THE OPTIMISATION

OF

TRAIN MAKE-UP AND TRAIN

HANDLING - SIMULATING LONGITUDINAL

TRAIN DYNAMICS

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ABSTRACT

The South African rail industry is undergoing a phase of restructuring and much focus is concentrated on re-engineering i.e. optimising the utilisation of available assets and using existing technology in order to improve efficiency; attention shifts to improved heavy haul asset management through train performance models.

The computer programs presented in this thesis have been developed to calculate longitudinal in-train forces accruing in long heavy haul trains and their effect on train operations. The model of the train is implemented by dedicated differential equations for the movements of each vehicle. The simulation is menu driven for all input and output decisions using Microsoft Excel while the engine for the dynamic analysis is ACSL (Advanced Continuous Simulation Language).

The main program is capable of simulating the operation of any train configuration over any route, including remote operation.

The thesis comprises: -

- a discussion on the need for alternative train configurations based on the current fleet and the potential of such operating changes;

- the comparison of the dynamic response of trains operating with only head-end locomotives, trains operating with both head-end locomotives and remote locomotives and trains operating with different class locomotives in one locomotive consist;

- the investigation of the lateral effects in the different train consists as a function of the longitudinal in-train force in the simulation environment;

- the advantages of operating with remote locomotives in terms of increased train length, reduced force spectrum on vehicle components and improved energy consumption;

- the implications of the optimum position of the in-train locomotive consist on loading and unloading operations;

- the implications of different train configurations on driver technique or train-handling and the need for an optimum driving strategy to gain maximum benefit from the locomotives.

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DEFINITIONS

Adhesion - The coefficient of friction between the wheel and the rail for acceleration and retardation.

Air Brake System - All of the devices and parts included in making an air brake for controlling the speed and stopping a locomotive or train.

Brake Cylinder - A cylinder, in which compressed air acts on a piston which, transmits the force of the compressed air to the associated brake rigging.

Braking Force - The total force in Newtons pressing the brake shoes against the wheels.

Coupler - An appliance for mechanically connecting rolling stock (railway vehicles) together. The coupler comprises a draw head and a knuckle.

Creep - Part-elastic, part-frictional behaviour intermediate between pure rolling and overall sliding of wheel on rail.

Draft Gear - A shock cushioning unit, installed to transmit compression and tension forces between the coupler and vehicle structure.

Draw Gear - semi-rigid coupling between vehicle structures comprising coupler, yoke, draft-gear element, loose rear stops and front follower.

Drawbar Pull - The force exerted on the coupler between the locomotive and trailing mass which is equal to the locomotive tractive effort less the rolling resistance of the locomotive.

Dynamic Brake - An electrical means used to convert some of the energy of a moving locomotive into an effective retarding force.

Grade - A measure of the inclination of railway track. In North American practice, grade is usually stated in per cent e.g. 1%. Elsewhere track grade is usually expressed in terms of the distance along the track for unit of rise or fall e.g. 1 in 100 (1:100).

Grid - An electrical resistor capable of dissipating quantities of electrical power.

Knuckle - The pivoted end joint of a coupler by means of which coupling is effected between adjacent vehicles when the knuckle is locked.

Locomotive - A unit propelled by any form of energy or a combination of such units operating from a single control station.

Retarding Force - The sum of external forces acting on a moving body tending to oppose continued motion.

Slack - There are two kinds of slack : One is termed "Free Slack" and is the accumulation of clearances and wear in the associated parts of the couplers. The other type of slack is often called "Spring Slack" and results from the compression of draft gears.

Tractive Effort - The force developed at all the locomotive driving wheels parallel to the rail to move the locomotive and wagons. This force is directly proportional to the locomotive horsepower and inversely proportional to the locomotive speed.

Wheel Slipping - The wheel rotating on its axis with motion existing between the wheel and rail at the area of contact.

Wheel Sliding - The wheel not rotating on its axis and relative motion existing between the wheel and rail at the area of contact.

Nomenclature

1.Modelling Approach

$[M]$ = mass matrix

$\{\ddot{x}\}$ = acceleration vector

$\{\dot{x}\}$ = velocity vector

$\{x\}$ = longitudinal displacement vector

y = lateral deflection of the wheelset from the centre of curve

r_o = radius of wheel

l = wheel centre to wheelset centre distance

R_c = radius of curve

γ = angle at which wheel-treads are machined

v_{cr} = over-turning speed

C_{11} = Creep coefficient

F_{long} = longitudinal force

Nomenclature

2. Longitudinal Train Dynamics

x_i = the longitudinal displacement of the ith vehicle

$\dot{x}_i$ = velocity of the ith mass

v = velocity of vehicle (km/h)

$\ddot{x}_i$ = acceleration of the ith vehicle

t = time

m , $mass$ = vehicle mass

g = gravitational acceleration

h = gradient

D = degree of curvature

$R(x)$ = draw-gear reaction force

Fp = draw-gear pre-load force

Fm = draw-gear maximum force

x = draw-gear travel

$\dot{x}$ = draw-gear velocity

a = draw-gear characteristic constant for compression

b = draw-gear characteristic constant for release

s = maximum draw-gear travel (stroke)

1. INTRODUCTION

As labour and fuel or power costs continue to escalate, so does the requirement to operate longer and heavier trains more efficiently. The operational change implies a reduction in cost to haul a tonnage of material. However, as train lengths increase, so do problems related to train handling. In-train forces increase, higher fatigue damage is incurred to rolling stock, and draft gear components and there is an increased risk of a train breaking.

The prime objectives of this simulation study were to:
• evaluate the effects of operating with alternative train configurations on :
- in-train forces and hence locomotive and wagon life cycle implications;
- derailment potential;
- energy consumption;
- traffic capacity and train length;
- running time;
- operating costs;

• optimise train make-up and train handling based on the current fleet.

This meant presenting information on the longitudinal behaviour of long heavy haul trains to allow the author to determine and to quantify the consequences of the proposed operating changes.

1.1   Railway Energy Consumption

The increase in oil prices rendered railway electrification more attractive because of its potential for reducing energy costs. The extent of this reduction depends, of course, on the cost of electrical power and on the future evolution of oil and electricity prices. Although electrification involves a large initial investment in fixed installations and locomotives, it produces operating and maintenance benefits, which increase with traffic. As a result, electrification becomes justified. There is also the

increased power capacity advantage that manifests itself in increased train speeds bringing capacity and productivity gains.

Typically, 85% of the railways' energy consumption is for traction and depends significantly on the driving techniques. For many railways, the most critical traction issue is locomotive availability. The emphasis should be on reliability taking into account environmental conditions, and maintenance facilities and procedures. These aspects together with supportability form a group of entities in the system engineering approach known as the "ilities". The importance of analysing the "ilities" in the design and upgrade of systems will be discussed in subsequent sections.

Railways all over the world have been studying different methods to reduce energy consumption. French Railways started developing programs for minimising energy consumption as far back as 1984. The main feature was speed-distance diagrams produced by central computers, off-line. Tests showed that when using these diagrams, drivers obtained energy savings of about 10% for freight trains. The Germans replied by studying the introduction of on-board microcomputers with expected reduction in consumption of up to 20%. North American experience shows that grouping vehicles to reduce wind resistance can reduce energy consumption by as much as 10% on a given run. Furthermore, improved marshalling strategies not only improve the overall efficiency of railway operations but also decrease energy consumption [1].

Substantial improvements in the railways' energy efficiency appear possible by improved train handling techniques. Computer-assisted driving could have substantial impacts. Given the railway's current rolling stock, a more realistic factor to consider in the quest to increase the railway's energy efficiency, would be better utilisation of capacity. This would also reduce railway costs all round. This introduces the need for a means of quantifying the merits of operating with different train configurations and increased train lengths.

Categories of Energy Efficiency Improvement

The major areas that can ensure improved energy efficiency are:

- operational techniques. These include efforts to drive with reduced energy consumption as the objective, better scheduling of vehicle operations and improved maintenance of vehicles.
- vehicle engineering techniques. The concept involves replacement of parts, sub-systems and systems of rail vehicles with improved or upgraded designs.
- replacement equipment techniques. Time-expired vehicles are replaced with new vehicles of upgraded design. Justification for the investment might include the reduction in maintenance costs, speed of service with energy cost reductions offering an incidental benefit.

1.2   Freight Business Structure

In the 89 years since it began life as South African Railways and Harbours, Transnet (a fitter name for the organisation that criss-crosses the country with a network of different forms of transportation) has become a hugely important component of the national economy and Spoornet is a division thereof. Transnet has evolved through a number of transformation stages of which the most recent one was the formation of a public company with the state as the only shareholder. This process was triggered by a number of factors. As a result of this move, Transnet was called upon to operate in a deregulated market on equal terms with its competitors.

1.2.1 How the efficiency of Spoornet compares with that of Canadian or European railways

In some areas, Spoornet is top of the league. For example, the company has a train of record length and size - the 16 locomotives, 660 wagons, carrying iron ore, 7.5 kilometres long and carrying 68 000 tons of freight - operating on the Sishen-Saldanha line; on the Ermelo-Richards Bay line, Spoornet regularly run trains of more than 21 000 tons, which makes the company a world leader. In other areas, however, the South Africans are not among the best.

Spoornet shouldn't be compared with the European lines in terms of efficiency since they are largely passenger-orientated while Spoornet carries mostly goods. But a comparison with Canada would be more appropriate. The Canadians are ahead - for example in saving manpower. From a macro-economic point of view, reducing the number of jobs is perhaps not the best approach for South Africa.

The latest reports show that several pronouncements have been made regarding privatisation of a number of Transnet's business undertakings, but at this stage, various options are being explored.
According to management, there is no way Spoornet will be privatised. For the time being, the possibility of concessioning certain divisions within the company will be looked into. The difference between concessioning and privatisation lies in the following. In the former, one gives the asset away for a specified period. Various conditions are then attached to the transaction - like specifying that the new partner would have to invest in the asset and that the maintenance must be of a certain standard. Privatisation is an outright sale, not feasible in this country since there is no open plan railway infrastructure. For now, Spoornet will have to concentrate on transformation and re-engineering. This means that the company needs to optimise the utilisation of its assets and use existing technology for improved efficiency.

Spoornet's recent past has been characterised by the need to meet the challenges placed on the business by its markets, customers, competition and shareholders. This has led to the conception of a business structure with 3 specialised business units - COALlink, benchmarked as a world best in providing a competitive edge to our export coal customers on the Richards Bay Coal Line, OREX, providing dedicated export iron ore transport on the Sishen-Saldanha Line. The remaining General Freight Services is grouped into 15 industry based business sectors which forms mining, heavy manufacturing, and light manufacturing divisions.

1.3   Transport Economics

Transport is the life-blood in the effective functioning of any entire economic system. The transport system is, without doubt, one of the most important components of any

infrastructure and particularly important to South Africa due to the long distances that have to be covered in moving goods - about 600km for coal and 860km for iron ore. Without the steady development of the rail network (now operating under the name of Spoornet), South Africa's economic and social development would have been rendered redundant, and so would that of other countries in the southern and central Africa, for they had long depended essentially on the surge provided by this country's economic expansion.

In South Africa, as in many other countries, the electrical operation of railways plays a significant role. The statistics of South Africa's railway undertaking give the following figures : of the total traffic demand in tonne-kilometres some 80% are carried by the railways. The gross tonne-kilometres performed, 82% were provided by electric traction and 18% by diesel traction. Steam traction was eventually terminated except for enthusiast trains.

In the above-mentioned regard, Spoornet is very much aware of the important role it has to play in the effective countrywide transportation system by means of the provision of acceptable rail services and facilities. This demands technical innovations to reduce the cost of existing rolling stock. Improved energy efficient technologies have to be introduced to rail transport at a rate consistent with changing competitive conditions and the need to achieve certain financial objectives.

Freight transport by rail comprises 2 principal types of operation all of which are operated exclusively by Spoornet. These operations are:
- bulk freight carried in trains each operated solely for an individual customer. The major portion of this operation is coal (33%) and iron-ore (18%), carried from mining field to harbour.
- general freight which constitutes 49% of the total market. This service includes solutions for industries, such as mining and mineral, steel, wood and timber, and consumer ware.

To provide these services in line with market demands, a market-oriented approach is required. This would lead to better utilisation of rail freight services. What is in effect

required is a market-oriented transport service with improved efficiency and effectiveness that can fulfil the present day needs of customers functioning in a dynamic economic environment. In these circumstances, continued research on development and the adaptation of services becomes a necessity to enable the operator or service provider (Spoornet) to remain economically viable.

1.3.1   Market-oriented Rail Freight Service

In so far as Spoornet is concerned, marketing of rail freight services should be seen in a more comprehensive context than merely the "selling" of the services. A wider spectrum of activities must be covered such as the following :

(1) Market Analysis
  - determining the scope and nature of the total market in question;
  - evaluating own strengths, weaknesses and opportunities;
  - identifying the segments of the total market;
  - establishing the degree to which the total demand is satisfied;
  - developing services to suit such needs.

(2) Interpretation and definition of transport needs.

(3) Development and adaptation of services to fulfil the changing transport needs.

(4) Improvement of existing services on aspects such as reliability, speed, effectiveness, performance, cost and competitiveness.

(5) The understanding of customer needs and problems with a view to increase customer satisfaction and improvement of the image of the organisation.

1.3.2   The Competitive Edge

South Africa is now part of the "global village" and will have to increase its productivity if the country is to stay competitive in international markets. Spoornet remains the indispensable link in the country's economy as it provides transport and related services in local, regional and world markets for profit. The challenge of

creating a modern, dynamic and reliable railroad is the key to survival. Every tool at our disposal will have to be utilised to accomplish this. Regardless of the type of industry involved, the "ilities" as discussed below play a key role in achieving this objective.

An operating system exists because it contributes towards the achievement of strategic objectives of its owner. Rolling stock exists because it contributes commercially to Spoornet where performance generates profit. Cost Effective Analysis (CEA) is a decision aid that can be used by decision-makers to consider all the technical attributes and performance characteristics of train systems and sub-systems within a unified evaluatory framework. This allows system effectiveness and costs to be predicted over the entire life cycle of the rolling stock. CEA is the subset of the overall systemic worth assessment procedure limited to technical / operational factors. Figure 1.1 shows subjective issues in evaluating system worth i.e. technical and economic factors, and socio-political factors [2]. A summary of the range of evaluating criteria that can be brought into the assessment of the overall systemic worth is shown. System effectiveness is a figure of merit that indicates how well the system meets operational requirements.
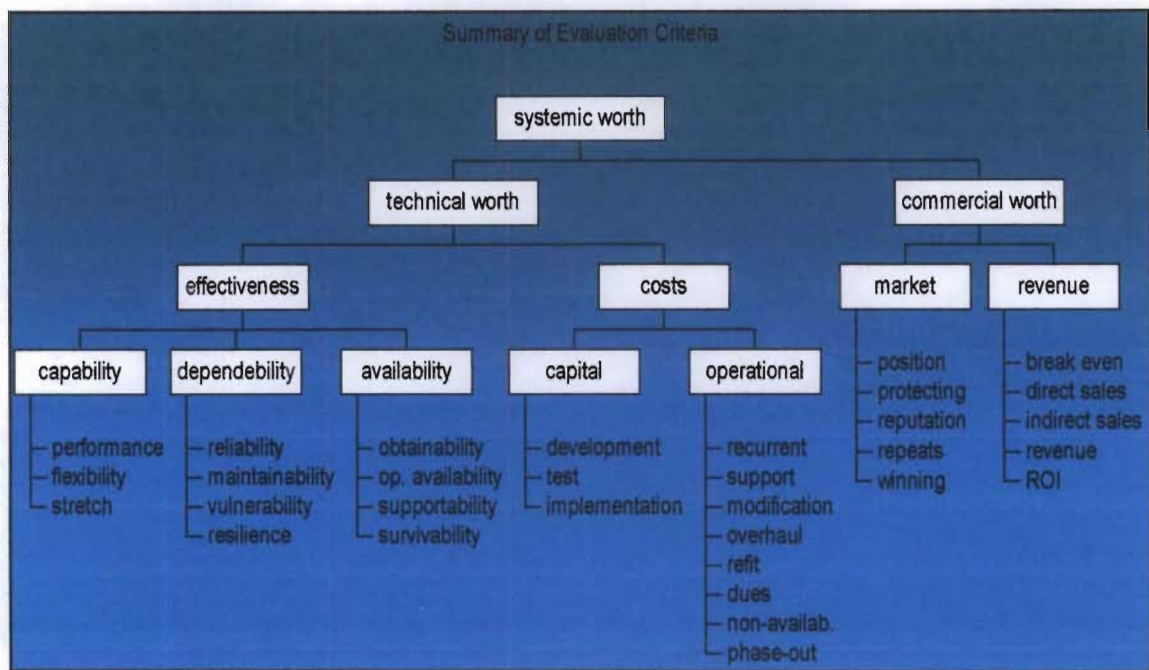
Figure 1.1(a) : Technical and Economic Criteria
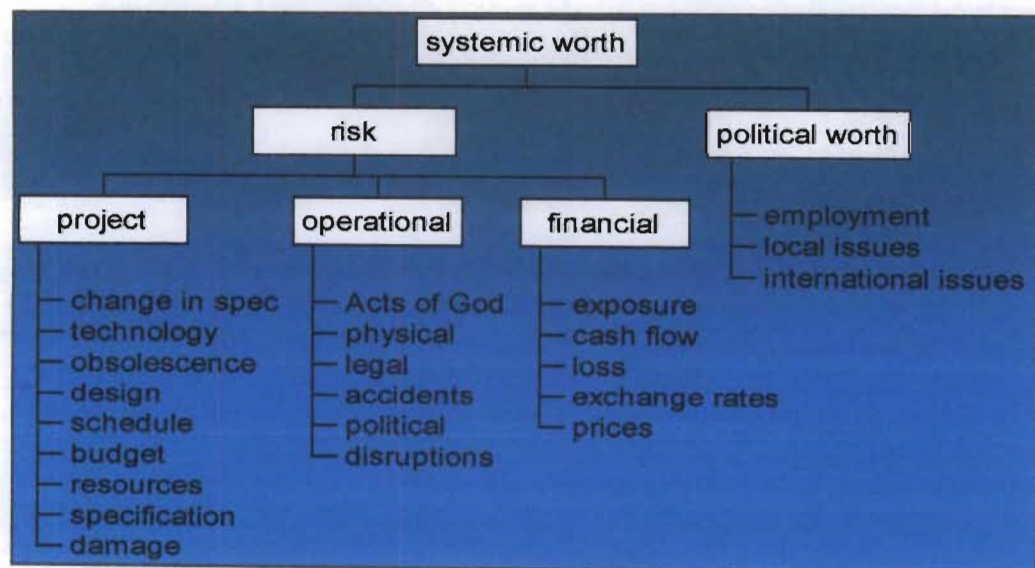
Figure 1.1 (b) : Socio-Political Issues

A simplified general model of CEA is shown in Figure 1.2 and a more complex model is presented by M'Pherson [2].
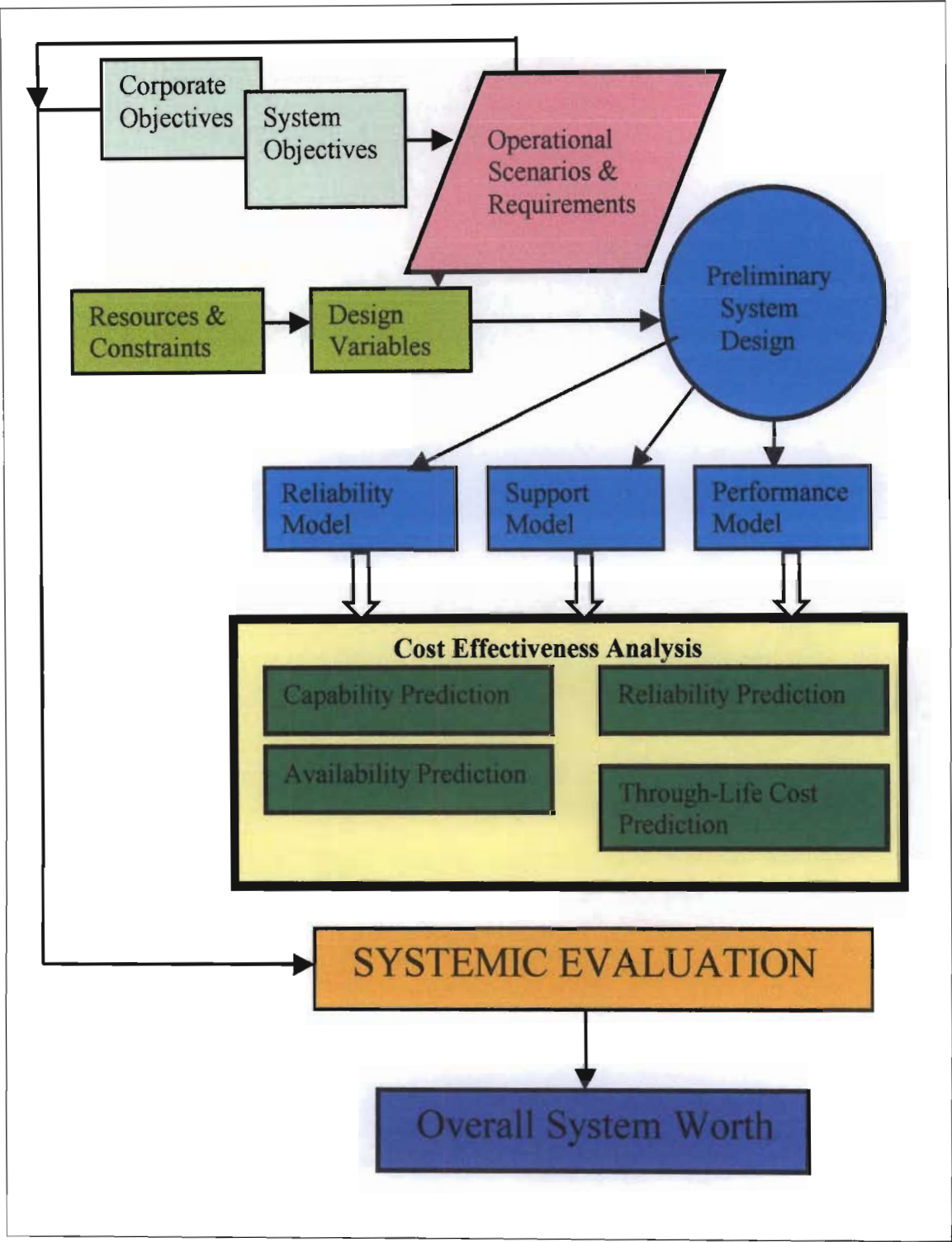
Figure 1.2 : General Model of Cost Effectiveness Analysis

1.3.3 Analysing the "ilities" in the Upgrade
Of Systems

When designing and/or upgrading a system, it is very important to analyse the so-called "ilities". These are :

• Availability

• Reliability

• Maintainability

• Supportability

The factors all affect the stock turnover rates and system operational costs.

