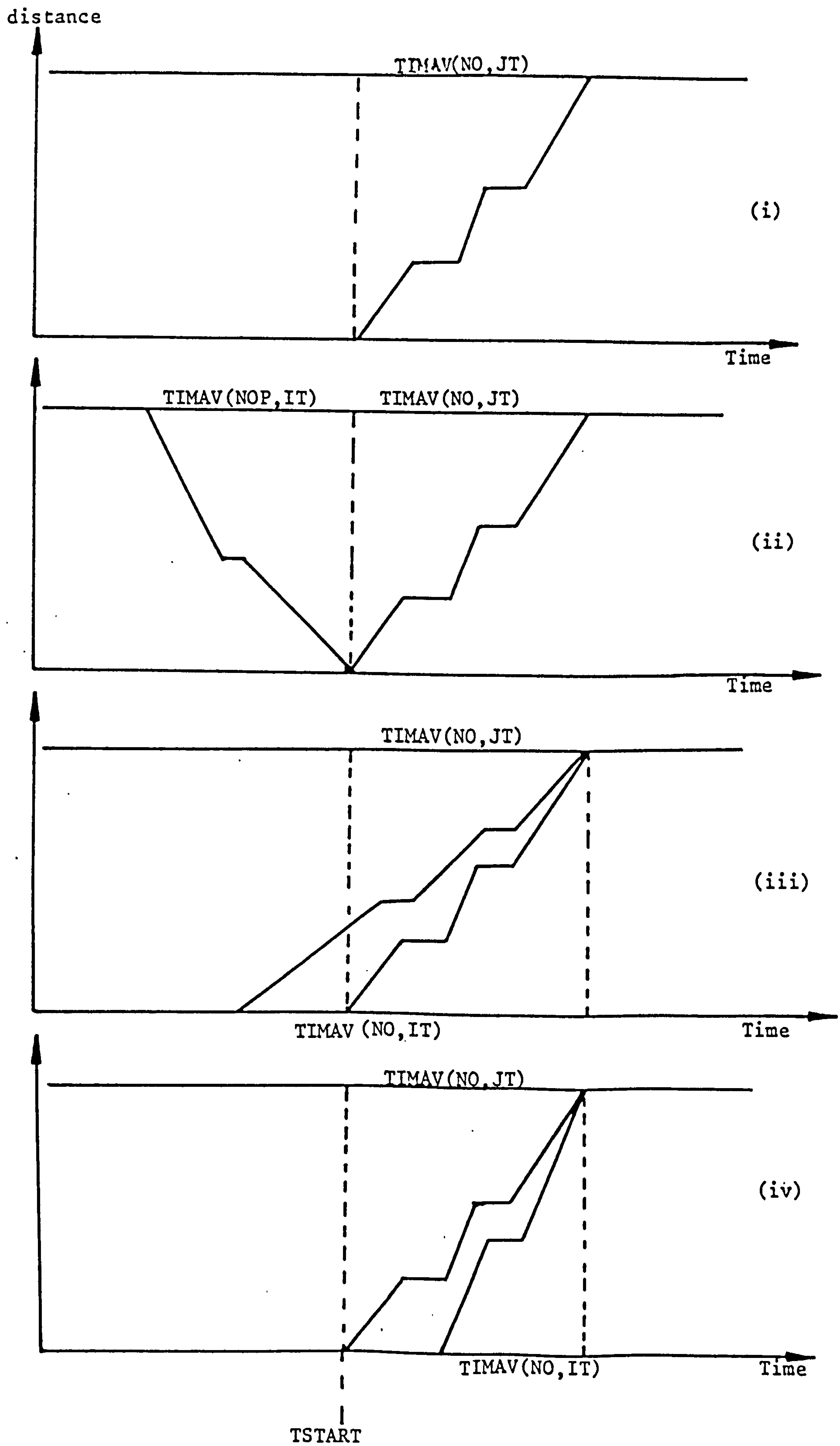
where the vertical bars indicate that the absolute value of the expression is taken.