Availability

Availability indicates the relative ability of the train system to be up and running when required to meet an operational requirement. It is mostly cost related and consistent with reliability and maintenance targets. Unavailability (forced or scheduled) may lead to loss of revenue while high availabilities lead to high capital or procurement costs. There is an optimum availability which is found by marginal costing techniques comparing capital and operating cost charges with revenue improvements due to increase availability. Proper maintenance and reliability of all rolling stock and sub-systems minimise forced unavailability. Figure 1.3 shows the relationships between costs and availability [2].

The two most important contributing cost / availability relationships are :

(1) Capital or procurement costs rise very steeply at high availabilities because of reliability assurance and system configuration costs;

(2) Breakdown costs or loss of revenue are negative and linear from 0 at 100% availability to total loss at zero availability.

It can be seen that an optimum availability exists. This optimum is found by marginal costing techniques comparing capital and operating cost charges with revenue improvements due to increased availability.
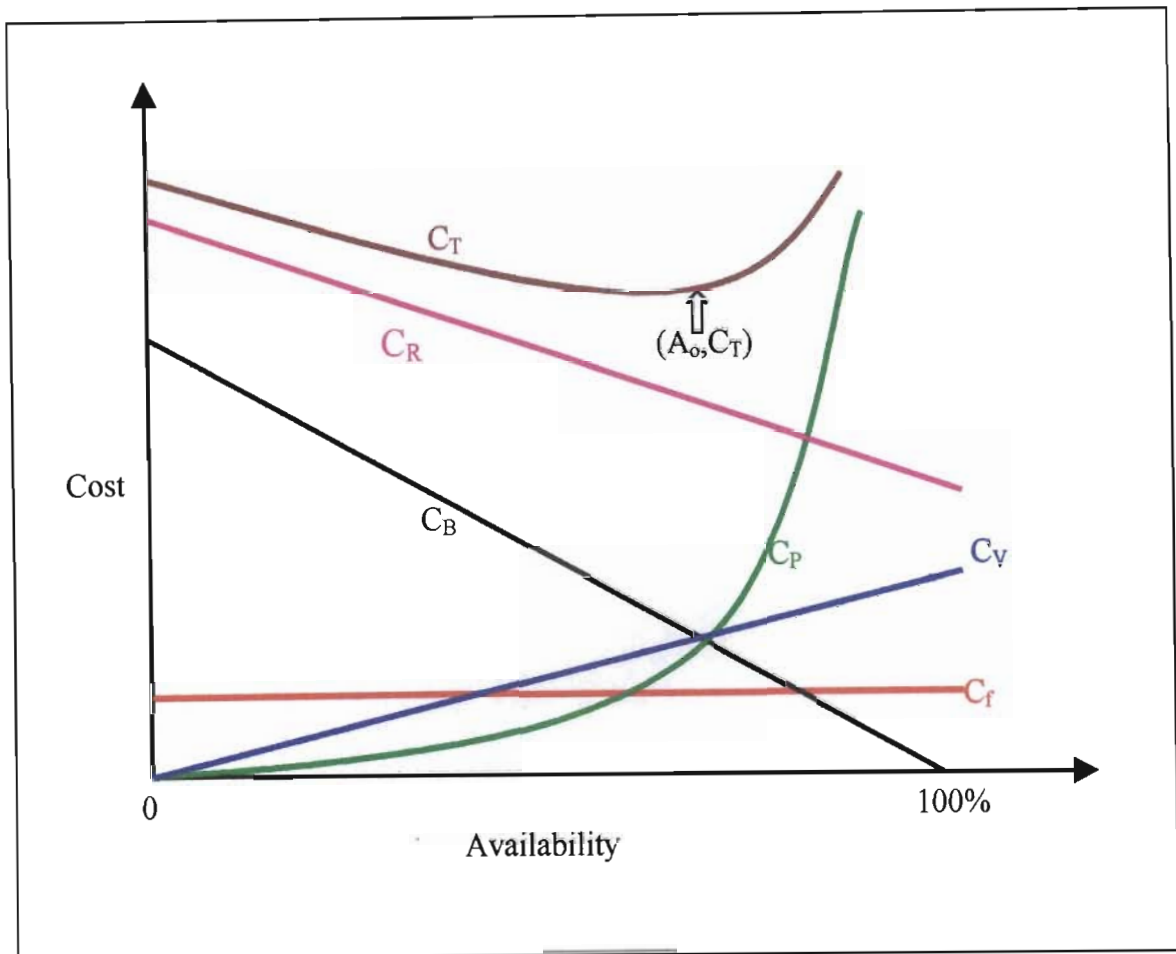
Figure 1.3 : Cost-Availability Model

C_T = Overall Costs

C_R = Total Running Costs

A_o = Optimum Availability

C_B = Breakdown Costs (or Lost Revenue)

C_p = Capital Cost

C_v = Variable Running Cost

C_f = Fixed Running Cost

Reliability

The importance of reliability in industry in relation to both economics and safety has grown enormously in the past decade. A technology of analysis, assessment and monitoring has grown and is now available to management and engineers to help them ensure reliability of products, systems and services. Reliability can be defined as :

"The characteristic expressed as a numerical probability of a system that it will

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perform a defined function in the required manner under all relevant conditions whenever it is required to do so."

Reliability considerations that need to be taken into account are :

- the environment in which the rolling stock must operate;
- the train system's design defects and all constituent components and sub-systems;
- degradation due to operations and maintenance procedures;
- management of the rolling stock and minimising penalties and danger.

Maintainability

Acceptable maintainability characteristics need to be ensured and hence the overall train system availability. With predefined train maintenance policies, operating environment and procedures strictly adhered to, high operational reliability can be maintained. Maintenance scheduling need to be brought into line with operational requirements. Further, life expectancy levels can be maintained and the risk of unavailability (and the implications thereof) is minimised.

Over the last half century, the philosophy of how and when maintenance has to be performed has changed.

According to [3], maintenance techniques have evolved through a number of generations viz. :

(1) **First generation (1940 - 1950)**

- Technique
  - Fix it when it broke

(2) **Second Generation (1950 - 1980)**

- Technique
  - Scheduled overhauls
  - Systems for planning and controlling work;
  - Use of big, slow computers.

(3) **Third Generation (1980 - 2000)**

- Technique
  - Condition Monitoring;
  - Design for reliability and maintainability;

- Use of small, fast computers and decision support tools such as failure mode and effects analysis, expert systems etc.;
- Multiskilling and team work.

The traction division of Spoornet is in the process of adopting the Reliability-Centred Maintenance (RCM) approach to maintaining its vehicles. The RCM process has been defined as follows :

Maintenance : ensuring that physical assets continue to fulfil their intended functions.

RCM : a process used to determine the maintenance requirements of any physical asset in its operating context.

Seven questions must be answered about each selected asset in the process of RCM and these are :

- what are the functions and associated performance standards in the operating context;
- in what way does it fail to fulfil its functions;
- what causes each failure;
- what happens when each failure occurs;
- in what way does each failure matter;
- what can be done to prevent each failure;
- what should be done if a suitable preventative task cannot be found?

Supportability

Supportability enhances the overall system effectiveness and assesses the implications of train system reliability and maintainability on system support. Defined at procurement stage, supportability requirements must be consistent with reliability and maintainability targets.

1.4 Operation Scenario

In the last two and a half decades, two main lines have been built to transport bulk export commodities viz., coal and iron-ore from mine to port. These two lines are the Sishen-Saldanha Bay Line , the so-called "Ore Line" and the Ermelo-Richards Bay Line , the so-called "Coal Line". For a variety of reasons, these roads have found it necessary to operate the longest , heaviest trains possible within the capabilities of the track structure, vehicle structure and locomotive haulage capacity. Not the least of these considerations is the need to minimise the total number of trains in the operating circuit to avoid line congestion while transporting between 22 million and 65 million tons of freight per annum. This in turn requires a thorough understanding of the longitudinal behaviour of such trains. To reach this goal, accurate and efficient simulations are essential to complement practical research.

Of particular interest in this case is the Coal Line. The line was built with the primary purpose of transporting coal in bulk for export from Richards Bay Harbour. Initially, about 10 million tons of coal was the annual export target through the port, but the figure has over the years been increased and currently rests on the 62.5 million ton mark. At first, it was decided that the line would be operated by diesel-electric locomotives. In 1973, as a direct result of the energy crisis and increased costs of imported fuel, it was decided that the line should be electrified and 25KV AC traction has now been introduced.

In recent times, even the price of locally produced electric power has increased enormously and energy efficiency improvement has become of primary importance. It is therefore an opportune time to consider the economics of electric traction and on this line in particular. To transport 62.5 million tons of coal from Ermelo to Richards Bay, the gross traffic handled amounts to 170 million tons annually and the quantity of electrical energy is more than 380 million kWh per annum based on current operating strategies. This figure should not vary significantly with different locomotive combinations and the sizes of individual trains nor the usual variation in speed on this line. A question that will be answered is that of the influence of remotely controlled locomotives on this figure.

1.5 Management of Train Operations

The effective technical management of rolling stock is the foundation for success of any railroad. An essential element of railroad heavy haul asset management is the use of computer models for operations planning and as decision support tools to optimise the present investment in plant and equipment. The use of such models allows heavy haul railroads to optimise the physical plant and maximise the productivity of each train set.

To provide a very focused approach to the life cycle management of rolling stock , i.e. managing the system effectiveness, life cycle cost, and safety, a department known as Rolstock was created in 1988 to act as a custodian of all rolling stock belonging to Spoornet. The most important issues in this concept are the functions of Business Management, Project Engineering, Technical Fleet Management, and Technical Ownership. In Rolstock, the life cycle management is handled in two distinct stages as shown in Figure 1.4. Stage one consists of the system definition and specification, design and development, and manufacture and procurement phases of the life cycle. Stage two focuses on operating and support, and retirement and disposal phases of the life cycle. For effective working of this process, people and information play an integral role; the ultimate aim being the support of customer requirements and not only Spoornet's survival but the provision and care of reliable rolling stock to enable Spoornet to achieve maximum advantage from the market.
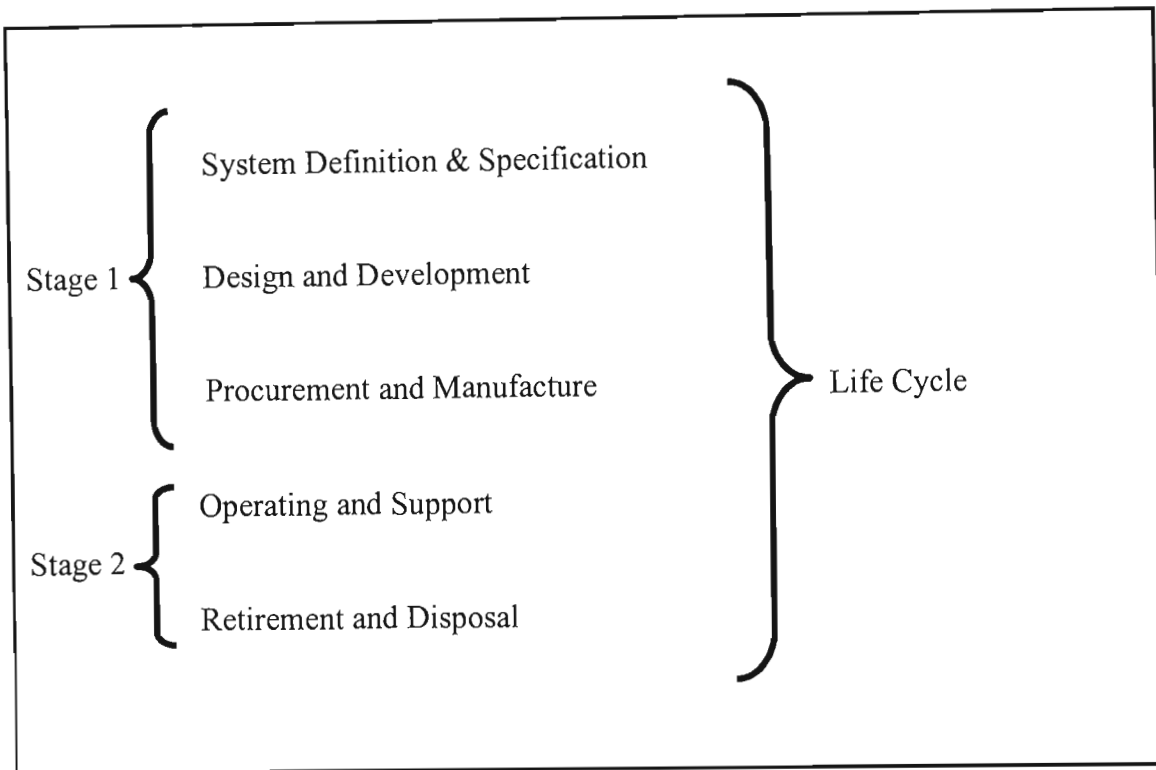
Figure 1.4 : The Two Stages of Life Cycle Management

Six main departments exist within the Rolstock organisation and these are (with their functions) as described by de Bruyn [4] :

- Business Management that:
    - establishes and interprets customer requirements as either new rolling stock, modified rolling stock or changes in the maintenance plan;
    - monitors customer satisfaction.
- Engineering Services that:
    - takes responsibility for stage one of life cycle management through the Project Management group;
    - contributes towards the effective management of technology through "Very Important Technology" owners (VIT owners). Examples of VIT areas are Bogie design, Couplers & Drawgear, Brake System and Traction Control Systems.

    ⇒**VIT owners** identify the technology needed to balance the customer requirements with Spoornet's survival.
- Fleet Services that :

- takes responsibility for stage two of technical management of rolling stock through Technical Fleet Managers, Technical Owners, Maintenance Engineering, Maintenance Operations, Industrial Engineering and Configuration Management .

  ⇒The focus of the **Technical Owner** is the technical management of the rolling stock in the operational environment. He takes ownership of the asset and integrates the technical management with the customers and establishes long, medium and short-term maintenance plans according to the condition of the fleet.

  There are in total 17 technical owners in Rolstock managing a total of approximately 3200 locomotives, 131 180 wagons and 1300 main line coaches.

  ⇒The **Technical Fleet Manager** takes responsibility for the long-term fleet planning of a logical grouping of rolling stock; this includes replacement and modification decisions, capital plans and matching client requirements with the available fleet. He monitors the utilisation of rolling stock assets within the operational environments.

  ⇒ **Maintenance Engineers** establish the condition of local fleets and the influence of local conditions on the performance and reliability of the rolling stock, identify and eliminate faults on rolling stock, facilitate short-term maintenance planning and scheduling.

- supports the rolling stock in the operational environment through fleet planning and maintenance activities.

  ⇒ **Configuration Management** supports the asset and maintenance process by ensuring that maintenance procedures are carried out according to instruction.

- Asset Management that :
  - supports the effective technical management of rolling stock through Risk Management (including statutory requirements), Materials Management, Quality Assurance, Management of Capital spending, and Information Systems.

- Finance Management;

• Human Resources.

Much of the discussion above centred on a concept representing the "hard' assets of heavy haul rail system. It has become more difficult to squeeze productivity improvements out of the "hard" assets and focus shifts to using the above mentioned process together with what is known as the "soft" side of railroading i.e. the use of computer modelling. Used in tandem, they will allow the heavy haul planner to optimise train service, train schedules, maintenance windows, and physical plant improvements.

1.6   Characteristics of Coal Line Trains

The export Coal Line uses the following rolling stock :-

Type	Name	Rating (kW)	Rating (kV)	Balancing Speed(km/h)	Tractive Effort (kN)	Mass (ton)
Locomotive	11E	3880	25	34	580	174
	7E3	3000	25	34	450	168
Wagon	CCL - 1					80
	CCL - 3					80
	CCL - 5					104
	CCL - 7					104
	CCL - 8					104
	CCL - 9					104

Table 1.1 : Summary of Rolling Stock Working the Coal Line

It is current practice on the Coal Line to run :

- 100 wagon trains with the wagons coupled together in pairs;

- 200 wagon trains with the wagons coupled together in rakes of four wagons.

The rakes are coupled via standard draw gear assemblies . Within the rake, the wagons are coupled via a draw bar. The characteristics of the coupling mechanisms will be discussed in detail in Chapter 5.

Dutton [5] discusses the merits of train consists comprising semi-rigidly coupled rakes of rigidly coupled wagons and puts the concept of "slackless" into perspective. Focus was on extending component life cycles by incorporating a coupling mechanism which would reduce the in train forces experienced by the wagons.

Advantages of the slackless system include the following :

- Reduced potential for train separations, derailments and lading damage due to an improved force spectrum;

- Moderate slack action is experienced;

- Air brake problems are reduced due to the elimination of conventional glad hand type connections;

- The solid connections minimise jack knifing capability and hence lateral forces;

- The aerodynamics of the train is improved due to pulling the wagons together and reducing inter-wagon turbulence and drag.

- The Coal Line is approximately 580 km long with a ruling gradient of 1:160.

Based on current operating data, the locomotive design is optimal in that any additional train mass will have to be accompanied by additional locomotives with the associated increase in costs based on the operating techniques. We then have to look at other ways to improve utilisation of the current fleet and optimise its capability.

1.7 Objectives

This thesis will attempt to answer the questions listed below along with appropriate recommendations :

- what are the effects of operating with remote locomotive consists on in-train forces and component life cycles, energy consumption and train length;
- what is the optimum position of the in-train locomotive consist given different boundary conditions such as force spectra etc.;
- what are the effects of operating with mixed locomotive consists and their implications;
- what are the implications of such operating changes on train handling and how a train is made up;
- is there an optimum way such trains could be driven to gain maximum benefit from the locomotives;
- would the introduction of such train configurations have an effect on derailment potential;
- is an active draw gear unit or passive draw gear unit required for the locomotive consists.

2. MODELLING APPROACH

2.1 Introduction

A model represents essentially 3 aspects of knowledge about the system :-

- structure of the system;
- parameter values;
- response of the model.

To assess the validity of the model, several questions must be answered after a set of validation criteria has been defined. These questions include the following :

- Can the model with the given structure describe the actual behaviour of the train;
- What simplifications and neglections are justified;
- What parameter values give an optimum correspondence between theory and experiments;
- Are these parameters different for different velocities, class of vehicle(s), operating conditions and train configurations;
- What is the accuracy of the optimum description;
- Is the description of forces correct.

The model would not have been particularly good because it had many degrees of freedom or many parameters, or because it includes non-linearities; only its capability to compute the force distribution and assess stability would determine the reliability of the mathematical model.

2.2 Railway Vehicle System Models

The study of the dynamic behaviour of rolling stock and train consists can be divided into two basic groups : the study of the dynamic response and the study of dynamic stability. The former concentrates on predicting the dynamic behaviour of the system under different operating conditions while the latter is aimed at investigating the stability of the system under different operating conditions.

Garg and Dukkipati [6] suggest that railway vehicle system models can be divided into 8 main groups viz. :

(1) Vehicle Dynamics

    (a) Vertical/Lateral Dynamics Models designed to study the dynamic response of a vehicle to track irregularities.

    (b) Lateral Stability Models used to predict the critical speed, wheel-rail forces, suspension and vehicle body forces and displacements.

    (c) Curving Models used to calculate the dynamic or quasi-static forces of a vehicle during curve negotiation.

(2) Train Dynamics

    (a) Longitudinal Dynamics Models used primarily in studies of in-train forces i.e. forces between adjacent vehicles.

    (b) Lateral Stability Models aimed at investigating the effects of coupler alignment control, length of couplers, and vehicle geometry on train stability in the lateral plane.

    (c) Vertical Stability Models used primarily to study a string of vehicles for coupler separation under impact conditions.

(3) Freight Dynamics

    (a) Freight Impact Models used to study lading damage caused by impact in switching yards.

    (b) Freight Damage Models aimed at investigating freight damage due to the dynamic actions that occur in transit.

Generally, in constructing a mathematical model for studying the dynamic behaviour of a train consist, the components of the system are assumed to be rigid bodies with the characteristic six degrees of freedom which correspond to 3 displacements (longitudinal, lateral and vertical) and 3 rotations (roll, pitch and yaw). 6N differential equations would be required to represent the system mathematically. N is the number of components in the system.

Relatively weak coupling exists between the vertical and lateral motions of a vehicle. It is thus not necessary to include the lateral degrees in the vertical response and vice

versa. For vertical response, bounce, pitch and roll degrees of freedom suffice for the analysis while in the case of lateral response, it would be adequate to use lateral, yaw and roll degrees of freedom. In studies of longitudinal behaviour, the longitudinal, pitch and roll degrees of freedom of components can be included in the model. In this study, only the longitudinal degree of freedom will be considered to predict coupler forces, speed, distance and time relationships etc.

2.3 Longitudinal Train Dynamics

Longitudinal train dynamics models have been developed over the years expressly for use in studies concerning train makeup, train handling, braking system design and to investigate cushioning devices and their design.

Longitudinal forces are very important and must be monitored since they are primarily responsible for broken draw gears, wear and fatigue involving broken components and they can affect train operations noticeably. Factors that affect these forces include :

- number of locomotives and wagons and their related weights, dimensions and positions;
- grades or the curvatures over which the train operates;
- characteristics of the braking system used;
- types of drawgears used;
- the speed of the train and the types of throttle used in brake manipulation to control the train.

Train movement and traction duty cycle results in dynamic interactions among individual vehicles and between vehicles and the track. The longitudinal in-train coupler forces play a significant role in safe, efficient and stable train operations. The area of longitudinal train dynamics deals primarily with the study of the development of these in-train forces and their resulting effect in the vertical, lateral, and longitudinal directions.

2.3.1 Longitudinal In-train Forces

In this chapter, the parameters significant to train dynamics , and in particular longitudinal train dynamics, are introduced. These represent patterns to be looked out for in the simulations presented in Chapter 5.

With head-end powered trains, in-train force variations are primarily due to:

- variations in the steady state forces;
- impact forces.

Steady-state Forces

These forces occur due to the combined influence of various external forces acting on the train, including those due to the track gradient, rolling and curve resistance, tractive effort and train brakes.

Impact Forces

Impact forces are usually superimposed onto the steady-state forces and occur when run-in or run-out waves pass through the train due to the transition existing between wagons in tension and those in compression in response to variations in the steady-state forces. As the name suggests, they result from the impact between single wagons or a block of wagons.

With trains using remotely controlled locomotives, in-train force variations are primarily due to:

- variations in the steady-state forces;
- impact forces;
- longitudinal vibration of a fully stretched or fully compressed train.

The description of the first two types of forces is the same as the case of head-end powered trains. The third type of force, i.e. longitudinal vibration, takes place in two stages, one preceding the other in the following manner:

(1) Cyclic Vibration - occurs as the train attempts to reach an equilibrium state. This creates local impact forces in the vicinity of the remote locomotives.

(2) Longitudinal Sustained Vibration - occurs when the total train is in tension or compression. If some excitation (e.g. motoring or braking) is applied to the train, the whole train vibrates like a continuous body.

The longitudinal vibration will continue until:

- a change of state occurs anywhere along the length of the train and at least one draw gear is in the relaxed state.
- the in-train force anywhere along the length of the train is sufficiently low for the coupler to enter the relaxed state.
- the vibration has been damped out by the structural damping from the couplers.

2.3.2 Slack Run-ins or Run-outs

A train can either be in buff or draft mode. In the former, all the vehicles in the train consist are subjected to compressive forces while in the latter, tensile forces dominate. Slack run-ins or run-outs manifest themselves as peak forces of brief duration at any location within the train. Run-in (longitudinal in-train compressive) and run-out (longitudinal in-train tensile) train actions are initiated as a train passes over track having grade changes of sufficient magnitude to overcome the available tractive effort or braking.

Run-ins:

- may crush a truck frame;
- break a coupler;
- cause wheel climb on outer rail on a curve and damage to the track by accentuating the angularity between adjoining couplers;
- may cause overspeeding of locomotives resulting in derailment.

Run-outs:

- are more damaging when they peak near the front or rear end of the train;
- may cause train separation through failure of coupler, knuckle, yoke or draft gear lugs;
- may cause wheelclimb on inside rail and thus may overturn the inside rail on a

curve;

- may rupture the underframe of a wagon.

2.3.3 Vehicle Model

To determine total train forces, information on all the forces acting on each vehicle is required. The couplings between vehicles in Figure 2.1 (a) denote spring and damping elements. The forces shown in Figure 2.1 (b) are considered to act on each vehicle during train movement.
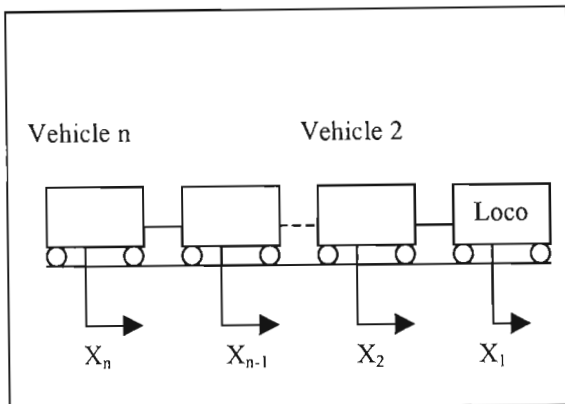
Figure 2.1(a) : The co-ordinate system each
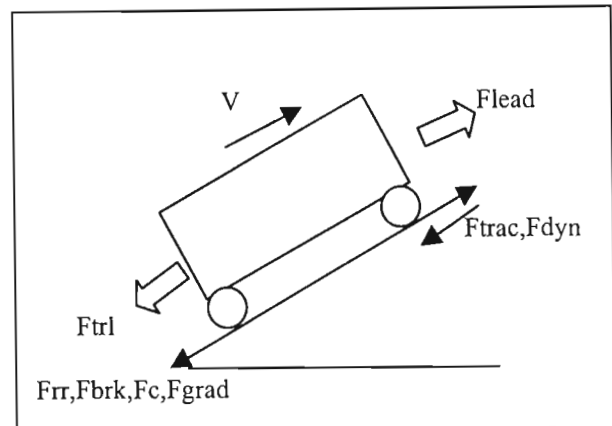
Figure 2.1(b) : Forces acting on Vehicle

$Fbrk$ = Force due to air brake application

Fc = Force due to curve resistance

$Fgrad$ = Force due to grade resistance

$Ftrac/Fdyn$ = Drawbar force due to tractive effort or dynamic braking force

Frr = Rolling resistance due to friction between wheel and rail

$Ftrl$ = Rear coupler force

$Flead$ = Front coupler force

The development of each of the above-mentioned external forces is discussed in Chapter 5. Once the external forces are known, the acceleration or deceleration of the entire train mass can be calculated. Each vehicle is treated as a single mass at all times and a general system of equations developed to calculate the motion of the train at all

times. The equations of motion (discussed in detail in Chapter 5) for the entire train system are written as :

$$[M]\{\ddot{x}\} = \{g(x,\dot{x})\} \qquad (2.1)$$

where g is a function of the response, x, and $\dot{x}$

2.4 Lateral Effects and Derailment Potential

The study presented in this thesis focuses on longitudinal train dynamics. Under certain conditions e.g. high compressive forces on straight track and high tractive forces in sharp curves, lateral dynamics and derailment potential investigations pose special interest. The lateral effects are examined as a function of the longitudinal in-train force and draftgear system configuration. Overturning in sharp curves is assessed through the wheel unloading on the outer rail. This should not exceed 60%.

2.4.1 Lateral Effects

This section is aimed at presenting a global idea of how in-train forces influence the lateral response of wagons in a long train. The lateral wagon movement due to in-train forces can be explained as follows:

Due to gauge clearance between a wheelset and the rails, the wagon can move laterally between two rails as shown in Figure 2.2. The wheel-treads are machined at an angle γ to the rotational axis of the axle so that when the wheelset is displaced laterally with respect to the track, a rolling radius differential is generated between the wheels of the wheelset. The radius differential generated by the wheelset accommodates the difference in the distance rolled between the inner and outer wheels in a curve or when the wheelset is executing a centering motion on straight track (Figure 2.2) and radial alignment on curved track (Figure 2.3) all presented by Tournay [7].
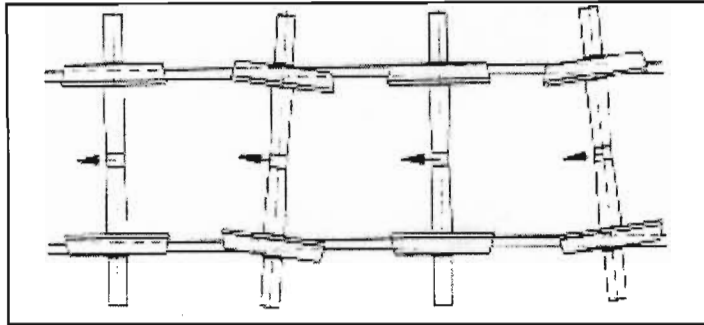
Figure 2.2 : Wheelset Kinematic Motion on
Straight Track
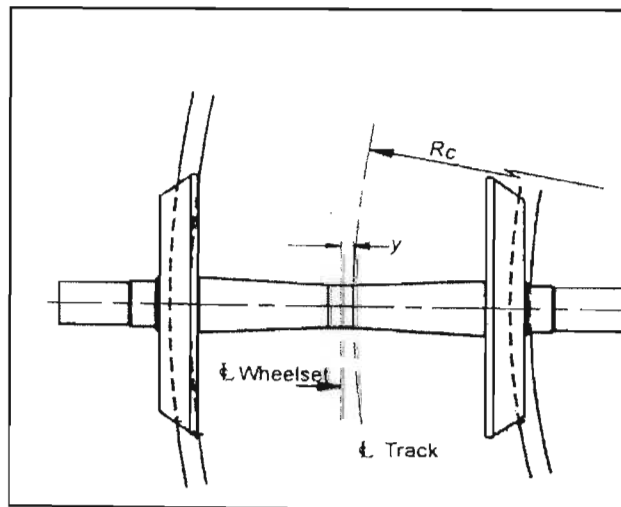
Figure 2.3 : Radial Position of the Wheelset
in a Curve
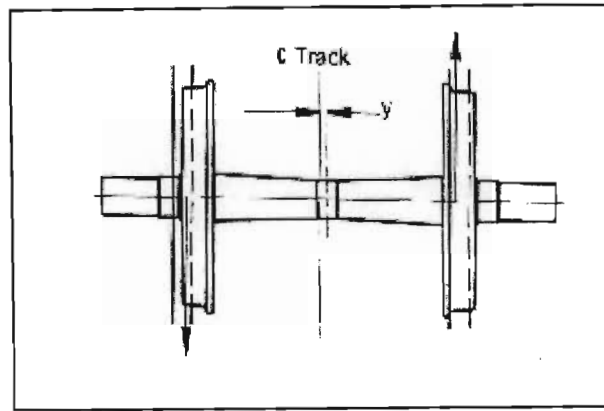
Figure 2.4 : The Railway Wheelset

The lateral deflection of the wheelset from the centre of the curve for pure rolling is :

$$y = \frac{r_o l}{R_c \gamma} \qquad (2.2)$$

There is also some lateral play and compliance within the bogie and within the draftgear system. If the train is subjected to a tensile in-train force, the centre lines of the wagons would form a straight line and no lateral force will be needed to keep the wagons on the track. However, if the train is subjected to a compressive in-train force, each wagon would tend to buckle away from the track centre line. The front bogie of each wagon tends to the right resulting in the so-called jack-knifing phenomenon. To keep the train on the track, the rail exerts lateral forces on the wheels.

Reasons for concern about these lateral forces and the jack-knifing phenomenon include the following :
• many of the derailed wagons on the coal line come to rest in a jack-knifed pattern;
• excessive lateral displacement on the bogie can cause additional wheel wear due to increased wheel creep forces;
• the HS-type bogies used on the coal line have low lateral stiffness which may aggravate the jack-knifing behaviour.

Assuming that the drawbar rotates around its vertical centre, the lateral jack-knifing displacement between two wagons can be calculated from two lateral drawbar displacements in the manner presented in Figure 2.5. van der Westhuizen *et al* [8]

present the jack knifing measurement between the first two wagons from actual tests on the track on two sections. The first section represents data recorded the 20 km post to the 40-km post. The second section shows data recorded between the 40-km post and the 69-km post.
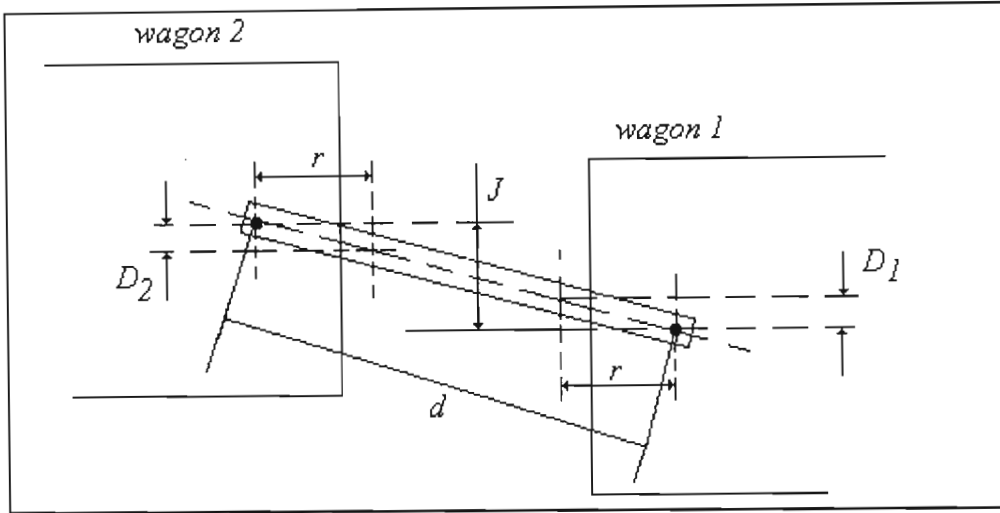
Figure 2.5 : Jack-knifing Measurement

$$J = \frac{(d/2)}{r}D_2 - \frac{(d/2)}{r}D_1 \tag{2.3}$$

Where :

J = Relative lateral jack-knifing displacement between wagon 1 and wagon 2.

d = Draw bar length between pivot centres.

r = Distance between drawbar pivot centre and lateral displacement measurement point.

D_1 = Lateral displacement of the drawbar relative to wagon 1.

D_2 = Lateral displacement of the drawbar relative to wagon 2.

The lateral movement of the drawbar relative to each wagon body can be measured using two displacement transducers :

$$F_{it} = kD_i \tag{2.4}$$

F_{it} = in-train force

k= constant = 40×10^6 N/m

From the jack-knifing vs. in-train plots, the maximum lateral load on the drawbar pivot can be estimated in the following manner :
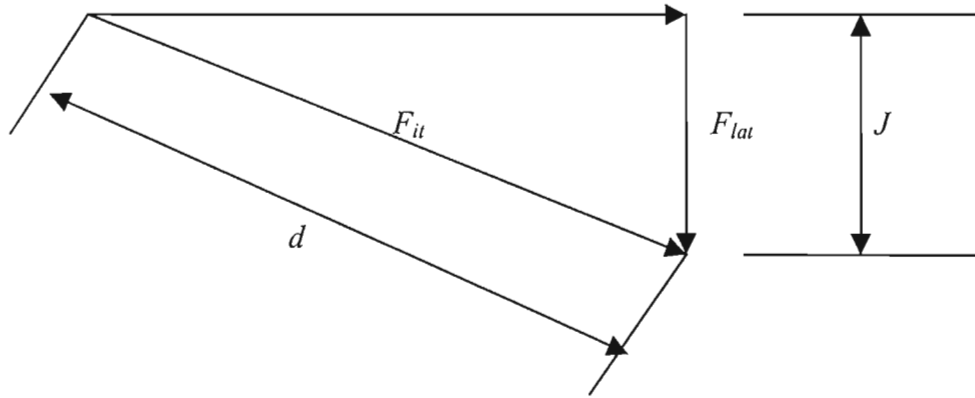
$$F_{lat} = \frac{J}{d} Fit \qquad (2.5)$$

F_{lat} = Lateral load on draw bar pivot point.

Assuming that the jack-knifed wagon rotates about its vertical centreline, the lateral load on the bogie can be calculated according to equation (2.6).
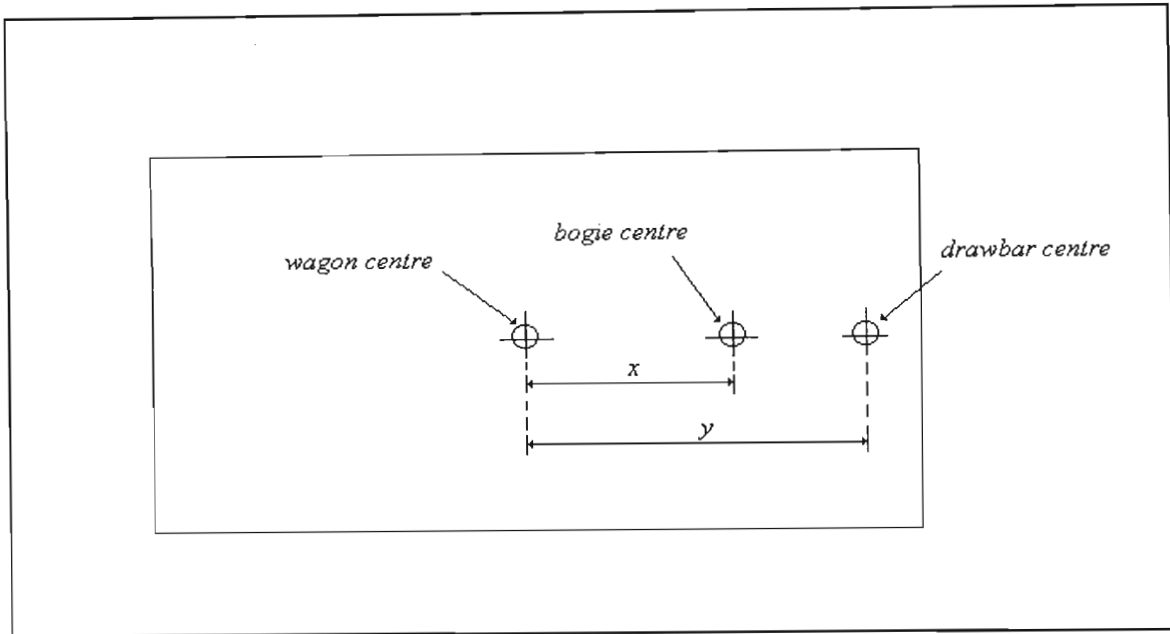
Figure 2.6 : Wagon Geometry

$$F_{lat(Bogie)} = F_{lat} \times \frac{y}{x} \qquad (2.6)$$

Where :