Thus:-

$$\mathrm{XOTAKE(NO,JT,IT)} = \frac{\mathrm{XTEWPD(IT)}}{(1440 - \mathrm{TCLOSE})} \times |(\mathrm{TIMAV(NO,IT)} - \mathrm{TIMAV(NO,JT)})|$$

Equation A8.2

Figure A8.1 Time - distance diagrams of meets and overtakes



APPENDIX NINE

Expressions for waiting times in TVEC(NO,JT,IT)

In this appendix, expressions are given for each element of the vector for waiting times described in Section 5.3.6. Elements of TVEC(NO,JT,IT) are defined as follows:-

Way in which intersection and compulsory stop coincide	Manned or Unmanned	Meet or Overtake	Paper Order	Van Schoor	Colour Light
Compulsory stop for train (NO,JT) in common with intersection for train of type IT, whether or not that train is at a compulsory stop.	manned	meet	1	1	1
	unmanned		2		
	manned	overtake	3	2	2
	unmanned		4		
Intersection between train (NO,JT) and train of type IT when neither train is at a compulsory stop.	manned	meet	5	3	3
	unmanned		6		
	manned	overtake	7	4	4
	unmanned		8		
Intersection between train (NO,JT) and train of type IT when the train of type IT is at a compulsory stop and train (NO,JT) is not.	manned	meet	9	5	5
	unmanned		10		
	manned	overtake	11	6	6
	unmanned		12		

Expressions for element of $\overline{TVEC(NO,JT,IT)}$

Paper Order Working

Element Number

1 $RPRMET(NO,JT,IT) \times (TPOINT+TSAFE)$

2 $RPRMET(NO,JT,IT) \times (0.018 \times DCROSS+TPOINT+TSAFE)$

3 $RPROV(NO,JT,IT) \times (TPOINT+TSAFE)$

4 $RPROV(NO,JT,IT) \times (0.018 \times DCROSS+TPOINT+TSAFE)$

5 For $RPRMET(NO,JT,IT)>0$ and $\dfrac{TDELMT(NO,JT,IT)}{RPRMET(NO,JT,IT)} > \dfrac{TPOINT+TPAP}{2}$

$$TDELMT(NO,JT,IT) + RPRMET(NO,JT,IT) \times \left(\frac{TPOINT}{2} + \left(\frac{XMAN-XCOMAN(NO,JT)}{XMAN}\right) \times TACC(NO,JT) + TSAFE\right)$$

For $RPRMET(NO,JT,IT)>0$ and $\dfrac{TPOINT}{2} < \dfrac{TDELMT(NO,JT,IT)}{RPRMET(NO,JT,IT)} =< \left(\dfrac{TPOINT+TPAP}{2}\right)$

$$TDELMT(NO,JT,IT) \times \frac{XCOMAN(NO,JT)}{XMAN}$$

$$+ RPRMET(NO,JT,IT) \times \left(\frac{TPOINT}{2} + \left(\frac{XMAN-XCOMAN(NO,JT)}{XMAN}\right) \times \left(\frac{TPOINT}{2} + TPAP+TACC(NO,JT)+TSAFE\right)\right)$$

For $RPRMET(NO,JT,IT)>0$ and $\dfrac{TDELMT(NO,JT,IT)}{RPRMET(NO,JT,IT)} =< \dfrac{TPOINT}{2}$

$$RPRMET(NO,JT,IT) \times \left(TPOINT + \left(\frac{XMAN-XCOMAN(NO,JT)}{XMAN}\right) \times (TPAP+TACC(NO,JT)) + TSAFE\right)$$

For $RPRMET(NO,JT,IT) = 0$

0

Paper Order Working continued

Element Number

6 For $RPRMET(NO,JT,IT)>0$ and $\frac{TDELMT(NO,JT,IT)}{RPRMET(NO,JT,IT)} > \left(0.018 \times DCROSS + \frac{TPOINT}{2}\right)$

$$TDELMT(NO,JT,IT)$$

$$+ RPRMET(NO,JT,IT) \times \left(\frac{TPOINT}{2} + \frac{(XCROSS-XMAN-XCOMP(NO,JT)+XCOMAN(NO,JT))}{(XCROSS-XMAN)} \times TACC(NO,JT) + TSAFE\right)$$

For $RPRMET(NO,JT,IT)>0$ and $\frac{TDELMT(NO,JT,IT)}{RPRMET(NO,JT,IT)} =< \left(0.018 \times DCROSS + \frac{TPOINT}{2}\right)$

$$RPRMET(NO,JT,IT) \times \left(0.018 \times DCROSS + TPOINT + \frac{(XCROSS-XMAN-XCOMP(NO,JT,)+XCOMAN(NO,JT))}{(XCROSS-XMAN)} \times TACC(NO,JT) + TSAFE\right)$$

For $RPRMET(NO,JT,IT) = 0$

$$0$$

7 For $RPROV(NO,JT,IT)>0$ and $\frac{TDELOV(NO,JT,IT)}{RPROV(NO,JT,IT)} > \left(\frac{TPOINT}{2} - THEAD + TPAP\right)$

$$TDELOV(NO,JT,IT) + RPROV(NO,JT,IT) \times \left(\frac{TPOINT}{2} + THEAD + \left(\frac{XMAN-XCOMAN(NO,JT)}{XMAN}\right) \times TACC(NO,JT) + TSAFE\right)$$