$F_{lat\ (Bogie)}$ = Lateral load on bogie centre

x = Distance between bogie centre and wagon centre

y = Distance between drawbar pivot centre and wagon centre

2.5.2 Wheel Unloading and Traction

Wheel loads vary with variation in lateral acceleration of the vehicle. This is particularly apparent in curves when the vehicle is subject to centrifugal acceleration. Figure 2.7 shows the quasi-static forces acting on a vehicle in a curve [9].
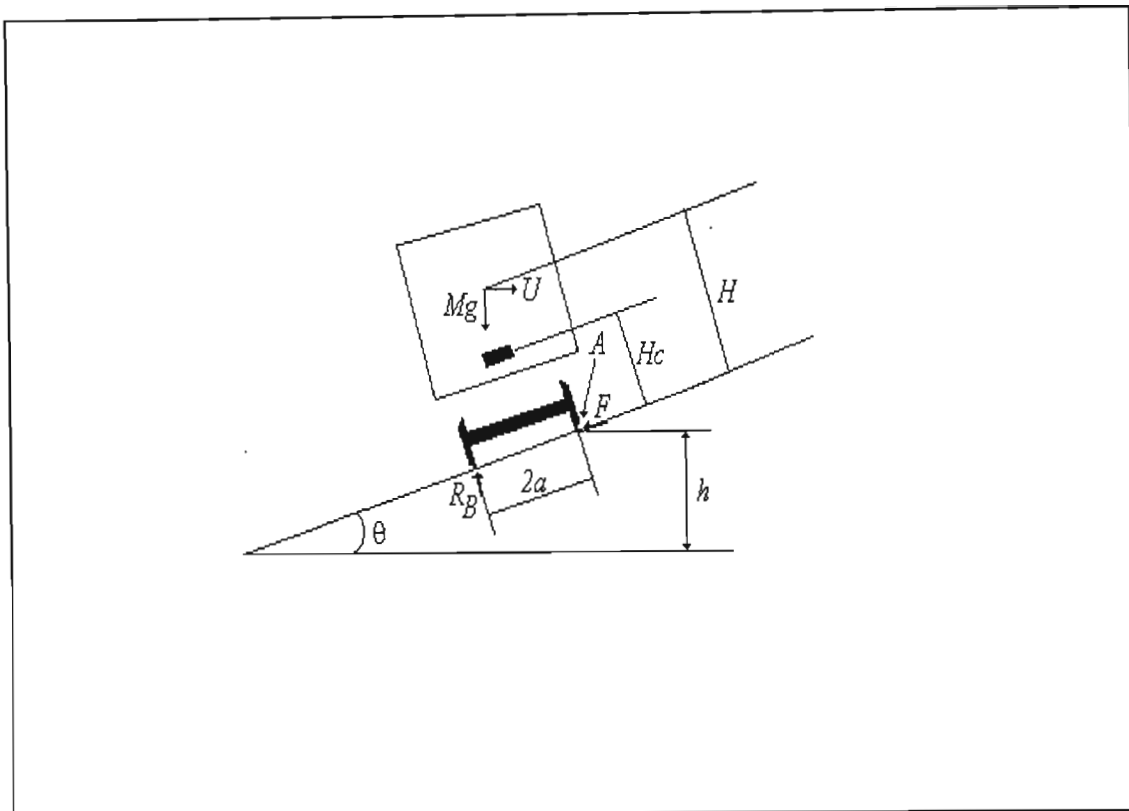
Figure 2.7 : Forces in a Curve

M = total mass of the vehicle

U = centrifugal force

V = vehicle speed

H = height of the centre of gravity above rail level

h = track cant

θ = Cant angle (Approximately $\dfrac{h}{2a}$ for small angles)

g = gravitational acceleration

F = lateral force

$2a$ = track gauge

R_c = radius of the curve

Taking moments about A:

$$R_B 2a - (Mg\cos\theta + U\sin\theta)a + (U\cos\theta - Mg\sin\theta)H = 0 \qquad (2.7)$$

For small θ, $\cos\theta \approx 1$ and $\sin\theta \approx \theta$;

$$R_B 2a - (Mg + U\theta)a + (U - Mg\theta)H = 0 \qquad (2.8)$$

The centrifugal acceleration is $\dfrac{V^2}{R_c}$ and thus :

$$U = M\frac{V^2}{R_c} \qquad (2.9)$$

Summation of forces in the lateral direction yields :

$$F = U\cos\theta - Mg\sin\theta \qquad (2.10)$$

For small θ,

$$F = U - Mg\theta \qquad (2.11)$$

$$F = M\left(\frac{V^2}{R_c} - g\theta\right) \qquad (2.12)$$

Excessive traction forces in sharp curves can cause a train to be pulled to the inside of the curve, and excessive compression forces can push wagons off to the outside. The critical or overturning speed is reached when :

$$\left(\frac{V_{cr}^2}{R_c} - g\sin\theta\right)H \geq ga \qquad (2.13)$$

For $2a = 1.13$,

$$V_{cr} = \sqrt{R_c\left(\frac{71.8}{H} + 0.11247h\right)} \qquad (2.14)$$

The tractive effort exerted on couplers to give 60% wheel unloading is

$$F_{trac(crit)} = \frac{M}{\cos\alpha(2a\sin\theta + 2H_c\cos\theta)}\left[g\left(\frac{2a\cos\theta}{2} - H\sin\theta\right) - 0.2g(2a) + \frac{0.0772V^2}{R_c} + H\cos\theta\right]$$

$$\ldots\ldots\ldots\ldots (2.15)$$

$\alpha =$ angle between the coupler and axis of the wagon

$$\alpha = bg\cos\left[\frac{b}{2R_c}\right] + bg\cos\left[\frac{L_1}{2R_c}\right] - 90$$

$$\theta = bg \sin\left[\frac{h}{2a}\right]$$

L_l = Distance between coupler mounting points

b = Distance from mounting point of coupler on one wagon to the same point on the next wagon in metres.

H_c = Height of the coupler above rail level in metres.

Results

Table 2.1 shows the influence of speed and degree of curvature on wheel unloading and stability during curving.

Speed (km/h)	Radius (m)						
	100	125	150	200	300	400	500
10	436.97	435.64	435.04	433.94	432.82	432.56	432.23
20	456.89	451.58	448.33	443.9	439.47	437.55	436.21
30	490.08	478.14	470.48	460.51	450.55	445.85	442.87
40	536.56	515.29	501.48	483.77	466.05	457.49	452.17
50	596.32	563.12	541.35	513.66	485.98	472.45	464.14
60	669.36	621.55	590.07	550.21	510.34	490.75	478.77

Table 2.1 : Critical Tractive Effort in Curves
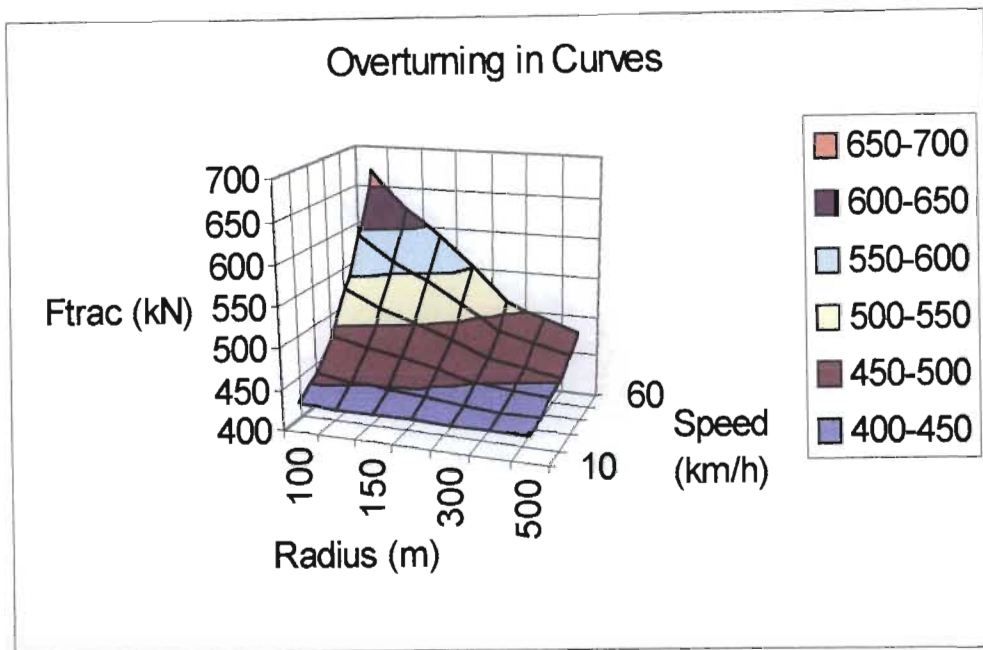
Figure 2.8 : Overturning in Curves

The results depicted in Table 2.1 and Figure 2.8 are presented in the form of the maximum allowable tractive effort at a given line speed in a curve of a particular radius.

Discussion

Inspection of the results illustrates the following :

• At low speeds, the tractive effort that will cause 60% wheel unloading on the outer rail in a particular curve is less than that at high speeds. The low speed enables the locomotives to exert high tractive forces that could cause a significant sideways component of the coupler forces.

• There is a greater variation in the critical tractive effort at higher speeds as the radius of curvature increases and the critical tractive effort decreases as the radius of curvature increases for any given constant line speed.

- At speeds greater than 50km/h and curve radii between 100m and 150m, there is reduced chance of overturning. The maximum tractive effort that the 11E locomotive is capable of delivering in this region is only 270 kN while the minimum tractive effort required to cause wheel unloading is 590 kN.

Conclusion

- Care must be taken in train handling when negotiating sharp curves at low speeds due to the high tractive forces that can be developed in this mode. Wheel unloading may result in instability and hence derailment.

3. SOLUTION TECHNIQUES

3.1 Introduction

A train is a multiple-degree-of-freedom system in which vehicles represent the masses and inertias, couplers denote spring elements and drawgears are damping elements as shown in Figure 3.1 below [10].
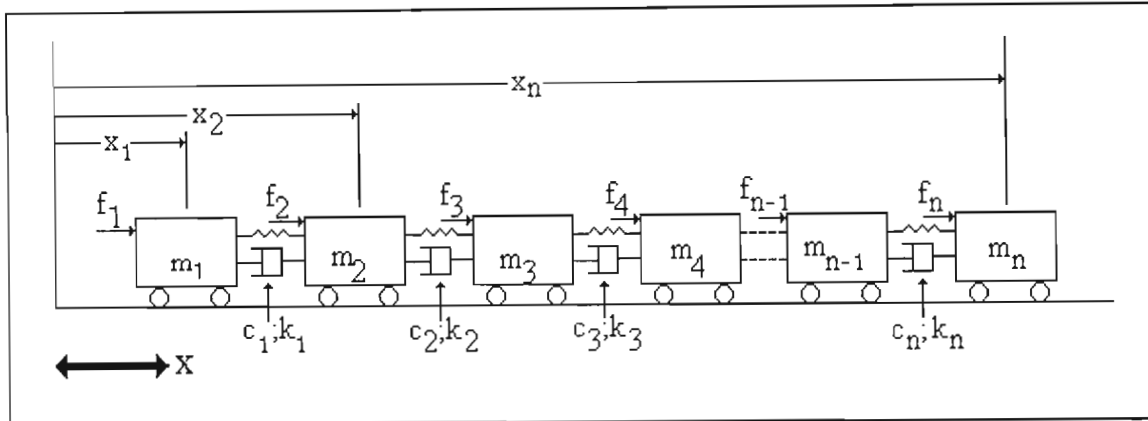
Figure 3.1 : Co-ordinate System for the Model

The dynamic model is based on differential equations relating system parameters to each other with time as the independent variable. There are many forms in which these equations may be formulated for solution, the most common being a set of state equations for the system. This form has not been easily adapted to the modelling of vehicle dynamics due to the difficulty of relating the parameters of the physical system to the coefficients required in the state-variable formulation. However, state-variable equation solutions have been invaluable in the analysis of many vehicle subsystems. The direct differential equation formulation approach has been more widely used, with the early solutions obtained by means of analogue computers. The analogue computer has largely been supplanted by software packages for digital computers designed to simulate the operation and programming techniques used on analogue computers. These packages include CSMP (Continuous System Modelling Program), Simscript, ACSL (Advanced Continuous Simulation Language) and many others. The software utilised to conduct the dynamic simulation was ACSL and its features will be discussed in later sections.

3.2   Analytical Techniques

The equation of motion for a multiple-degree-of-freedom system are written as :

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} = \{F(t)\}$$ (3.1)

$[M]$, $[C]$ and $[K]$ are the n×n mass, damping, and stiffness matrices, respectively. The dynamic analysis involves time-, velocity- and position-dependent externally applied forces. Not only do excitations and responses vary with time but at any instant, the derivatives of one or more variables depend on the values of the system variables at that instant. In most non-linear problems, it is not possible to obtain closed-form analytical solutions for the equations of motion and computer simulation comes into play. Further, as system complexity increases, such calculations become time consuming, expensive and prone to error.

Several numerical schemes employed in computer simulations to obtain the approximate solution of equations of motion or sets of such equations. Examples include Explicit Schemes e.g. Fourth-Order Runge-Kutta Scheme, Implicit Schemes e.g. Houbolt Scheme etc.

The model analysis of the railway vehicle system consists of the solution of a forced vibration problem. This involves time domain solution in which the equations of motion are numerically integrated in time.

Consider the multiple-degree-of freedom system presented in Figure 3.1. The damping and spring effects are accounted for in the excitation forces and the general equation of motion becomes :

$$[M]\{\ddot{x}\} = \{\widetilde{F}(t, x, \dot{x})\}$$ (3.2)

where $\widetilde{F}$ is the excitation force function

Equation 3.2 can be solved by using the numerical integration schemes discussed in subsequent sections or by digital simulation.

The analytical treatment of only a single body from the system takes the form presented below.

First, the system is reduced to an autonomous system i.e. t does not appear explicitly in the equation and appears only as a differential dt. The equation becomes :

$$m\ddot{x} = \widetilde{F}(x,\dot{x}) \tag{3.3}$$
$$\ddot{x} = f(x,\dot{x}) \tag{3.4}$$

where $f = \dfrac{\widetilde{F}}{m}$ (3.5)

Let $x = x_1$ and $\dot{x} = x_2$

$$\therefore \qquad \dot{x}_1 = x_2 \text{ and } \dot{x}_2 = \ddot{x} \tag{3.6}$$

From Equation (3.6),

$$\dot{x}_2 = f(x_1, x_2) \tag{3.7}$$

Equation (3.4) has then been expressed as two simultaneous first order differential equations in $\dot{x}_1$ and $\dot{x}_2$.

This can further be reduced to the following single equation in which time is implicit:

$$\frac{dx_2}{dx_1} = \frac{f(x_1, x_2)}{x_2} \tag{3.8}$$

The solution of the equation above can be portrayed in a phase plane where the co-ordinates are $(x, \dot{x})$ or (x_1, x_2) i.e. a family of trajectories in the phase plane gives a perspective of the general solution of the equation.

3.3 Numerical Integration Schemes

Several numerical schemes can be employed to obtain the approximate solution of the equations of motion for any multiple-degree-of-freedom system. A complete discussion of numerical integration schemes is beyond the scope of this study but there are many available textbooks on the subject [11]. In this chapter, selected numerical integration schemes widely used for non-linear dynamic analyses are discussed. For the solution of non-linear equations of motion, direct numerical integration methods are mandatory. In a direct integration method, the equations of motion are integrated successively by using a step-by-step numerical procedure. Time derivatives are generally approximated by using difference formulas that involve one or more increments of time. There are two basic approaches used in the direct

integration method : explicit and implicit. In the former, the response quantities are expressed in terms of previously determined values of displacement, velocity, and acceleration; in the latter, the difference equations are combined with the equations of motion, and the displacements are calculated directly by solving the equations. Of particular interest is the Second-Order Runge-Kutta Scheme since it is the chosen algorithm for all simulations for its accuracy, stability and it uses less computer time [12].

The Predictor-Corrector Technique

This section is dedicated to the numerical solution of eq. (3.4).

$$\ddot{x} = f(t, x, \dot{x}) \tag{3.9}$$

Evaluating the initial acceleration (at time $t = 0$) from eq. (3.9) yields :

$$\ddot{x}_0 = f(0, x_0, \dot{x}_0) \tag{3.10}$$

The velocity $\dot{x}_i$ at time t_i is approximated as :

$$\dot{x}_i = \dot{x}_{i-1} + \frac{\ddot{x}_{i-1} + \ddot{x}_i}{2} \Delta t_i \tag{3.11}$$

where $\dot{x}_{i-1}$ is the velocity at the preceding time t_{i-1} and the acceleration in the step Δt_i is taken to be the average of $\ddot{x}_{i-1}$ and $\ddot{x}_i$. Similarly, the displacement x_i is approximated by the trapezoidal rule as :

$$x_i = x_{i-1} + \frac{\dot{x}_{i-1} + \dot{x}_i}{2} \Delta t_i \tag{3.12}$$

where the velocity in the step is taken to be the average of $\dot{x}_{i-1}$ and $\dot{x}_i$. Substitution of eq. (3.11) into eq. (3.12) yields :

$$x_i = x_{i-1} + \dot{x}_{i-1}\Delta t_i + (\ddot{x}_{i-1} + \ddot{x}_i)\frac{(\Delta t_i)^2}{4} \tag{3.13}$$

In applying this method, eq. (3.13) is not used directly but eqs. (3.11) and (3.12) are used in succession and the solution is iterative in each step. The following expressions represent the jth iteration of the ith step :

$$(\dot{x}_i)_j = A_{i-1} + (\ddot{x}_i)_{j-1} \Delta t_i / 2 \qquad (j \succ 1) \tag{3.14}$$

$$(x_i)_j = B_{i-1} + (\dot{x}_i)_j \Delta t_i / 2 \tag{3.15}$$

$$(\ddot{x}_i)_j = f[t_i, (x_i)_j, (\dot{x}_i)_j] \tag{3.16}$$

where :

$$A_{i-1} = \dot{x}_{i-1} + \ddot{x}_{i-1}\Delta t_i / 2 \tag{a}$$

$$B_{i-1} = x_{i-1} + \dot{x}_{i-1}\Delta t_i / 2 \tag{b}$$

After evaluating $\ddot{x}_0$ from (3.10), $\dot{x}_1$ for the first step may be approximated by:

$$(\dot{x}_1)_1 = \dot{x}_0 + \ddot{x}_0\Delta t_1 \tag{i}$$

The approximations for x_1 and $\ddot{x}_1$ are obtained from eqs. (3.15) and (3.16),

respectively. All subsequent iterations for the first time step require the use of eqs.

(3.14), (3.15) and (3.16).

To start the iteration in the ith time step,

$$(\dot{x}_i)_1 = \dot{x}_{i-1} + \ddot{x}_{i-1}\Delta t_i \tag{3.17}$$

When $\dot{x}_i$ in eq. (3.17) is substituted into eq. (3.12), the following expression is

obtained:

$$x_i = x_{i-1} + \dot{x}_{i-1}\Delta t_i + \ddot{x}_{i-1}(\Delta t_i)^2 / 2 \tag{3.18}$$

The principal term of the local truncation error is :

$$R''_{x1} = \frac{(\Delta t)^3}{12}\dddot{x}_{i-1} \tag{3.19}$$

In all the cases considered thus far, the effect of damping has not been included in the

analyses. The subsequent schemes will consider simplified interconnecting units

(linear spring model with damping).

3.3.1 Explicit Schemes

Runge-Kutta Methods

Runge-Kutta routines evaluate the derivatives at various points across the integration

step, and a weighted combination of these derivatives is used to step across the

interval. Figure 3.2 shows the procedure for the Fourth-Order algorithm.

x = state

Δt = integration step size

t = time

k_1, k_2, k_3, k_4 = approximate derivative values computed in the interval $t_k \leq t \leq t_{k+\Delta t}$
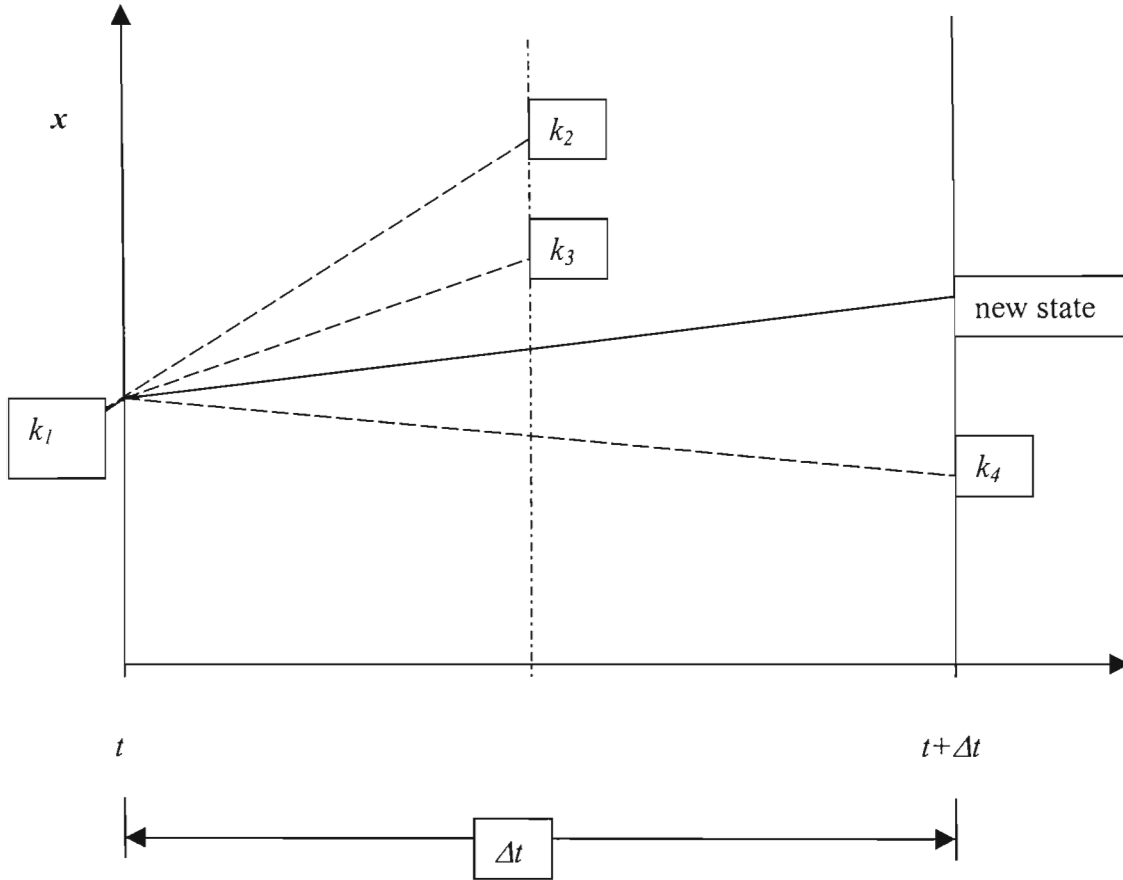
Figure 3.2 : Runge-Kutta Fourth Order Algorithm

The new state is calculated by :

$$\{y_{t+\Delta t}\} = \{y_t\} + \frac{\Delta t}{6}\left[k_1 + 2k_2 + 2k_3 + k_4\right] \tag{3.20}$$

where :

$$k_1 = \{f(t, y_t)\}$$

$$k_2 = \left\{f(t + \frac{\Delta t}{2}, y_t + k_1\frac{\Delta t}{2})\right\}$$

$$k_3 = \left\{f(t + \frac{\Delta t}{2}, y_t + k_2\frac{\Delta t}{2})\right\}$$

$$k_4 = \{f(t + \Delta t, y_t + k_3\Delta t)\}$$

The truncation error e_t is in the form :

$$e_t = k(\Delta t)^5 \tag{3.21}$$

The Second-Order Runge-Kutta Scheme follows a similar procedure, making one derivative evaluation at the beginning and another at a point two-thirds across the step. In the fourth-order scheme, the second derivative evaluation is at a point halfway across the step. Here, the new state is weighted by one-fourth and three-fourths and calculated by :

$$\{y_{t+\Delta t}\} = \{y_t\} + \frac{\Delta t}{4}[k_1 + 3k_2] \tag{3.22}$$

where :

$$k_1 = \{f(t, y_t)\}$$

$$k_2 = \left\{ f(t + \frac{2\Delta t}{3}, y_t + k_1 \frac{2\Delta t}{3}) \right\}$$

The system equations are converted into state variable form i.e. both displacements and velocities are treated as unknowns $\{y\}$ defined by :

$$\{y\} = \left\{ \begin{array}{c} \{\dot{x}\} \\ \{x\} \end{array} \right\} \tag{3.23}$$

The Runge-Kutta Scheme has the advantage that, because its use at each stage of the advancing calculation does not require information relevant to the previous time steps, the method is completely self-starting and is particularly suitable when computer requirements are to be minimised. Its principal disadvantage consists of the fact that each forward step requires several calculations, increasing the cost of computation.

Trapezoidal Rule Scheme

The incremental form of the equation of motion under consideration, at any time t is expressed :

$$[m]\{\Delta\ddot{x}_t\} = \{\Delta F_t\} - [k]\{\Delta x_t\} - [c]\{\Delta\dot{x}_t\} \tag{3.24}$$

In the first iteration cycle, increments in the velocities and displacements are estimated by using the following formulae : -

(1) For the first time step :

$$\{\Delta \dot{x}_t\} = \Delta t \{\ddot{x}_{t-\Delta t}\} \qquad (3.25)$$

(2) For other time steps :

$$\{\Delta \dot{x}_t\} = 2\Delta t \{\ddot{x}_{t-\Delta t}\} - \{\Delta \dot{x}_{t-\Delta t}\} \qquad (3.26)$$

$$\{\dot{x}_t\} = \{\Delta \dot{x}_{t-\Delta t}\} + \{\Delta \dot{x}_t\} \qquad (3.27)$$

$$\{\Delta x_t\} = \frac{1}{2}\Delta t (\{\dot{x}_{t-\Delta t}\} + \{\dot{x}_t\}) \qquad (3.28)$$

Increments in the accelerations are evaluated by solving (3.24) :

$$\{\Delta \ddot{x}_t\} = [m]^{-1} (\{\Delta F_t\} - [k]\{\Delta x_t\} - [c]\{\Delta \dot{x}_t\}) \qquad (3.29)$$

and $\quad \ddot{x}_t = \{\ddot{x}_{t-\Delta t}\} + \{\Delta \ddot{x}_t\} \qquad (3.30)$

In the second iteration cycle, increments in the velocities and accelerations are redefined as:

$$\{\Delta \dot{x}_t\} = \frac{1}{2}\Delta t (\{\ddot{x}_{t-\Delta t}\} + \{\ddot{x}_t\}) \qquad (3.31)$$

$$\{\dot{x}_t\} = (\{\dot{x}_{t-\Delta t}\} + \{\dot{x}_t\}) \qquad (3.32)$$

$$\{\Delta x_t\} = \frac{1}{2}\Delta t (\{\dot{x}_{t-\Delta t}\} + \{\dot{x}_t\}) \qquad (3.33)$$

Finally, (3.30) is used to calculate the accelerations at time t.

Central Difference Predictor Scheme

The difference formulae in the central difference predictor scheme for velocity and acceleration are written as :

$$\{\dot{x}_t\} = (2\Delta t)^{-1} (\{x_{t+\Delta t}\} - \{x_{t-\Delta t}\}) \qquad (3.34)$$

$$\{\ddot{x}_t\} = \Delta t^{-2} (\{x_{t+\Delta t}\} - 2\{x_t\} + \{x_{t-\Delta t}\}) \qquad (3.35)$$

Substituting (3.34) and (3.35) into (3.1) yields :

$$[\overline{m}]\{x_{t+\Delta t}\} = \{\overline{F}_t\}$$ (3.36)

$$[\overline{m}] = \frac{1}{\Delta t^2}[m] + \frac{1}{2\Delta t}[c]$$ (3.37)

$$\{\overline{F}_t\} = \{F_t\} - \left([k] - \frac{2}{\Delta t^2}[m]\right)\{x_t\} - \left(\frac{1}{\Delta t^2}[m] - \frac{1}{2\Delta t}[c]\right)\{x_{t-\Delta t}\}$$ (3.38)

Displacements $\{x_{t+\Delta t}\}$ at time $t + \Delta t$ can be calculated by solving (3.36).

Velocities and accelerations at time t can be solved by substituting $\{x_{t+\Delta t}\}$ into (3.34)

and (3.35) respectively. Provided that Δt is reduced to account for the highest

frequency during the computations, the condition :

$\Delta t \leq \dfrac{2}{\varpi_{max}}$ is valid for stability i.e. the time step is limited by the highest frequency

of the discrete system.

3.3.2 Implicit Schemes

Houbolt Scheme

The Houbolt Scheme is based on third-order interpolation of displacements.

Multistep implicit formulae for velocity and acceleration are derived, in terms of

displacement, by using backward differences.

The difference formulae in the Houbolt Algorithm for velocity and acceleration are

written as :

$$\{\dot{x}_{t+\Delta t}\} = (6\Delta t)^{-1}(11\{x_{t+\Delta t}\} - 18\{x_t\} + 9\{x_{t-\Delta t}\} - 2\{x_t - 2\Delta t\})$$ (3.39)

$$\{\ddot{x}_{t+\Delta t}\} = \Delta t^{-2}(2\{x_{t+\Delta t}\} - 5\{x_t\} + 4\{x_{t-\Delta t}\} - \{x_{t-2\Delta t}\})$$ (3.40)

Substituting (3.39) and (3.40) into (3.1) yields :

$$[\overline{m}]\{x_{t+\Delta t}\} = \{\overline{F}_{t+\Delta t}\}$$ (3.41)

$$[\overline{m}] = \frac{2}{\Delta t^2}[m] + \frac{11}{6\Delta t}[c] + [k]$$ (3.42)

$$\{\overline{F}_{t+\Delta t}\} = \{F_{t+\Delta t}\} + \left(\frac{5}{\Delta t^2}[m] + \frac{3}{\Delta t}[c]\right)\{x_t\} - \left(\frac{4}{\Delta t^2}[m] + \frac{3}{2\Delta t}[c]\right)\{x_{t-\Delta t}\}$$
$$+ \left(\frac{1}{\Delta t^2}[m] + \frac{1}{3\Delta t}[c]\right)\{x_{t-2\Delta t}\}$$

(3.43)

Displacements $\{x_{t+\Delta t}\}$ at time step $t + \Delta t$ can be calculated by solving (3.41). Velocities and accelerations at time $t + \Delta t$ can be solved by substituting $\{x_{t+\Delta t}\}$ into (3.39) and (3.40). The method is not self-starting and requires a large core storage in a computer.

Wilson- θ Scheme

In the Wilson- θ Scheme, it is assumed that the acceleration varies linearly over an increment of time $\theta \geq 1.0$ and that the properties of the dynamic system remain constant during this time interval.
The difference formulae are written as :

$$\{\ddot{x}_{t+\theta\Delta t}\} = \frac{6}{\theta^2\Delta t^2}(\{x_{t+\theta\Delta t}\} - \{x_t\}) - \frac{6}{\theta\Delta t}\{\dot{x}_t\} - 2\{\ddot{x}_t\}$$

(3.44)

$$\{\dot{x}_{t+\theta\Delta t}\} = \frac{3}{\theta\Delta t}(\{x_{t+\theta\Delta t}\} - \{x_t\}) - 2\{\dot{x}_t\} - \frac{\theta\Delta t}{2}\{\ddot{x}_t\}$$

(3.45)

$$[m]\{\ddot{x}_{t+\theta\Delta t}\} + [c]\{\dot{x}_{t+\theta\Delta t}\} + [k]\{x_{t+\theta\Delta t}\} = \{F_{t+\theta\Delta t}\}$$

(3.46)

$$\{F_{t+\theta\Delta t}\} = \{F_t\} + \theta(\{F_{t+\Delta t}\} - \{F_t\})$$

(3.47)

$$[\overline{m}]\{x_{t+\theta\Delta t}\} = \{\overline{F}_{t+\theta\Delta t}\}$$

(3.48)

where :

$$[\overline{m}] = \frac{6}{\theta^2\Delta t^2}[m] + \frac{3}{\theta\Delta t}[c] + [k]$$

(3.49)

$$\{\overline{F}_{t+\theta\Delta t}\} = \{F_{t+\theta\Delta t}\} + \left(\frac{6}{\theta^2\Delta t^2}[m] + \frac{3}{\theta\Delta t}[c]\right)\{x_t\} + \left(\frac{6}{\theta\Delta t}[m] + 2[c]\right)\{\dot{x}_t\}$$
$$+ \left(2[m] + \frac{\theta\Delta t}{2}[c]\right)\{\ddot{x}_t\}$$

(3.50)

Now,

$$\{\ddot{x}_{t+\Delta t}\} = \frac{6}{\theta^2\Delta t^2}(\{x_{t+\Delta t}\} - \{x_t\}) - \frac{6}{\theta^2\Delta t}\{\dot{x}_t\} + \left(1 - \frac{3}{\theta}\right)\{\ddot{x}_t\}$$

(3.51)

$$\{\dot{x}_{t+\Delta t}\} = \{\dot{x}_t\} + \frac{\Delta t}{2}(\{\ddot{x}_{t+\Delta t}\} + \{\ddot{x}_t\}) \qquad (3.52)$$

$$\{x_{t+\Delta t}\} = \{x_t\} + \Delta t\{\dot{x}_t\} + \frac{\Delta t^2}{6}(\{\ddot{x}_{t+\Delta t}\} - 2\{\ddot{x}_t\}) \qquad (3.53)$$

Solution of (3.48) yields $\{x_{t+\theta\Delta t}\}$ which is substituted into (3.51) to obtain the accelerations at time $t + \Delta t$. Velocities and displacements at time $t + \Delta t$ can be solved by substituting (3.51) into (3.52) and (3.53) respectively. The overall scheme is conditionally stable when $\theta \geq 1.5$. Equilibrium is never satisfied at time $t + \Delta t$.

The Newmark - β Scheme

The Newmark-β Scheme uses parameters α and β to obtain integration accuracy and stability. These parameters can be changed to suit the requirements of the particular problem. The expressions for velocity and displacement are given by :

$$\dot{x}_{t+\Delta t} = \dot{x}_t + [(1-\alpha)\ddot{x}_t + \alpha\ddot{x}_{t+\Delta t}]\Delta t \qquad (3.54)$$

$$x_{t+\Delta t} = x_t + \dot{x}_t\Delta t + \left[\left(\frac{1}{2} - \beta\right)\ddot{x}_t + \beta\ddot{x}_{t+\Delta t}\right]\Delta t^2 \qquad (3.55)$$

The nett effect of α and β is to change the form of the acceleration variations during the interval Δt in the manner shown in Table 3.1.

α	β	Acceleration
1/2	0	Constant and equal to $\ddot{x}_t$ during each Δt
1/2	1/8	Constant from beginning as $\ddot{x}_t$ and changes to $\ddot{x}_{t+\Delta t}$ in the middle of Δt
1/2	1/6	Varies linearly from $\ddot{x}_t$ to $\ddot{x}_{t+\Delta t}$
1/2	1/4	Remains constant at an average value of $(\ddot{x}_t + \ddot{x}_{t+\Delta t})/2$

Table 3.1 : The Effect of α and β on Acceleration

The difference formulae for the Newmark-β algorithm are :

$$\{\ddot{x}_{t+\Delta t}\} = \frac{1}{\beta \Delta t^2}(\{x_{t+\Delta t}\}-\{x_t\}) - \frac{1}{\beta \Delta t}\{\dot{x}_t\} - \left(\frac{1}{2\beta}-1\right)\{\ddot{x}_t\} \tag{3.56}$$

$$\{\dot{x}_{t+\Delta t}\} = \frac{\alpha}{\beta \Delta t}(\{x_{t+\Delta t}\}-\{x_t\}) - \left(\frac{\alpha}{\beta}-1\right)\{\dot{x}_t\} - \Delta t\left(\frac{\alpha}{2\beta}-1\right)\{\ddot{x}_t\} \tag{3.57}$$

$$[\overline{m}]\{x_{t+\Delta t}\} = \{\overline{F}_{t+\Delta t}\} \tag{3.58}$$

where :

$$[\overline{m}] = \frac{1}{\beta \Delta t^2}[m] + \frac{\alpha}{\beta \Delta t}[c] + [k] \tag{3.59}$$

$$\{\overline{F}_{t+\Delta t}\} = \{F_{t+\Delta t}\} + \left[\frac{1}{\beta \Delta t^2}[m] + \frac{\alpha}{\beta \Delta t}[c]\right]\{x_t\} + \left[\frac{1}{\beta \Delta t}[m] + \left(\frac{\alpha}{\beta}-1\right)[c]\right]\{\dot{x}_t\}$$
$$+ \left[\left(\frac{1}{2\beta}-1\right)[m] + \Delta t\left(\frac{\alpha}{2\beta}-1\right)[c]\right]\{\ddot{x}_t\} \tag{3.60}$$

Solution of (3.58) yields $\{x_{t+\Delta t}\}$ which is substituted into (3.56) and (3.57) to obtain the accelerations and velocities at time $t + \Delta t$. The greatest disadvantage of this scheme is the fact that for a multiple-degree-of freedom system, the peak amplitude may not be correct.

The Park Stiffly Stable Scheme

The velocity formula in the Park Stiffly Stable Scheme is derived by using a linear combination of the velocity difference formulae in the Houbolt Algorithm i.e. :

$$\{\dot{x}_{t+\Delta t}\} = (6\Delta t)^{-1}(11\{x_{t+\Delta t}\} - 18\{x_t\} + 9\{x_{t-\Delta t}\} - 2\{x_{t-2\Delta t}\}) \tag{3.39}$$

and the velocity formula at time $t+\Delta t$ in the Gear two-step method i.e. :

$$\{\dot{x}_{t+\Delta t}\} = (2\Delta t)^{-1}(2x_{t+\Delta t} - 4x_t + x_{t-\Delta t})$$

Giving :

$$\dot{x}_{t+\Delta t} = (6\Delta t)^{-1}(10x_{t+\Delta t} - 15x_t + 6x_{t-\Delta t} - x_{t-2\Delta t}) \tag{3.61}$$

Similarly :

$$\ddot{x}_{t+\Delta t} = (6\Delta t)^{-1}(10\dot{x}_{t+\Delta t} - 15\dot{x}_t + 6\dot{x}_{t-\Delta t} - \dot{x}_{t-2\Delta t})$$ (3.62)

The difference formulae are :

$$\{\dot{x}_{t+\Delta t}\} = (6\Delta t)^{-1}(10\{x_{t+\Delta t}\} - 15\{x_t\} + 6\{x_{t-\Delta t}\} - \{x_{t-2\Delta t}\})$$ (3.63)

$$\{\ddot{x}_{t+\Delta t}\} = (6\Delta t)^{-1}(10\{\dot{x}_{t+\Delta t}\} - 15\{\dot{x}_t\} + 6\{\dot{x}_{t-\Delta t}\} - \{\dot{x}_{t-2\Delta t}\})$$ (3.64)

$$[\overline{m}]\{x_{t+\Delta t}\} = \{\overline{F}_{t+\Delta t}\}$$ (3.65)

where the effective mass matrix is :

$$[\overline{m}] = \frac{100}{36\Delta t^2}[m] - \frac{10}{6\Delta t}[c] + [k]$$ (3.66)

and the effective force vector is :

$$\{\overline{F}_{t+\Delta t}\} = \frac{15}{6\Delta t}[m]\{\dot{x}_t\} - \frac{[m]}{\Delta t}\{\dot{x}_{t-\Delta t}\} + \frac{[m]}{6\Delta t}\{\dot{x}_{t-2\Delta t}\}$$

$$+ \left(\frac{150}{36\Delta t^2}[m] + \frac{15}{6\Delta t}[c]\right)\{x_t\} - \left(\frac{10}{6\Delta t^2}[m] + \frac{1}{\Delta t}[c]\right)\{x_{t-\Delta t}\}$$

$$+ \left(\frac{[m]}{36\Delta t^2} + \frac{[c]}{6\Delta t}\right)\{x_{t-2\Delta t}\}$$

(3.67)

The solution of (3.65) yields $\{x_{t+\Delta t}\}$ which is substituted into (3.63) to obtain

velocities.

$\{\dot{x}_{t+\Delta t}\}$ is substituted into (3.64) to obtain accelerations. The method is non-self

starting and requires large computer memory to store the velocity and displacement

values from the two previous time steps.

Backward Difference Approximations

The backward difference approximations used in developing the various central

differences in this chapter are as follows :

$$f_i'' = \frac{1}{h^2}(\Delta^2 f_{i-1}) = \frac{f_{i+1} - 2f_i - f_{i-1}}{h^2}$$

$$f_i' = \frac{f_{i+1} - f_{i-1}}{h}$$

3.4   Digital Simulation

Advanced Continuous Simulation Language (ACSL)

ACSL is produced by Mitchell and Gauthier Associates (MGA) Inc. The language has been developed expressly for the purpose of modelling and evaluating the performance of continuous systems described by time-dependent non-linear differential equations. Although the systems being modelled are time-dependent, the independent variable may be something other than time e.g. distance or angle. An important feature of ACSL is its ability to sort the continuous model equations, in contrast to general-purpose languages such as FORTRAN where program execution depends critically on statement order.

The ACSL program code can be derived from:
-   block diagrams;
-   mathematical equations ;
-   conventional Fortran statements.

Language Highlights

- free form input;
- function generation of up to 3 variables;
- independent error control on each integrator;
- flexibility in plotting the behaviour of models under a number of external forcing functions;
- many simulation-oriented operators are included and are readily accessible. These operators include variable time delay, dead zone, backlash and quantization;
- global single or double precision calculation can be selected;
- sorting of the continuous model equations in contrast to other packages where program execution depends critically on statement order.

Job Processing

- Inputs to ACSL are in two parts, namely :

    (1) the program stored in a **.CSL** file defines the system being modelled;

    (2) the runtime commands stored in a **.CMD** file exercise this model (i.e. change

    parameters, execute runs, specify plots, etc.)

  See Figure 3.3.