For $RPROV(NO,JT,IT)>0$ and $\left(\frac{TPOINT}{2} - THEAD\right) < \frac{TDELOV(NO,JT,IT)}{RPROV(NO,JT,IT)} =< \left(\frac{TPOINT}{2} - THEAD + TPAP\right)$

$$TDELOV(NO,JT,IT) \times \frac{XCOMAN(NO,JT)}{XMAN}$$

$$+ RPROV(NO,JT,IT) \times \left(\frac{TPOINT}{2} + \left(\frac{XMAN-XCOMAN(NO,JT)}{XMAN}\right) \times \left(\frac{TPOINT}{2} + TPAP + TACC(NO,JT)\right) + \frac{XCOMAN(NO,JT)}{XMAN} \times THEAD + TSAFE\right)$$

For $RPROV(NO,JT,IT)>0$ and $\frac{TDELOV(NO,JT,IT)}{RPROV(NO,JT,IT)} =< \left(\frac{TPOINT}{2} - THEAD\right)$

$$RPROV(NO,JT,IT) \times \left(TPOINT + \left(\frac{XMAN-XCOMAN(NO,JT)}{XMAN}\right) \times \left(TPAP + TACC(NO,JT) + TSAFE\right)\right)$$

For $RPROV(NO,JT,IT) = 0$

$$0$$

Paper Order Working continued

Element Number

8 For $\mathrm{RPROV(NO,JT,IT)} > 0$ and $\dfrac{\mathrm{TDELOV(NO,JT,IT)}}{\mathrm{RPROV(NO,JT,IT)}} > \left(0.018 \times \mathrm{DCROSS} + \dfrac{\mathrm{TPOINT}}{2} - \mathrm{THEAD}\right)$

$$\mathrm{TDELOV(NO,JT,IT)}$$

$$+ \mathrm{RPROV(NO,JT,IT)} \times \left(\frac{\mathrm{TPOINT}}{2} + \mathrm{THEAD} + \frac{(\mathrm{XCROSS}-\mathrm{XMAN}-\mathrm{XCOMP(NO,JT)}+\mathrm{XCOMAN(NO,JT)})}{(\mathrm{XCROSS}-\mathrm{XMAN})} \times \mathrm{TACC(NO,JT)} + \mathrm{TSAFE}\right)$$

For $\mathrm{RPROV(NO,JT,IT)} > 0$ and $\dfrac{\mathrm{TDELOV(NO,JT,IT)}}{\mathrm{RPROV(NO,JT,IT)}} =< \left(0.018 \times \mathrm{DCROSS} + \dfrac{\mathrm{TPOINT}}{2} - \mathrm{THEAD}\right)$

$$\mathrm{RPROV(NO,JT,IT)} \times \left(0.018 \times \mathrm{DCROSS} + \mathrm{TPOINT} + \frac{(\mathrm{XCROSS}-\mathrm{XMAN}-\mathrm{XCOMP(NO,JT)}+\mathrm{XCOMAN(NO,JT)})}{(\mathrm{XCROSS}-\mathrm{XMAN})} \times \mathrm{TACC(NO,JT)} + \mathrm{TSAFE}\right)$$

For $\mathrm{RPROV(NO,JT,IT)} = 0$

$$0$$

9 $\mathrm{RPRMET(NO,JT,IT)} \times \left(\mathrm{TPOINT} + \mathrm{TPAP} + \left(\dfrac{\mathrm{XMAN}-\mathrm{XCOMAN(NO,JT)}}{\mathrm{XMAN}}\right) \times \mathrm{TACC(NO,JT)} - \dfrac{\mathrm{XCOMAN(NO,JT)}}{\mathrm{XMAN}} \times \mathrm{TPAP} + \mathrm{TSAFE}\right)$

10 $\mathrm{RPRMET(NO,JT,IT)} \times \left(0.018 \times \mathrm{DCROSS} + \mathrm{TPOINT} + \left(\dfrac{\mathrm{XCROSS}-\mathrm{XMAN}-\mathrm{XCOMP(NO,JT)}+\mathrm{XCOMAN(NO,JT)}}{\mathrm{XCROSS}-\mathrm{XMAN}}\right) \times \mathrm{TACC(NO,JT)} + \mathrm{TSAFE}\right)$