- The program is read by the ACSL translator which translates it into a Fortran

compile file **(.FOR)** . The Fortran code is then compiled, linked with the ACSL

runtime library (the **.PRX** file) and executed, finishing at an ACSL runtime prompt:

    ACSL >

- At this point, ACSL is waiting for runtime commands, which can be entered

    Interactively or by reading the command file. The commands are read, decoded

    and executed in sequence.
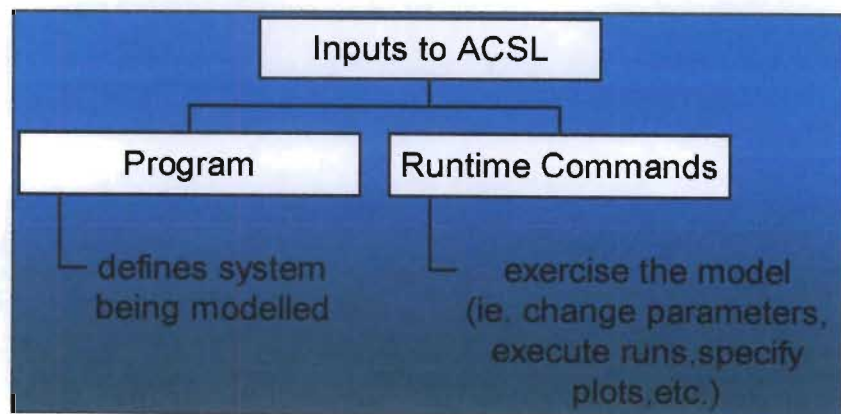
Figure 3.3 : Structure of Input to ACSL

Language Features

The language consists of :

(1) operators - arithmetic, relational and logical;

(2) standard functions e.g. SQRT (square root), MOD (modulus) , etc.;

(3) a set of special ACSL statements;

(4) a MACRO capability that allows the extension of special ACSL statements, either at the system level or for each installation, or for each individual user by defining new operators. If defined once, a macro can be invoked as many times and as from many places in the model code as needed.

Steps to Complete in Writing an ACSL Program for any Physical System

(1) Understand the physical system being described.

(2) Make simplifying assumptions.

(3) Determine the variables to be used.

(4) Derive the appropriate equations.

(5) Gather data on initial conditions, gains, boundary conditions, etc.

(6) Write the program code and command statements.

Structure of the Program Code

Figure 3.4 outlines the flow of an ACSL program with explicit structure [13]. This is the structure that all the programs presented in this thesis will follow. The outline of an explicitly structured program is presented below:

PROGRAM name

!..........comments

    Define Program Constants

  INITIAL

    Define variable types and initial conditions.

  END !.....of initial

```
DYNAMIC    !........moves forward in time
       ALGORITHM    IALG =?
       NSTEPS          NSTP=?
       MAXTERVAL   MAXT=?
       MINTERVAL   MINT=?
       CINTERVAL    CINT=0.01
   DERIVATIVE
       Contains differential equations and integration (statements to be integrated
          continuously).
   END !.......of Derivative


   DISCRETE     ! describes discrete events
       Statements executed at discrete points in time.
   END !........of Discrete


   Statements executed at each communication interval e.g. termination condition :
               TERMT (T.GE.TSTOP)
   END !........of Dynamic
   TERMINAL
       Statements executed after the run terminates.
   END !........of Terminal
END!.......of Program
```

ACSL Statements

The following statements are mandatory in any ACSL program following the explicit format i.e. every complex program.

- Integration Algorithm IALG defines the runtime integration routine.
  There are 9 integration algorithms available, hence the integration algorithm is an integer constant between 1 and 9. For most mechanical systems, the Runge-Kutta second order algorithm is recommended as the most efficient and takes on the value 4.

- Communication Interval CINTERVAL is the interval at which the dynamic section is executed and the variables on the OUTPUT and PREPARE lists (in the command file) have their values recorded. It is a real constant with a default value of 0.1 but a communication interval that generates 100 to 200 data points during a run gives sufficient detail.

- Maximum Calculation Interval MAXTERVAL is the upper bound on the integration step size for both variable and fixed step algorithms, and is a real constant.

- Minimum Calculation Interval MINTERVAL is the minimum value of the integration step size. Fixed step algorithms e.g. Runge-Kutta second order algorithm ignore MINTERVAL.

- The NSTEPS statement defines the integration step size in terms of the communication interval i.e., NSTEPS is the number of integration steps in a communication interval and is an integer constant.

Figure 3.4 : Main Program Loop of ACSL Model

The Simulation System

The heart of the simulation system is the integration operator that is called by either INTEG (simple integration) or INTVC (vector integration).

When building any model, all differential operators must be changed to integration operators. This is done by expressing the highest derivative of a variable in terms of lower derivatives and other variables.

Example:

Consider the system in figure 3.1 and take one vehicle excited by a given function of time, F(t). In general form, this is :

$$m\ddot{x} = F(t)$$

Expressing this equation in terms of the highest derivative, $\ddot{x}$ gives :

$$\ddot{x} = \frac{F(t)}{m}$$

$$\dot{x} = \int \ddot{x} \qquad ; \dot{x}(0) = \dot{x} \qquad\qquad (@t = 0)$$

$$x = \int \dot{x} \qquad ; x(0) = x \qquad\qquad (@t = 0)$$

In ACSL code, this becomes :

```
xdd = F(t)/m
xd = INTEG (xdd,xd0)
x = INTEG(xd,x0)
```

4. LOCOMOTIVES

4.1 Introduction

In order to understand the science of train make-up, train configuration and train handling, one needs to understand the intricacies of locomotive units as the prime movers.

Spoornet have had a number of years in-service experience with 7E type 25kV AC 50Hz, 9E type 50kV AC 50Hz, 10E type 3kV DC supply and 11E for 25kV AC 50Hz supply. The coal export program necessitates the haulage of about 65 million tons of coal between Ermelo and Richards Bay. Clearly there is an advantage to be gained in respect of capital investment and reduced maintenance if a lesser number of more powerful locomotives could be used to haul these heavy freight trains.

The principal requirement for the locomotives is to have the maximum tractive effort available and the performance characteristics of these locomotives are somewhat different. Electric traction has a faster rate of acceleration and a higher sustainable cruising speed because it can draw extra power from the supply system, whereas diesel is limited by the maximum output of it's on-board engine. Figure 4.1 below describes the various classes of locomotives.
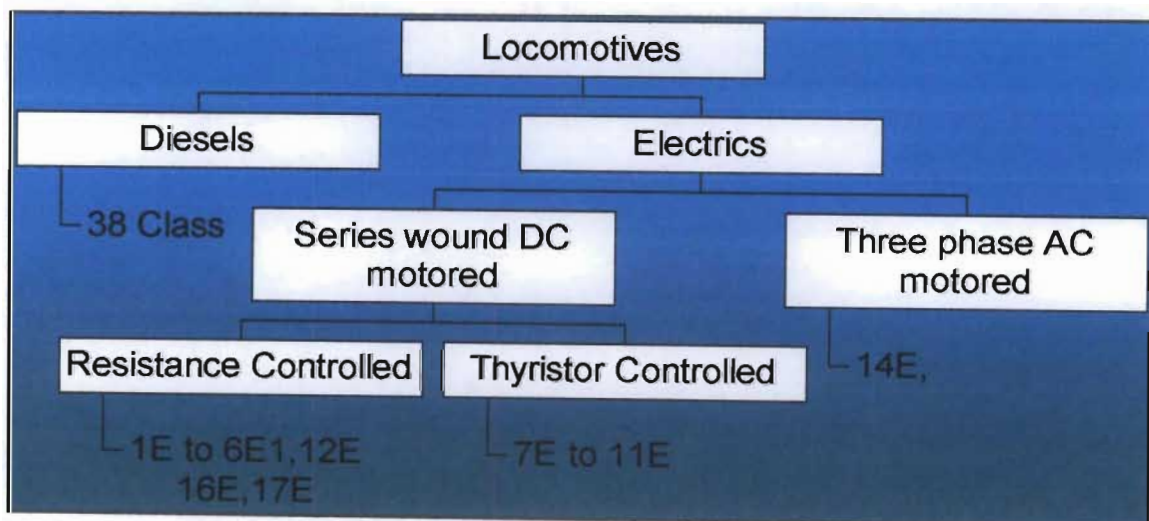
Figure 4.1 : Locomotives Operating on SA Railroads

This study deals solely with electric locomotives. Electric locomotives can (as seen above) be classified as either resistance controlled DC or thyristor controlled DC

according to the type of control system employed. Since 1985, Spoornet has been shifting from operating electric locomotives employing semi-conductor control systems to the application of microprocessor control systems on all fleet tender as the latter would lead to further improvements in performance and reliability. Plans exists to advance to working the Coal Line with three phase AC motored locomotives. The increased complexity of the three-phase drive has a number of advantages justifying it. These include :

• extended range of effective working speeds;

• increased practical adhesion levels due to very good wheel slip control;

• reduced maintenance requirements;

• allowing increased installed power.

4.2 Locomotive Rating

Power of an electric locomotive is that exerted at the wheel rim, whereas that of a diesel locomotive is the power of the engine itself; the power at the wheel rim is less power to auxiliaries and losses in the transmission. The kW rating of a locomotive affects the speed at which a load can be hauled, but does not influence the mass. The mass of the load which can be hauled is purely dependent on the mass of the locomotive and the nominal adhesion of the locomotive type.

When the traction motor ventilation system is capable of keeping the temperature rise of the motors to acceptable limits under all circumstances, the locomotives can be continuously worked at their usable adhesion limits at normal speeds.
The locomotives will thus be rated on starting, short term and continuous rating, with the continuously rated tractive effort not that much less than the one-hour rating. The one-hour rating defines the output which after one hour from a cold start results in the traction motors reaching their maximum safe temperature.

So far, this chapter has focused on horsepower as the measure of locomotive capacity. But there are, in fact , two other variables that determine how much the potential of a locomotive may be usefully applied. These are tractive effort and the factor of adhesion and will be discussed in subsequent sections.

4.3   Locomotive Characteristics

Information about tractive effort and dynamic brake effort characteristics of a locomotive at different speeds are required in order to study train dynamics[14]. Tractive effort is the force developed at all the locomotive driving wheels parallel to the rail to move the locomotive and cars while dynamic brake effort is a similar force but offers retarding action. The traction force is equal to the force provided by the traction converter, less lost torque introduced by the mechanical drive between motors and wheels. Although the basic function of a locomotive is to supply tractive effort to the train, the traction motors are also used to slow down the train, a function achieved by means of dynamic braking. The traction motor acts as a generator during braking and the generated electricity is either fed back to the overhead supply (regeneration) or dissipated in large banks of power resistors depending on the class of locomotive.

The locomotive characteristics are developed in terms of plots for each throttle position. For a given throttle position, the maximum power is known and the available tractive effort or dynamic brake effort at the rail corresponding to this power is a function of speed. An electric locomotive, theoretically, has no maximum power limitation since it is merely a converter of energy. It has a maximum limitation in practice of course but this limitation is due to the physical design limitations of its components and not due to power limitation of its own power source like a diesel or steam locomotive.

By using the throttle handle, the driver is able to select a notch which in actual fact represents the demand value. Given this demand value and locomotive speed, the pre-set operating point on the characteristic can be determined. It is necessary for every operating notch throughout the working range of speeds to be a running notch; that is, it must be possible to dwell indefinitely on any speed within the given loco characteristic and at a load current within the continuous rating. In order to understand the technical aspects of locomotive characteristics, a thorough understanding of a series wound traction motor must be completed.

4.3.1 Series Wound Traction Motors

Using Kirchoff's laws, the traction characteristics of a series wound traction motor, can be defined. A simplified version of the electric circuit is shown in Figure 4.2 below [15].
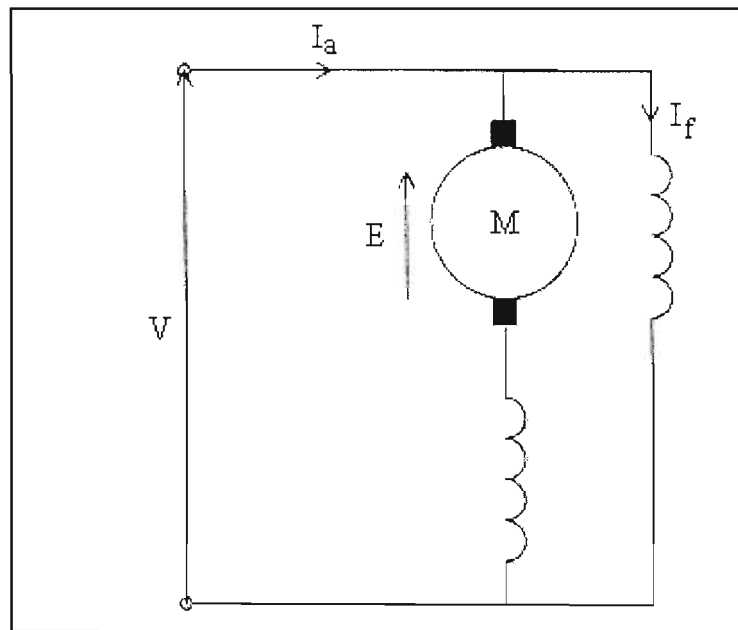
Figure 4.2 : Series Wound Traction Motor

From Figure 4.2, the following relationships can be derived (Kirchoff's Laws) :

$$V = E + R_a I_a + \Delta V_{br} \qquad (a)$$

where :

V = supply voltage

E = voltage across the motor

R_a = armature resistance

I_a = armature current

ΔV_{br} = brush voltage drop

But the $R_a I_a$ term in (a) is small compared to V , hence $V \approx E$.

$$E = k \times \varpi_r \times \phi \qquad (b)$$

where :

k = armature constant

ϖ_r = armature speed

ϕ = useful magnetic flux

The electromagnetic torque developed is :

$$T = k\phi I_a \hspace{5cm} (c)$$

The torque (or tractive effort) developed is proportional to the product of field strength and armature current. However, the field strength is dependent on and proportional to armature current and hence the torque developed is a function of current only; torque is proportional to the square of the armature current resulting in a parabolic relationship. The speed versus armature current curve is hyperbolic. Thus the natural motor characteristic of torque versus speed looks hyperbolic. These relationships are shown in Figure 4.3 below [16]. It follows that for variable torque (and hence tractive effort) the traction motor current will have to be variable. Further, if the electric power is to be kept constant, then voltage will also have to be variable. This is the basis of operation of the so-called constant power locomotives e.g. the 11E. Voltage does not determine or have anything directly to do with torque except that it determines the current.
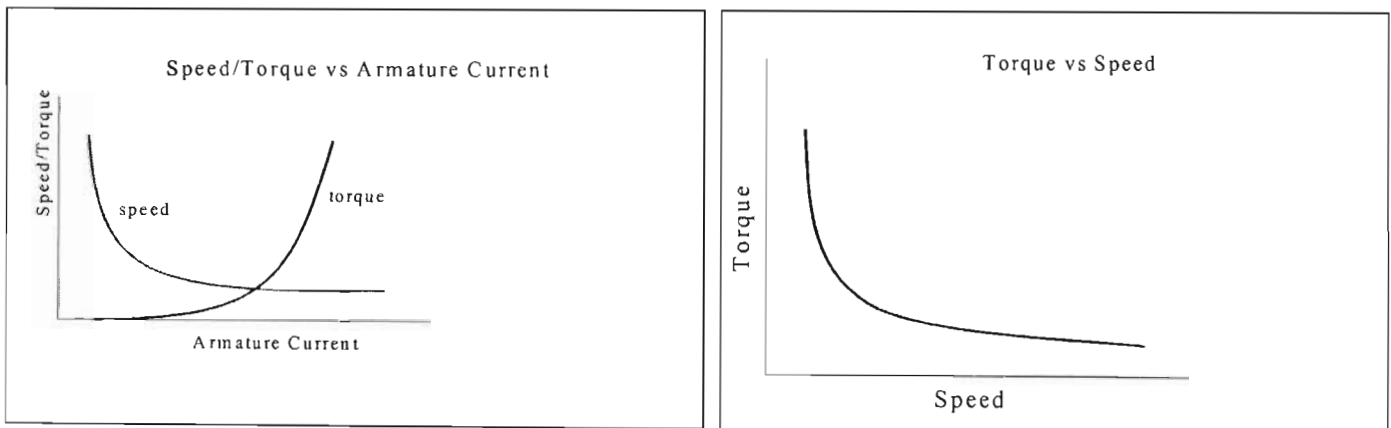
Figure 4.3 : Series Motor Characteristics

The constant voltage locomotives (e.g. 7E) see the introduction of two basic modes of speed control. In the first instance, speed is increased by increasing the voltage while the flux is at its maximum. If the armature current remains at its maximum during this process, the torque will remain at the full rated value. Secondly, the speed is increased by reducing the field current. It cannot be raised by increasing the supply voltage because it is already at its maximum. If the armature current remains at its maximum

value, the mechanical power output remains at full rated value. See Figure 4.4 below where the base speed is the speed corresponding to rated voltage, flux and torque.

Speed control using a series motor can be achieved by varying the terminal voltage through a series resistance, or field through diverter resistors.
In the separately excited motor, field excitation is obtained using a power supply separate from that for the armature circuit. Speed control is achieved by varying the armature voltage or the field current. The separately excited motor is suitable for traction because it may be controlled to produce high torque at low speeds, and yet utilise its rated power at high speeds.
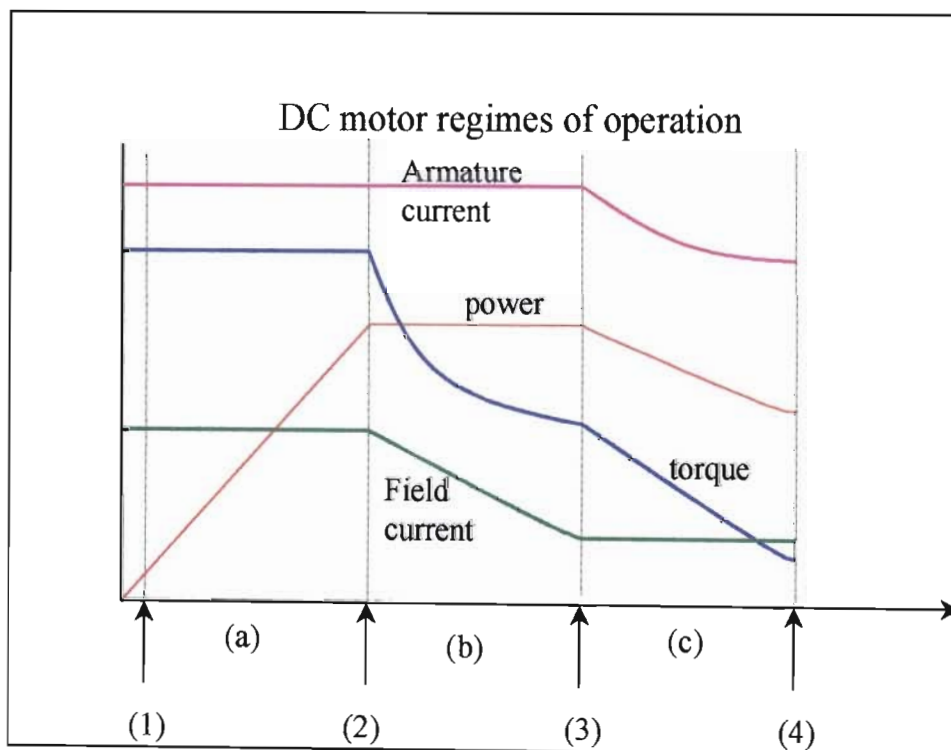
Figure 4.4 : DC motor traction drive regimes
Of Operation

The critical speeds labelled 1 to 4 in Figure 4.4 are:
(1) Minimum controllable speed at about one-tenth of the base speed, due to poor regulation at low speeds;
(2) Base Speed;
(3) Transition Speed;
(4) Maximum Speed.

The three control regimes are (as labelled in the figure) :

(a) Armature Voltage Control with rated field - torque is constant and power linearly increases with speed;

(b) Field Weakening with constant armature current giving constant power operation;

(c) Weak Field Operation where armature current, torque and power all decrease.

4.3.2 Traction Characteristics

The curves of tractive effort against speed represent the so-called "tractive effort" characteristics of a particular locomotive. Because power is a product of tractive effort and speed, it follows that for constant power, the tractive effort characteristic curve should be a hyperbola. This assumes that the transmission employed is capable of such conversion with 100% efficiency. In practice, such a transmission does not exist of course but the actual tractive effort versus speed characteristic is generally a fairly close approximation to a hyperbola. There is a high starting torque followed by a falling torque level with increasing speed. This feature is attractive for traction because it inherently allows wheelslip correction.

For all types of locomotives, and irrespective of the type or efficiency of transmission, there is an upper limit to the maximum tractive effort which can be exerted by the wheels. This is the adhesion limit which is unique for each condition of rail surface and axle loading and determined by the following expression:

$$Adhesion \quad = \frac{TE}{Weight} \qquad (4.1)$$

where: TE = tractive effort

$Weight$ = axle loading

A further practical limitation for all locomotives is the maximum running speed. The existence of these two practical limitations (maximum tractive effort and maximum speed) makes it unnecessary for the hyperbola to be extended to infinity at its two extremities. The limits of the speed/tractive effort characteristic can be altered by the gear ratio. An increased ratio will provide a higher maximum tractive effort but also a

corresponding reduction in maximum safe speed hence moving the performance range bodily up or down the constant power curve without altering the shape of the characteristic.

In order to increase the tractive effort at higher speeds, the motor series field must be weakened. This can be achieved by means of :

(1) a variable resistor connected in series with the motors. During the starting process, some electrical power will then be dissipated in the resistor;

(2) a chopper between the power supply and motors, the circuit being such that the armature current is diverted from the fields through the weak field converter. The controller ensures that the constant power limit and minimum weak field Envelope are not exceeded. The minimum field strength must be limited to avoid commutator flash over.

The classic direct current motor with the field and armature connected in series, compensates automatically for changes in load - a change in gradient for example. If the gradient changes, the speed on the gradient automatically changes the armature current and with it, the tractive effort at the wheel. The tractive effort characteristic curve is shown in figure 4.5. Particular tractive effort curves for the locomotives used in the simulations (i.e. the class 7E and 11E) are shown in the Appendices.
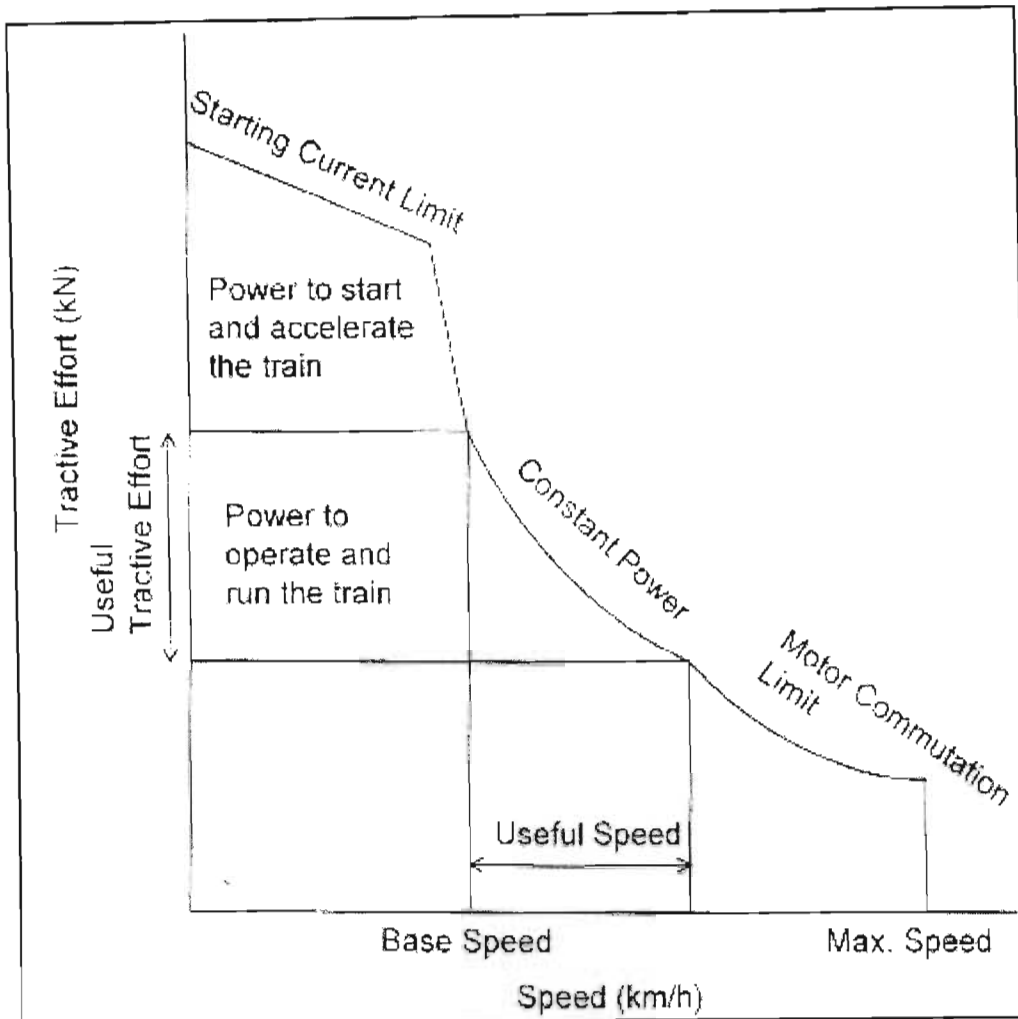
Figure 4.5 : Tractive Effort Curve

4.3.2.1 Resistance Controlled Locomotives

Although this class of locomotives does not form part of the study, it presents a good basis for comparison with the thyristor-controlled locomotives that are in operation on the Coal Line.

Operational Characteristics

- The field is reduced by diverting a portion of the motor current through shunt resistors. This implies electromechanical complexity leading to unreliability.
- Cannot deliver rated power other than at a few fixed speeds since the natural characteristic is the basic series motor characteristic characterised by a rapid fall in

power with increasing speed.

- Cannot be used at low speeds for long periods of time since the resistor banks get very hot due to the large voltage drops across them.

- Have a finite number of discrete notches with discontinuity between combinations. There are 21 notches made up of series full field, 10 series weak field, parallel full field and 9 weak field notches.

4.3.2.2 Thyristor Controlled Locomotives

With semi-conductor control of motor voltage and current, it is theoretically possible to obtain any shape of tractive effort curves. The first generation thyristor locomotives had analogue control while the later classes have microprocessor control.

Operational Characteristics

- The current across the armature is reduced by means of 'choppers' and this applies to adjusting the field strength as well.

- Have infinitely variable characteristics between marked notches in contrast to the previous class of locomotives.

- Have improved train handling at low speeds.

- Have a very flat characteristic at speeds below the natural full field motor characteristic curve, with the accompanying disadvantages when working heavy trains.

4.3.3 Dynamic Brake Characteristics

The dynamic brake (electric brake) is a flexible modulating factor to adjust train speed for variations in grade and curvature. It is important to optimise the application of the electric brake for two reasons:

Firstly, if too little electric brake is used, train wheels may overheat on long down grades because friction braking must contribute a disproportionate amount to the total brake effort. Secondly, if too much electric brake is used, it can lead to very high compressive forces between the train and the locomotives. This can lead to empty or lightly loaded wagons being forced out on sharp curves. The financial implications of

damaged and cracked wheels, and damage to lading and wagons cannot be overlooked.

Just as in traction, the curves of dynamic brake effort against speed represent "dynamic brake characteristics" of a particular locomotive. The braking throttle position represents a certain grid current, provided that the locomotive is above the speed of peak braking effort, approximately 45 km/h . The motor current then regulates to this grid current value. Above 45km/h, the braking effort drops as the locomotive speed increases because, although the armature current remains constant, the field current decreases in order to maintain this current. Consequently, the braking effort decreases. If the train speed is increased because grade becomes steeper, the braking current remains constant, but the braking effort decreases.

The upper limit to the maximum dynamic brake effort which can be exerted by the wheels is the heat dissipation limit. The curves are limited by the maximum running speed on the high-speed end. The control of armature current and field strength follows a similar course to that used during motoring. The dynamic brake characteristics of the locomotives that work the Coal Line are shown in the Appendices section. A typical dynamic braking curve is shown in Figure 4.6.
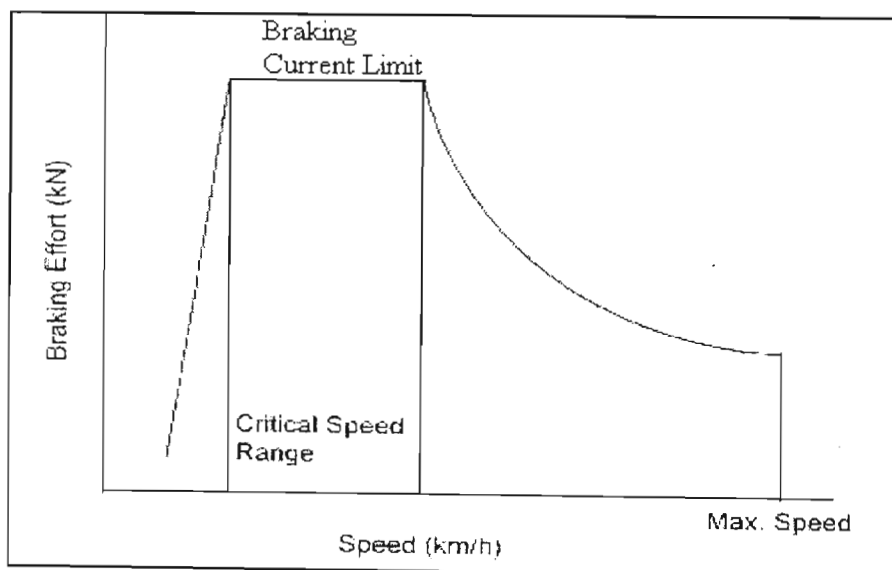
Figure 4.6 Braking Effort Curve

4.3.3.1 Resistance Controlled Locomotives

Operational Characteristics

- Achieve electric braking through regeneration with the generated power fed directly into the overhead lines. Regenerative braking is limited in both range and effectiveness and is also unreliable. Under rare conditions, the generated energy can be re-used thus reducing the overall energy consumption. In many cases though, the energy has no user resulting in regenerating locomotives tripping out.
- Electric braking build up and release is quick.
- Prone to "motoring in regen" with resultant poor load distribution characteristics between axles.

4.3.3.2 Thyristor Controlled Locomotives

This class of locomotives has a brake characteristic that comprises of a maximum braking effort envelope; the intermediate notches are a series of straight lines from the no brake effort at 0km/h mark to the continuous power curve.

Operational Characteristics

- The intermediate notches have a "fail safe" characteristic of rising brake force with rising speed up to the rated braking power of the locomotive.
- Once the continuous power curve is reached, all notches are the same. This means that sensory feedback to the driver is reduced and this is undesirable for good train handling.
- The peak of this characteristic can cause unacceptably high compression forces. Later classes e.g. 11E have a flat-top characteristic with the slope of the straight Line portion of the curve steepened to improve train handling at low speeds.

4.4 Wheel-rail Parametric Relationships

4.4.1 Introduction

The dynamic behaviour of a railway vehicle is significantly affected by the interactive forces between the wheel and rail. These forces depend on the adhesion, creep and wear characteristics. The basic wheel rail parametric relationships are shown in Figure 4.7 . Under steady state conditions, the adhesion - creep - wear characteristics are affected by the following parameters :-

- Geometry of the Wheel and Rail. This is because the creep forces are significantly influenced by the area of contact and contact stresses between the wheel and the rail;

- Surface and Environmental Conditions. Surface roughness and contamination due to water, oil, dirt and other factors usually influence adhesion-creep-wear characteristics;

- Material Properties. The hardness, toughness, shear moduli of elasticity of the wheel and rail materials also play a role in this regard. These in turn are related to the grain structure, chemical composition and the heat treatment of the two materials;

- Load-related Parameters. Normal load per wheel, area of contact between wheel and rail, the forward velocity of the wheel, the distance slipped by the wheel, the operating and maximum coefficients of friction between the wheel and rail surfaces, time, and angle of attack between the wheel and rail.
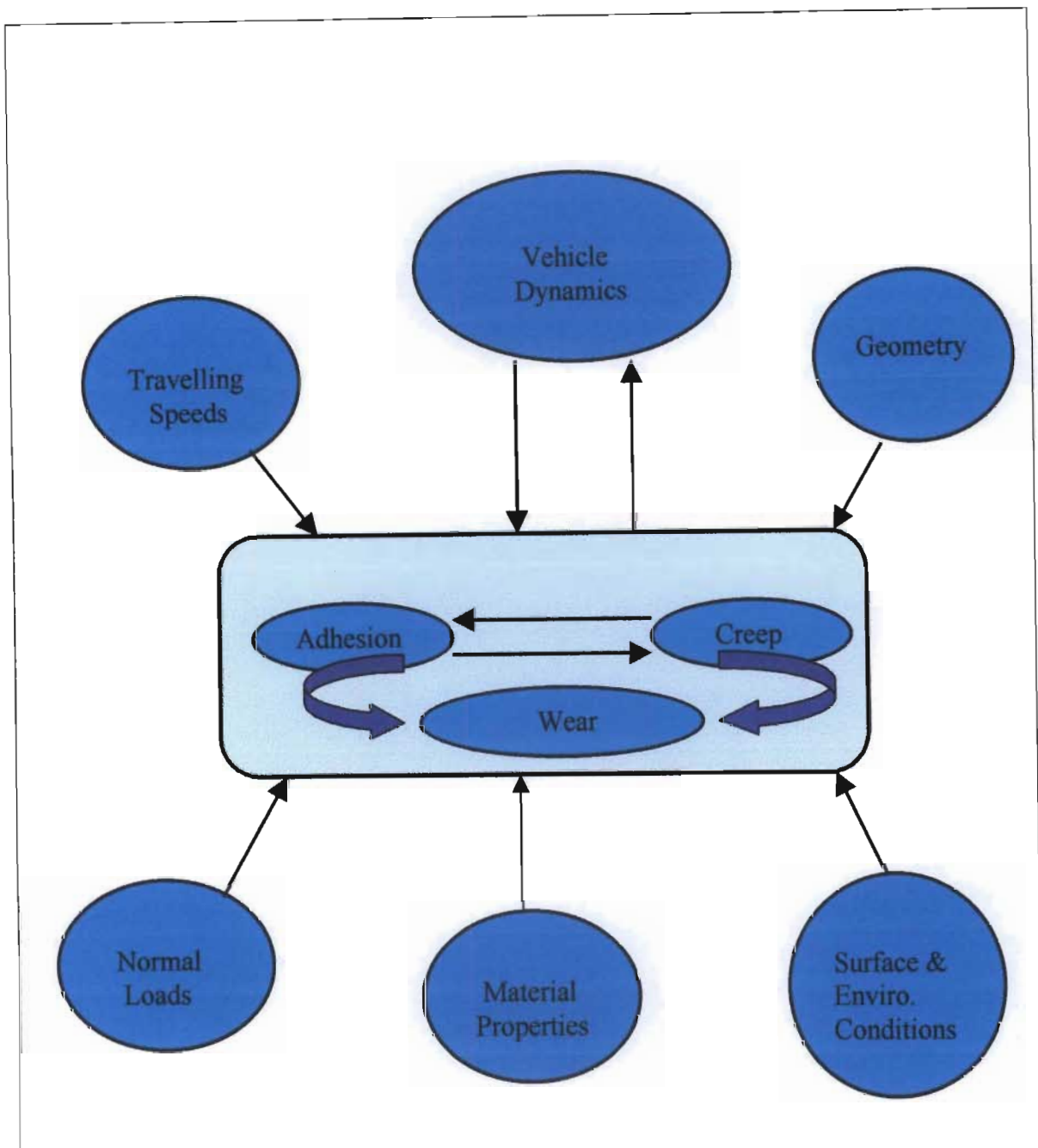
Figure 4.7 : Wheel-Rail Parametric Relationships

4.4.2 Adhesion

Close control of tractive effort is desirable to ensure that locomotives operate as close as possible to the limit of adhesion. Adhesion can be defined as the resistance to slipping between the wheel and rail. It is a complex phenomenon often simplified to a coefficient of friction μ and expressed as a percentage. This means that the force

transferred from the wheelset to rail is equal to the product of the axle load and adhesion. The limiting effect of adhesion explains why same axle load locomotives on the same track have the same tractive effort on starting , regardless of the horsepower rating. The magnitude of the maximum coefficient of adhesion which can be utilised is obtained from basic operating data with existing locomotives on existing tracks. The adhesion values used in all simulations will be between 18% and 25%. This is the range recommended where reliable operations must be maintained.

This coefficient of adhesion is significantly smaller than the theoretical maximum possible coefficient of friction between wheel and rail.

Once the constant power curve is reached, however, power rapidly makes its presence felt. A further point to consider is that adhesion drops with increasing speed all else being equal.

Factors Affecting Adhesion

The contact between wheel and rail can be affected by the following factors, in practice :

(1) Vehicle factors -

- locomotive weight and axle load distribution on driver axles;
- weight transfer due to traction and geometry of the locomotive body and bogie components, and dynamic behaviour of locomotives;
- speed. The two aspects of speed which affect adhesion are:
    - dynamic effect of the friction-creep relationship;
    - dynamic effect of speed on the wheel load due to vertical track profile;
- wheel size variations (wheel diameter differences) due to wear;
- electrical transmission and distribution;

(2) Track factors -

- rail surface condition and an important factor to consider is contamination - by water, lubricants, rust and other contaminants. Adhesion is reduced in comparison with clean dry rail;

- rail profile - vertical irregularities;
- track curvature - tangent or curved track;

(3) Contact area common factors -
- wheel-rail materials;
- Hertz stress and the contact geometry between driving wheels and track;
- relative slip.

4.4.3   Creep

Creep is part-elastic, part-frictional behaviour intermediate between pure rolling and overall sliding of wheel on rail and is of fundamental importance in the study of curving [17]. The limiting case of creep i.e. complete slip of wheel on rail, is important for studies of traction and braking.

The value of adhesion for rail vehicles has a maximum of about 0.4 . It decreases slightly with absolute wheel velocity, and after an initial sharp rise, decreases more steeply with wheelslip velocity.

The physical processes determining wheel/rail adhesion are complex. Figure 4.8 shows the relationship between wheel-rail creep and the adhesion coefficient. This is an averaged curve compiled from many experimental measurements [18]. The relative velocity between the wheel and rail must be non-zero to exert a tractive force. If the creep is allowed to increase beyond a certain threshold (5%), a region of unstable operation will be entered resulting in uncontrolled wheelslip. This normally occurs when high applied propulsion or braking forces exceed the available adhesion force. Practical wheel slip/slide control schemes must exploit the relationship of Figure 4.8 to maintain an optimum creep velocity in order to maximise the adhesion force. The understanding of wheel creep stability is therefore closely related to traction controller design.
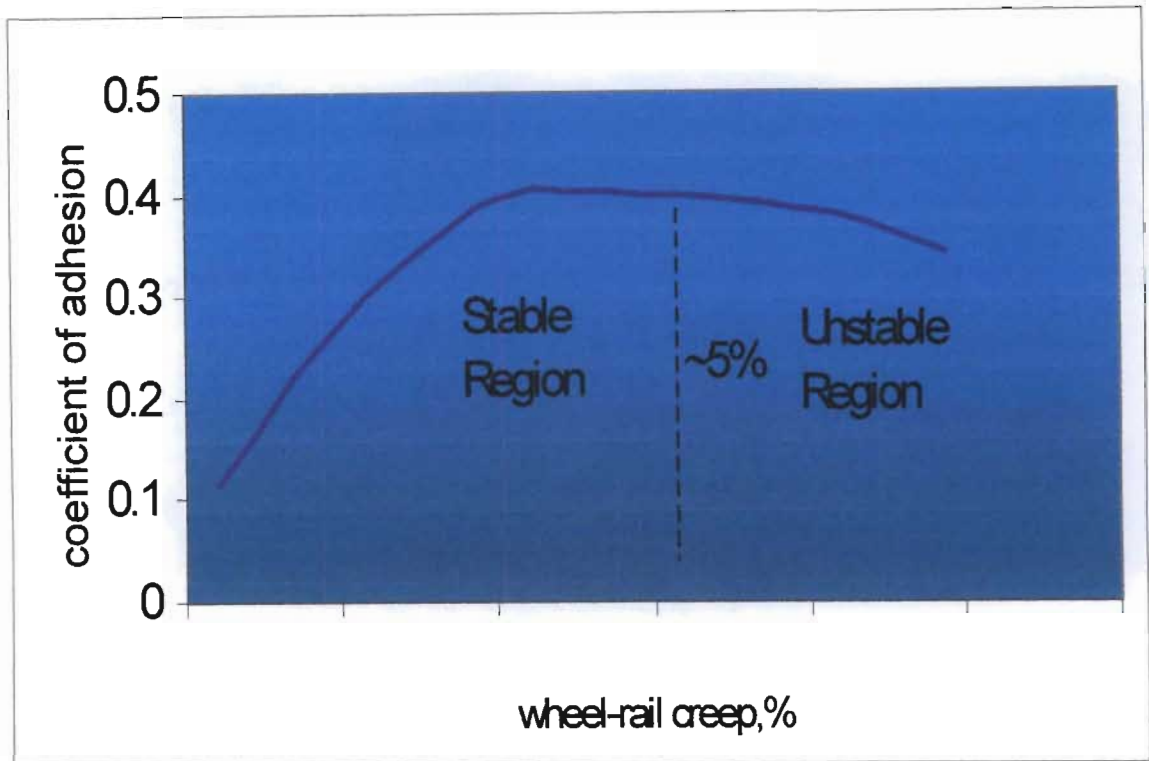
Figure 4.8 : The Relationship between Creep and the
Adhesion Coefficient

The work of Kalker and subsequent non-linear numerical studies by him have become accepted as the most accurate and convenient means of predicting rolling contact. Analytical and experimental investigations relate the creep experienced by a wheel and the tangential force transmitted between the wheel and the rail in the manner shown in Figure 4.9.

μ = coefficient of friction;

N = total normal force between the wheel and rail.