11 $\mathrm{RPROV(NO,JT,IT)} \times \left(\mathrm{TPOINT} + \mathrm{TPAP} + \left(\dfrac{\mathrm{XMAN}-\mathrm{XCOMAN(NO,JT)}}{\mathrm{XMAN}}\right) \times \mathrm{TACC(NO,JT)} - \dfrac{\mathrm{XCOMAN(NO,JT)}}{\mathrm{XMAN}} \times \mathrm{TPAP} + \mathrm{TSAFE}\right)$

12 $\mathrm{RPROV(NO,JT,IT)} \times \left(0.018 \times \mathrm{DCROSS} + \mathrm{TPOINT} + \left(\dfrac{\mathrm{XCROSS}-\mathrm{XMAN}-\mathrm{XCOMP(NO,JT)}+\mathrm{XCOMAN(NO,JT)}}{\mathrm{XCROSS}-\mathrm{XMAN}}\right) \times \mathrm{TACC(NO,JT)} + \mathrm{TSAFE}\right)$

Element Number	
1	RPRMET(NO,JT,IT) x TPOINT
2	RPROV(NO,JT,IT) x TPOINT
3	For RPRMET(NO,JT,IT)>0 and $\frac{TDELMT(NO,JT,IT)}{RPRMET(NO,JT,IT)} > \frac{TPOINT}{2}$
	TDELMT(NO,JT,IT) + RPRMET(NO,JT,IT) x $\left(\frac{TPOINT}{2}+TSAFE\right)$
	For RPRMET(NO,JT,IT)>0 and $\frac{TDELMT(NO,JT,IT)}{RPRMET(NO,JT,IT)} =< \frac{TPOINT}{2}$
	RPRMET(NO,JT,IT x (TPOINT+TSAFE)
	For RPRMET(NO,JT,IT) = 0
	0
4	For RPROV(NO,JT,IT)>0 and $\frac{TDELOV(NO,JT,IT)}{RPROV(NO,JT,IT)} > \left(\frac{TPOINT}{2}-THEAD\right)$
	TDELOV(NO,JT,IT) + RPROV(NO,JT,IT) x $\left(THEAD+\frac{TPOINT}{2}+TSAFE\right)$
	For RPROV(NO,JT,IT)>0 and $\frac{TDELOV(NO,JT,IT)}{RPROV(NO,JT,IT)} =< \left(\frac{TPOINT}{2}-THEAD\right)$
	RPROV(NO,JT,IT) x (TPOINT+TSAFE).
	For RPROV(NO,JT,IT) = 0
	0
5	RPRMET(NO,JT,IT) x (TPOINT+TSAFE)
6	RPROV(NO,JT,IT) x (TPOINT+TSAFE)

Colour Light Signalling

Element Number

1 $RPRMET(NO,JT,IT) \times TPOINT$

2 $RPROV(NO,JT,IT) \times TPOINT$

3 For $RPRMET(NO,JT,IT)>0$ and $\frac{TDELMT(NO,JT,IT)}{RPRMET(NO,JT,IT)} > \frac{TPOINT}{2}$

$$TDELMT(NO,JT,IT) + RPRMET(NO,JT,IT) \times \left(\frac{TPOINT}{2} + \frac{(XCROSS-XCOMP(NO,JT))}{XCROSS} \times TACC(NO,JT) + TSAFE\right)$$

For $RPRMET(NO,JT,IT)>0$ and $\frac{TDELMT(NO,JT,IT)}{RPRMET(NO,JT,IT)} =< \frac{TPOINT}{2}$

$$RPRMET(NO,JT,IT) \times \left(TPOINT + \frac{(XCROSS-XCOMP(NO,JT))}{XCROSS} \times TACC(NO,JT) + TSAFE\right)$$

For $RPRMET(NO,JT,IT) = 0$

0

4 For $RPROV(NO,JT,IT)>0$ and $\frac{TDELOV(NO,JT,IT)}{RPROV(NO,JT,IT)} > \left(\frac{TPOINT-THEAD}{2}\right)$

$$TDELOV(NO,JT,IT) + RPROV(NO,JT,IT) \times \left(\frac{TPOINT+THEAD}{2} + \frac{(XCROSS-XCOMP(NO,JT))}{XCROSS} \times TACC(NO,JT) + TSAFE\right)$$

For $RPROV(NO,JT,IT)>0$ and $\frac{TDELOV(NO,JT,IT)}{RPROV(NO,JT,IT)} =< \left(\frac{TPOINT-THEAD}{2}\right)$

$$RPROV(NO,JT,IT) \times \left(TPOINT + \frac{(XCROSS-XCOMP(NO,JT))}{XCROSS} \times TACC(NO,JT) + TSAFE\right)$$

For $RPROV(NO,JT,IT) = 0$

0

5 $RPRMET(NO,JT,IT) \times \left(TPOINT + \frac{(XCROSS-XCOMP(NO,JT))}{XCROSS} \times TACC(NO,JT) + TSAFE\right)$

6 $RPROV(NO,JT,IT) \times \left(TPOINT + \frac{(XCROSS-XCOMP(NO,JT))}{XCROSS} \times TACC(NO,JT) + TSAFE\right)$

APPENDIX TEN

Expressions for numbers of intersections in XVEC(NO,JT,IT)

In this appendix, expressions are given for each element of the vector for number of intersections described in Section 5.3.6. Elements of XVEC(NO,JT,IT) are numbered in the same way as those in TVEC(NO,JT,IT). The definition of each element number was given at the begining of Appendix 9.

Expression for element of $\overline{XVEC(NO,JT,IT)}$

Paper Order Working

Element Number

1 $$\frac{XMEET(NO,JT,IT) \times XCOMAN(NO,JT) \times (TCOMP(NO,JT)+TPAP)}{TIMIN(NO,JT)}$$

2 $$\frac{XMEET(NO,JT,IT) \times (XCOMP(NO,JT)-XCOMAN(NO,JT)) \times TCOMP(NO,JT)}{TIMIN(NO,JT)}$$

3 $$\frac{XOTAKE(NO,JT,IT) \times XCOMAN(NO,JT) \times (TCOMP(NO,JT)+TPAP)}{TIMIN(NO,JT)}$$

4 $$\frac{XOTAKE(NO,JT,IT) \times (XCOMP(NO,JT)-XCOMAN(NO,JT)) \times TCOMP(NO,JT)}{TIMIN(NO,JT)}$$

5 $$\frac{XMEET(NO,JT,IT)}{TIMIN(NO,JT) \times TIMIN(NOP,IT)} \times \frac{XMAN}{XCROSS}$$

$$\times (TOTTIM(NO,JT)+XCOMP(NO,JT) \times TACC(NO,JT)) \times (TOTTIM(NOP,IT)+XCOMP(NOP,IT) \times TACC(NOP,IT))$$

6 $$\frac{XMEET(NO,JT,IT)}{TIMIN(NO,JT) \times TIMIN(NOP,IT)} \times \frac{(XCROSS-XMAN)}{XCROSS}$$

$$\times (TOTTIM(NO,JT)+XCOMP(NO,JT) \times TACC(NO,JT)) \times (TOTTIM(NOP,IT)+XCOMP(NOP,IT) \times TACC(NOP,IT))$$

Paper Order Working continued

Element Number

7 $$\frac{\text{XOTAKE(NO,JT,IT)}}{\text{TIMIN(NO,JT)} \times \text{TIMIN(NO,IT)}} \times \frac{\text{XMAN}}{\text{XCROSS}}$$

$$\times \text{ (TOTTIM(NO,JT)+XCOMP(NO,JT)xTACC(NO,JT))} \times \text{ (TOTTIM(NO,IT)+XCOMP(NO,IT)xTACC(NOP,IT))}$$

8 $$\frac{\text{XOTAKE(NO,JT,IT)}}{\text{TIMIN(NO,JT)} \times \text{TIMIN(NO,IT)}} \times \frac{\text{(XCROSS-XMAN)}}{\text{XCROSS}}$$

$$\times \text{ (TOTTIM(NO,JT)+XCOMP(NO,JT)xTACC(NO,JT))} \times \text{ (TOTTIM(NO,IT)+XCOMP(NO,IT)xTACC(NO,IT))}$$

9 $$\frac{\text{XMEET(NO,JT,IT)}}{\text{TIMIN(NO,JT)} \times \text{TIMIN(NOP,IT)}} \times \text{ (TOTTIM(NO,JT)+XCOMP(NO,JT)xTACC(NO,JT))} \times \text{ XCOMAN(NOP,IT)} \times \text{ (TCOMP(NOP,IT)+TPAP)}$$

10 $$\frac{\text{XMEET(NO,JT,IT)}}{\text{TIMIN(NO,JT)} \times \text{TIMIN(NOP,IT)}} \times \text{ (TOTTIM(NO,JT)+XCOMP(NO,JT)xTACC(NO,JT))} \times \text{ (XCOMP(NOP,IT)-XCOMAN(NOP,IT))} \times \text{ TCOMP(NOP,IT)}$$

11 $$\frac{\text{XOTAKE(NO,JT,IT)}}{\text{TIMIN(NO,JT)} \times \text{TIMIN(NO,IT)}} \times \text{ (TOTTIM(NO,JT)+XCOMP(NO,JT)xTACC(NO,JT))} \times \text{ XCOMAN(NO,IT)} \times \text{ (TCOMP(NO,IT)+TPAP)}$$

12 $$\frac{\text{XOTAKE(NO,JT,IT)}}{\text{TIMIN(NO,JT)} \times \text{TIMIN(NO,IT)}} \times \text{ (TOTTIM(NO,JT)+XCOMP(NO,JT)xTACC(NO,JT))} \times \text{ (XCOMP(NO,IT)-XCOMAN(NO,IT))} \times \text{ TCOMP(NO,IT)}$$

Van Schoor Working

Element Number

1 $$\frac{\text{XMEET(NO,JT,IT)}}{\text{TIMIN(NO,JT)}} \text{ x (XCOMP(NO,JT)xTCOMP(NO,JT)+XCROSSxTTOK+(XCROSS-XMAN)x0.018xDCROSS)}$$

2 $$\frac{\text{XOTAKE(NO,JT,IT)}}{\text{TIMIN(NO,JT)}} \text{ x (XCOMP(NO,JT)xTCOMP(NO,JT)+XCROSSxTTOK+(XCROSS-XMAN)x0.018xDCROSS)}$$

3 $$\frac{\text{XMEET(NO,JT,IT)}}{\text{TIMIN(NO,JT) x TIMIN(NOP,IT)}}$$

$$\text{x (TOTTIM(NO,JT)+XCROSSxTACC(NO,JT)) x (TOTTIM(NOP,IT)+XCROSSxTACC(NOP,IT))}$$

4 $$\frac{\text{XOTAKE(NO,JT,IT)}}{\text{TIMIN(NO,JT) x TIMIN(NO,IT)}}$$

$$\text{x (TOTTIM(NO,JT)+XCROSSxTACC(NO,JT)) x (TOTTIM(NO,IT)+XCROSSxTACC(NO,IT))}$$

5 $$\frac{\text{XMEET(NO,JT,IT)}}{\text{TIMIN(NO,JT) x TIMIN(NOP,IT)}} \text{ x (TOTTIM(NO,JT)+XCROSSxTACC(NO,JT))}$$

$$\text{x (XCOMP(NOP,IT)xTCOMP(NOP,IT)+XCROSSxTTOK+(XCROSS-XMAN)x0.018xDCROSS)}$$

6 $$\frac{\text{XOTAKE(NO,JT,IT)}}{\text{TIMIN(NO,JT) x TIMIN(NOP,IT)}} \text{ x (TOTTIM(NO,JT)+XCROSSxTACC(NO,JT))}$$

$$\text{x (XCOMP(NO,IT)xTCOMP(NO,IT)+XCROSSxTTOK+(XCROSS-XMAN)x0.018xDCROSS)}$$

Colour Light Working

Element Number

1 $$\frac{\mathrm{XMEET(NO,JT,IT)} \times \mathrm{XCOMP(NO,JT)} \times \mathrm{TCOMP(NO,JT)}}{\mathrm{TIMIN(NO,JT)}}$$

2 $$\frac{\mathrm{XOTAKE(NO,JT,IT)} \times \mathrm{XCOMP(NO,JT)} \times \mathrm{TCOMP(NO,JT)}}{\mathrm{TIMIN(NO,JT)}}$$

3 $$\frac{\mathrm{XMEET(NO,JT,IT)}}{\mathrm{TIMIN(NO,JT)} \times \mathrm{TIMIN(NOP,IT)}}$$

$$\times\ \mathrm{(TOTTIM(NO,JT)+XCOMP(NO,JT)xTACC(NO,JT))} \times \mathrm{(TOTTIM(NOP,IT)+XCOMP(NOP,IT)xTACC(NOP,IT))}$$

4 $$\frac{\mathrm{XOTAKE(NO,JT,IT)}}{\mathrm{TIMIN(NO,JT)} \times \mathrm{TIMIN(NO,IT)}}$$

$$\times\ \mathrm{(TOTTIM(NO,JT)+XCOMP(NO,JT)xTACC(NO,JT))} \times \mathrm{(TOTTIM(NO,IT)+XCOMP(NO,IT)xTACC(NO,IT))}$$

5 $$\frac{\mathrm{XMEET(NO,JT,IT)}}{\mathrm{TIMIN(NO,JT)} \times \mathrm{TIMIN(NOP,IT)}}$$

$$\times\ \mathrm{(TOTTIM(NO,JT)+XCOMP(NO,JT)xTACC(NO,JT))} \times \mathrm{XCOMP(NOP,IT)} \times \mathrm{TCOMP(NOP,IT)}$$

6 $$\frac{\mathrm{XOTAKE(NO,JT,IT)}}{\mathrm{TIMIN(NO,JT)} \times \mathrm{TIMIN(NO,IT)}}$$

$$\times\ \mathrm{(TOTTIM(NO,JT)+XCOMP(NO,JT)xTACC(NO,JT))} \times \mathrm{XCOMP(NO,IT)} \times \mathrm{TCOMP(NO,IT\ )}$$

APPENDIX 11

COST EQUATIONS

General equations for annual equivalent cost of capital

A11.1 If the rate of interest is greater than zero:-

$$CAN = \frac{(CPRES - (CSCRAP/(1 + RINT)^{xlife})) \times RINT}{1 - (1 + RINT)^{-xlife}}$$

A11.2 If the rate of interest is zero:-

$$CAN = \frac{CPRES - CSCRAP}{XLIFE}$$

CAN	the annual equivalent cost of capital.
CPRES	the capital cost of the goods.
CSCRAP	the scrap value of the goods.
XLIFE	the economic life of the goods in years.
RINT	the yearly rate of interest expressed as a fraction.

Rolling stock depreciation

A11.3 Economic life of rolling stock.

XLIFL = the smaller of:-

XLIFOBL(IKLOC)

and:-

XLIFKL(IKLOC)/XLOCKM(IKLOC)

XLIFW = the smaller of:-

XLIFOBW(IKMAT)

and:-

XLIFKW(IKMAT)/XWAGKM(IKMAT)

XLIFL	the economic life of a locomotive.
XLIFW	the economic life of a wagon.
XLIFOBL	the time it takes for a locomotive to become obsolescent.
XLIFOBW	the time it takes for a wagon to become obsolescent.
XLIFKL	the kilometres which a locomotive can run before reaching the end of its economic life.
XLIFKW	the kilometres which a wagon can run before reaching the end of its economic life.
XLOCKM	locomotive - km per locomotive per year.
XWAGKM	wagon - km per wagon per year.
IKLOC	a counter describing locomotive types.
IKMAT	a counter describing wagon types.

A11.4 Annual equivalent costs of rolling stock.

For each vehicle, these are obtained using equation A11.1 or A11.2, using the values for XLIFL and XLIFW as described in equations A11.3.

Locomotive maintenance

A11.5
$$CLOCTT(IWSHP) = CLOCFX(IWSHP) + \sum_{ikloc=1}^{krfloc} [CLOCNM(IWSHP,IKLOC) \times XLOCRQ(IKLOC) + CLOCKM(IWSHP,IKLOC) \times XTLCKM(IKLOC)]$$

Where:-

IWSHP	takes the value 1 for workshops and 2 for running sheds.
IKLOC	are locomotives types represented by integers from 1 to KRFLOC.
CLOCTT	total mainline locomotive costs (for running sheds or workshops).
CLOCFX	the fixed element of locomotive costs (for running sheds or workshops).
CLOCNM	maintenance cost per locomotive per year.
CLOCKM	maintenance cost per locomotive - km per year.
XLOCRQ	number of locomotives.
XTLCKM	number of locomotive - km for locomotives.

Wagon maintenance - workshops

A11.6
$$CWAGTT(1) = CWAGFX(1) + \sum_{ikmat=1}^{krfwag} [CWAGNM(1,IKMAT) \times XCARRQ(IKMAT) + CWAGJO(IKMAT) \times XWAG(IKMAT)]$$

Variables:-

CWAGFX(1)	fixed element of wagon maintenance for workshops.
IKMAT	integers from 1 to KRFWAG representing wagon and carriage types.
CWAGNM(1,IKMAT)	annual workshop maintenance cost per wagon or carriage.
XCARRQ	number of wagons or carriages.
CWAGJO	workshop maintenance cost per carriage or wagon journey.
XWAG	annual number of wagon or carriage journeys.

Wagon maintenance costs - running sheds

A11.7
$$CWAGTT(2) = CWAGFX(2) + \sum_{ikmat=1}^{krfwag} [CWAGNM(2,IKMAT) \times XCARRQ(IKMAT) + CWAGKM(IKMAT) \times XTWGKM(IKMAT)]$$

Variables:-

CWAGTT(2)	total wagon and carriage running shed maintenance costs.
CWAGFX(2)	fixed element of running shed maintenance.
CWAGNM(2,IKMAT)	running shed cost per wagon or carriage.
XCARRQ(IKMAT)	number of wagons or carriages.
CWAGKM(IKMAT)	running shed cost per wagon - km.
XTWGKM(IKMAT)	wagon - km per year.

Track maintenance costs

A11.8 $CMNTRC = CFTRAC \times DISCRS + CVTRAC \times WGRKM^{cptrac}$

Where:-

CMNTRC	are total track maintenance costs.
CFTRAC	are fixed track maintenance costs per track - km.
DISCRS	is total track - km.
WGRKM	is total gross tonne - km.
CVTRAC,CPTRAC	describe variability of track maintenance costs per gross tonne - km.

Track renewal costs

A11.9 Economic life of track.

$$XLIFTR = XCONTR - RLIFTR \times WGRTOT$$

Where:-

XLIFTR	is the economic life of track.
XCONTR	is the economic life if no traffic ran on the track.
RLIFTR	is the years of track life lost per gross tonne carried.
WGRTOT	is the annual gross tonnes carried per year.

A11.10 Annual equivalent cost of track renewal.

Capital and scrap cost per km, the rate of interest, and XLIFTR as derived above are substituted into equation A11.1 or A11.2 to obtain an annual equivalent cost of track per km. This is multiplied by the line length including crossing loops to give total annual track costs.

Trains working method

A11.11 CADTWM fixed cost of trains working method administration.

Trains working method operation and maintenance

A11.12 $$CTWMRC = (XMAN + 2) \times CTWMMN + (XCROSS + 2) \times CTWMNT$$

Variables:-

CTWMRC	recurrent costs (operation and maintenance) of the trains working method.
CTWMMN	recurrent trains working method cost per manned loop.
XMAN	number of manned loops on the line (+2 for the ends of the line).
XCROSS	number of crossing loops on the line (+2 for the ends of the line).

Trains working method depreciation - equipment

A11.13 $$CATWMT = CATWML \times (XCROSS + 2) + CATWMM \times (XMAN + 2)$$

Variables:-

CATWMT	total annual depreciation costs of the trains working method (excluding the control centre).
CATWML	annual equivalent capital cost of trains working method equipment per crossing loop (zero for paper order)
CATWMM	annual equivalent capital cost of trains working method equipment per manned loop (zero for Van Schoor and colour light).
XMAN	number of manned loops
XCROSS	number of crossing loops.

Trains working method depreciation - buildings

A11.14 CASTN = (XMAN + 2) x CASTMN + XUNMAN x CASTUN

Variables:-

CASTN	annual depreciation costs of all buildings required for trains working method.
CASTMN	annual depreciation cost per minor manned station.
CASTUN	annual depreciation cost per unmanned staton.

Extra costs at main stations

A11.15 CTMAIN = CRMAIN x XMAIN + CAMAIN x XMAIN

Variables:-

CTMAIN	extra costs at main stations.
CRMAIN	extra recurrent cost per main station (over and above that incurred at a minor manned station).
CAMAIN	extra depreciation cost per main station (over and above that incurred at a minor manned station.

Yard costs

A11.16 CYARD = CYRFIX + CYRVAR x WTRTOT

Variables:-

CYARD	total yard costs.
CYRFIX	total fixed costs in yards.
CYRVAR	variable yard cost per gross tonne.
WTRTOT	number of gross tonnes per year excluding locomotives passing through yards.

Administration costs

A11.17 CADM Administration costs excluding those involved with the trains working method.

Crew costs

A11.18 CCREW = CRWHR x XTRHRT + CRWKM x XTRKMT

Variables:-

CCREW	total crew costs.
CRWHR	crew costs per train hour.
XTRHRT	number of train hours.
CRWKM	crew costs per train.
XRKMT	number of train km.

Fuel costs

A11.19 $CTOTFL = XFUEL \times |GAVLIN|^{pgav} \times WGRSKM \times CFUEL$

Variables:-

CTOTFL	total annual fuel costs.
WGRSKM	total gross tonne - km per year (trailing load only; excludes weight of locomotives).
XFUEL	a constant expressing variability of fuel consumption.
|GAVLIN|	modulus average gradient of line expressed as per cent.
PGAV	a constant expressing variability of fuel consumption.
CFUEL	cost per litre of diesel.

Oil costs

A11.20 $CTOTOL = XOIL \times COIL \times XOILKM$

Variables:-

CTOTOL	total oil costs.
XOIL	oil consumption in litres per locomotive - km.
XOILKM	total annual locomotive - km.
COIL	cost per litre of oil.