The linear portion implies that under small creepage, the force transmitted between wheel and rail is proportional to creep. As creepage increases, proportionality disappears and the curve asymptotically approaches the limiting adhesion (μN). Note that as the creepage increases, the size of the area of adhesion in the contact area reduces.
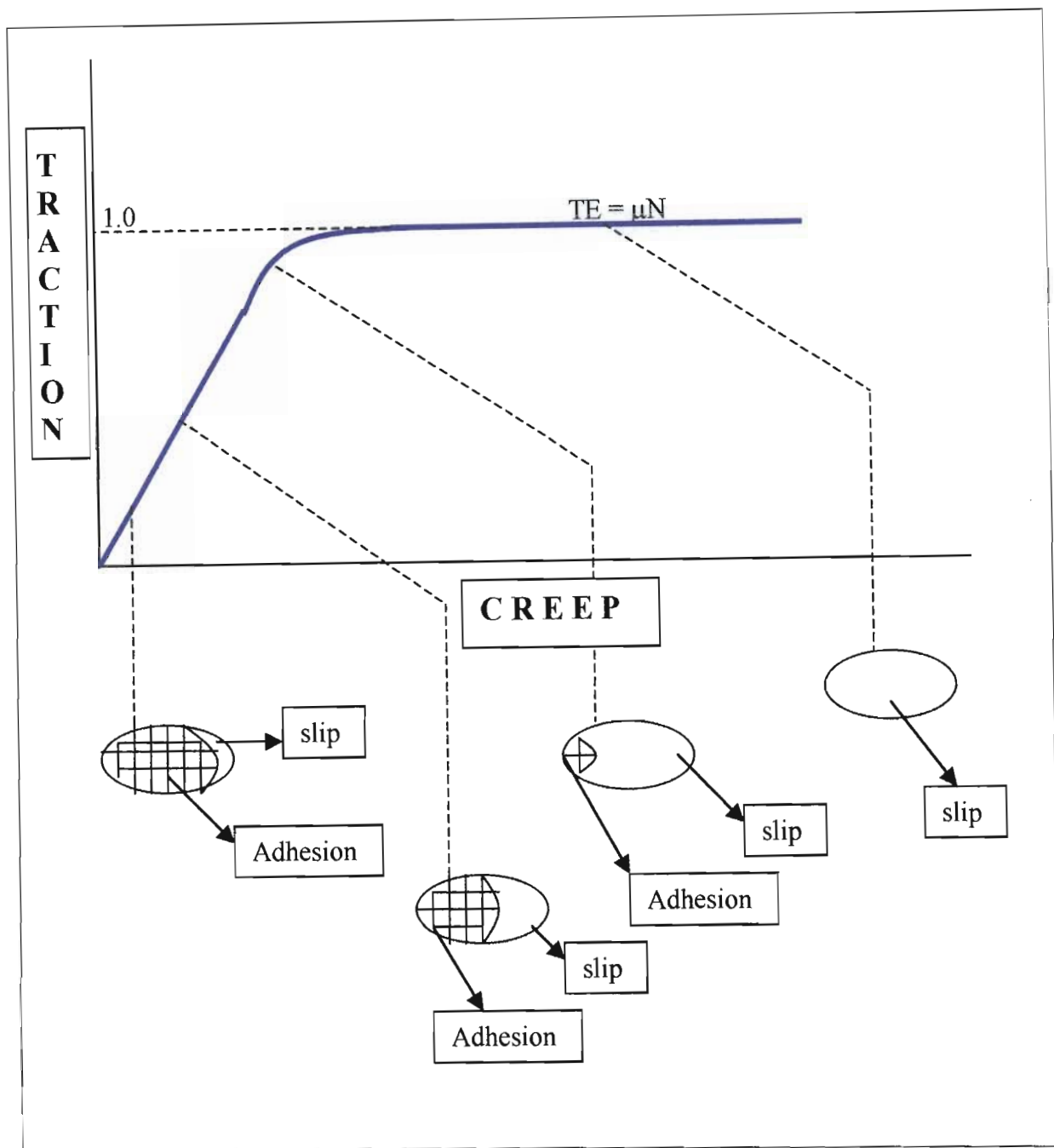
Figure 4 .9 : The Traction-Creep Curve

4.4.3.1 Friction-Creep Relationships

The factor having the greatest influence on the friction-creep curve is the surface condition of the rail. There is no simple description of any friction-creep relationship for the wheel-rail interface of a locomotive as explained above. The basic friction-

creep curve is in essence a broad band of values affected by many factors. Figure 4.10 shows the friction-creep curve on dry tangent track.
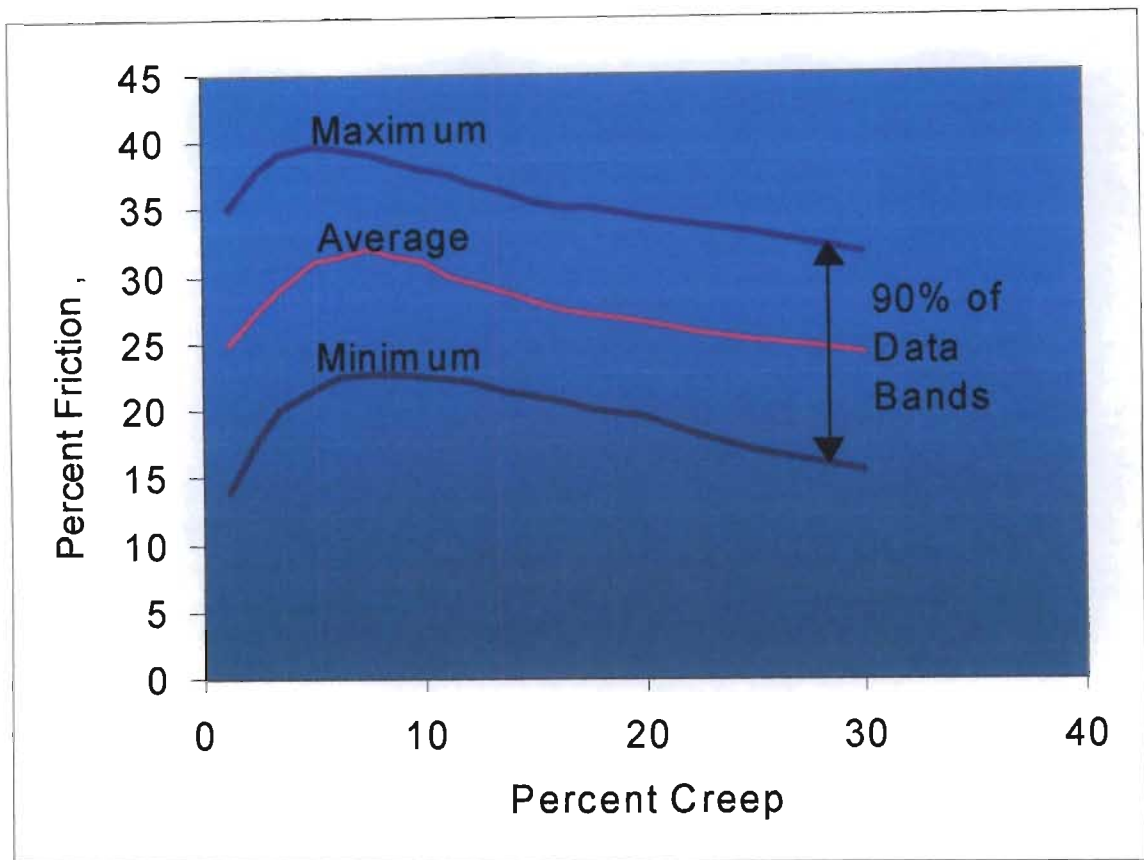
Figure 4.10 : Friction-Creep Curve on Dry Tangent
Track – All Speeds -. 16 – 32 km/h

There is a dramatic difference between the characteristic shapes of the friction-creep curves in traction and in dynamic brake. The Electro-Motive Division of General Motors has, since 1967, conducted a series of comprehensive tests aimed at investigating the friction-creep characteristics that exist between steel wheels and rails on railroads. A summary of the conclusions derived is presented below [19].

Dynamic Brake Friction-Creep Study

- Friction between wheel and rail cannot be substantially improved by letting a locomotive's wheels operate above the 2 to 3 % creep level that a normal slide correction system allows;

- Peak friction level occurs between 3 and 5 % creep with no marked benefit for operation above 3 % creep;

- Rail contamination lowers the friction level with no significant change in the creep value at which friction level change occurs;
- Sand causes the peak of the characteristic to move to a lower creep level and increases the friction level by over 50 %;
- Track curvature reduces the friction level but does not significantly affect the creep level at which the peak occurs;
- There is no significant improvement in rail friction for the trailing wheels when higher creep levels are allowed to occur on the lead wheels of the locomotive.

Traction Friction-Creep Study
- Friction between wheel and rail can be improved by letting a locomotive's wheels operate above the 1 to 2 % creep level that a normal slide correction system allows;
- Peak friction level always occurs at 1 % creep but no marked benefit for operation above 15 % creep;
- Rail contamination lowers the friction level at the peak and causes the peak to occur at a higher creep level;
- Sand causes the peak of the characteristic to move to a lower creep level and may sometimes increase the peak friction value;
- Track curvature reduces the friction level and increases the percentage creep at the peak of the curve;
- When higher creep levels are allowed to occur in the lead wheels of the locomotive, these wheels tend to improve rail friction levels for the trailing wheels.

4.5 Temperature Rise of Motors

It is necessary to predict with reasonable accuracy the temperature rise of the motors at any particular point of the route over which a specific weight of train is required to operate. This temperature rise occurs on the locomotives as a result of motoring or dynamic braking as well as the transition between these two phases.

A direct calculation of the temperature rise is almost an impossible task when it is considered what numerous variables will have to be accounted for even after making certain justifiable assumptions.

The components of the traction motor would have to be considered separately and each of the components has more than one heat source [20]. The armature for example is composed of three main heat sources, namely :

(1) the armature winding;

(2) the commutator;

(3) the armature teeth and core under the slope.

The temperature rise at any instant is given by :

$$T = \left[\frac{W}{K_c A} + T_a \right] \left[1 - e^{\frac{-t}{C_t}} \right]$$ (4.2)

where:

T = temperature rise of component at time t

W = total armature loss comprised of :

- no-load core loss
- brush friction loss
- brush contact friction
- armature loss

K_c = cooling factor or rate of heat dissipation from armature surface

A = total armature surface

T_a = average temperature rise of cooling air in machine

t = time from start at ambient temperature

C_t = thermal time constant

$$= \frac{C_s M_A}{K_c A}$$

where M_A = weight of armature

In the case of the field coils, the calculation is simpler because there is only one heat source and is the I^2R loss at maximum temperature.

$$C_t = \frac{C_s M_F}{K_c A}$$

M_F = weight of copper per coil

For continuous running at a constant load, t becomes infinity so that the temperature rise becomes :

$$T = \frac{W}{K_c A} + T_a \tag{4.3}$$

Conclusion

- The theoretical consideration of all the heat sources in the armature, together with the rate of heat transfer from the teeth and core to and from the conductors through the insulating wall can be a fascinating mathematical exercise. For the purposes of this study, such complications are not justified. The monitoring of the armature current will suffice in gauging the temperature rise of the motors and hence if any damage is incurred. This means that a qualitative approach based on armature current will be followed.

5 TRAIN DYNAMIC RESPONSE

5.1 Longitudinal Train dynamics

5.1.1 Introduction

For analysis of dynamic systems, it very useful to have a viable simulation model of the system under study. Such a model can contribute valuable insights which may be difficult or impossible to obtain by direct observations of the actual system. This is the principal reason for attempting to simulate the longitudinal dynamics of railway trains; actual measurement or tests of dynamic effects in trains is both time and cost consuming, and difficult. The procedure of actual tests needs planning and provision of staff, vehicles (including special test coaches), lading and the track. Therefore, only a few situations can be chosen to run test trains. Such limitations do not exist as far as computerised simulations are concerned. Furthermore, a simulation can be realised without any risks regarding staff, the infrastructure and the tested trains. A further advantage of computer-based simulation is the possibility of the immediate control regarding boundary conditions of the tests. Various situations can be set up and simulated in a very short time.

Train simulation involves mathematical modelling of train dynamics involving large numbers of parameters and is therefore complex. With the advent of digital computers, it is now possible to simulate various train systems and track characteristics and deduce their interaction. Cost however, has been the major deterrent to simulation of train dynamics. Simplifying the model to a completely linear system eases computational requirements considerably, but unfortunately eliminates the most important features of the train. A balance must therefore be reached between ease of computation, cost and validity of the model.

In general a vehicle is subjected to coupler forces due to curvature and gradient of the track, rolling resistance of the vehicle (depending on its geometry and design features) and braking force. If the vehicle is a locomotive then the tractive effort and dynamic brake effort will also contribute.

5.1.2 Model Assumptions

In developing the train action model, the following assumptions were made :

(1) Suspension effects are not considered and bogies on each vehicle are considered rigid.

(2) Rigid couplers are used i.e. no knuckle contouring is allowed.

(3) No alignment mechanisms are present and hence alignment control effects are neglected.

(4) Tractive effort and dynamic brake effort are represented by linear, quadratic and hyperbolic curve segments for any speed range of interest.

(5) Each vehicle is assigned the longitudinal degree of freedom only.

(6) Transient forces due to coupler slacks are approximated by a dynamic approach.

(7) The centre of gravity of any vehicle is at the level of the couplers to cancel the effect of pitching.

(8) Wagon underframes remain elastic i.e. no impact can permanently deform an underframe.

(9) Track irregularities are ignored.

(10) The lading in the vehicles is assumed to be integral with the wagon body.

(11) Each vehicle acts as a single mass at all times.

(12) Traction motors are equi-directionally installed to cancel the effect of pitching of the bogie frame.

5.1.3 Equations of Motion of Vehicle

The ith vehicle is considered and force relationships developed.

x_i = the longitudinal displacement of the ith vehicle.

x_{i-1}, x_{i+1} = longitudinal displacement of the fore and aft vehicle respectively.

The forces acting on the vehicle are:

• The air brake force

$$Fbrk = f(x_i, t)$$

- The curve resistance

$$Fc = f(x_i, Curve\_Radius)$$

- The grade resistance

$$Fgrad = f(x_i, gradient)$$

- The rolling resistance

$$Frr = f(\dot{x}_i)$$

- The rear coupler force

$$Ftrl = f\left(x_i, x_{i+1}, \left|\dot{x}_i - \dot{x}_{i+1}\right|\right)$$

- The front coupler force

$$Flead = f\left(x_i, x_{i-1}, \left|\dot{x}_{i-1} - \dot{x}_i\right|\right)$$

- The tractive effort

$$Ftrac = f(notch, \dot{x}_i)$$

- The dynamic brake effort

$$Fdyn = f(notch, \dot{x}_i)$$

From Newton's Second Law of Motion :

$$m_i \ddot{x}_i = \sum_{j=1}^{8} F_{ij}$$

$$m_i \ddot{x}_i = \pm Flead_i \pm Ftrl_i - Fbrk_i + Ftrac_i - Fdyn_i - Fc_i \pm Fgrad_i - Frr_i$$

It is evident from the above section that for simulating train dynamics, models describing the coupler force, tractive effort, dynamic brake effort, rolling resistance and air brake are required. Track data, i.e. gradient and curvature changes, as well as speed restrictions and location of signals are also required by the train performance program during execution.

5.2 Train Components and their Mathematical Models

5.2.1 The Air Brake
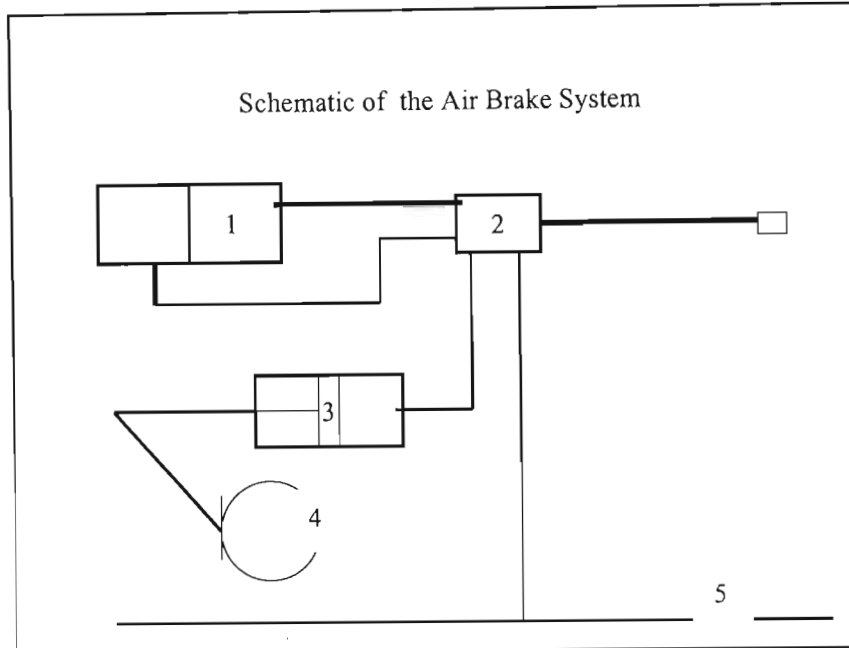
Figure 5.1 : The Air Brake System

1- Combined auxiliary and emergency reservoir

2- Control Valve

3- Brake cylinder and piston

4- Brake shoe and wheel arrangement

5- Train pipe

The primary objectives in braking are to:

• control train speed on descending grades and undulating territory;

• slow the train down to safe speeds for negotiating turnouts or passing critical
  locations;

• effect a smooth train stop at and not beyond specific locations.

Components

• **compressor** on the locomotive(s) that supplies compressed air to the braking units
  on cars.

• **combined emergency and auxiliary reservoirs** on each car that store the

compressed air delivered from the compressor.

- **ABDW control valve** that regulates the pressure of air from the reservoirs to the brake pipe pressure carried for the particular application or release.
- **brake pipe** that extends through each locomotive and car from one end of the train to the other.
- **brake cylinder** that activates the linkage mechanism.
- **brake linkage mechanism** that presses or releases each brake shoe against each wheel tread.

Operation

Brake Application

- The brake pipe, auxiliary and emergency reservoirs are at this stage charged to the same pressure, 550 kPa.
- The locomotive engineer opens the brake valve to atmosphere and the pressure in the brake pipe is reduced.
- The control valve on each car responds to the reduction in the brake pipe pressure by allowing a specific amount of compressed air to flow from the auxiliary reservoir to the brake cylinder.
- The brake cylinder piston, because of the force exerted by the compressed air, moves and activates a linkage mechanism that presses the brake shoe against each wheel tread. Once applied, the brakes will remain applied at a constant pressure, if brake pipe pressure is maintained at a constant value.

The amount of compressed air delivered from the auxiliary reservoir is determined by the type of brake application initiated i.e. either service application or emergency application. There are 3 service applications, namely :

- minimum service which is the first brake pipe reduction made in the application of brakes 35 kPa (5-7 Psi).
- partial service which corresponds to a 100 kPa brake pipe reduction at the service rate.
- full service which corresponds to a 160 kPa (23-26 Psi) brake pipe reduction.

When circumstances dictate a very rapid brake cylinder application with higher brake cylinder pressure and resultant higher retarding forces than obtained during a service application, the brake pipe is quickly vented at an uncontrolled rate through a large opening to atmosphere - the emergency application.

Brake Release

- The brake pipe and auxiliary reservoir on each car are charged by supplying compressed air from the locomotive(s).
- Brake cylinder air is simultaneously released to atmosphere, allowing the brake cylinder piston to move back to the released brake position where it remains under spring force, keeping the brakes released until the next brake application. The brake pipe pressure is kept at its maximum.
- The application of brakes is enabled by reducing the pressure in the brake pipe by progressive steps. Partial release of brakes cannot be accomplished.

Notes

- Brakes used by Spoornet are direct release brakes which means that as soon as release is initiated, the train brakes are released fully.
- The brakes are not inexhaustible. It takes some time to fully recharge the brake system after any release. This means that a series of short brake applications and releases in sequence will result in the air reservoirs becoming depleted and affecting the train's ability to stop.

The Air Brake Model

The braking force exerted on each wheel depends on the brake rigging, brake pipe reduction, and duration of brake application. It is important to determine the time of brake application as dictated by the transmission speed of the brake pipe pressure drop along the train length (pressure wave's travel times) and hence the total length of the train. Further, the distance of a given car from the vehicle at which brake pipe pressure is initially reduced is an important factor.

The air brake model described is based on an analysis of the pneumatic circuit of a train and individual vehicles and is described by Reddy [21].

The brake cylinder pressure is calculated as a function of time and position of the particular vehicle on the train consist. For time less than the time required to reach maximum force, the relationship is linear but beyond t_b, cubic curves can be fitted. This pressure is used to calculate the brake cylinder force using brake cylinder geometry. Finally, the retarding force is calculated from the brake cylinder force incorporating all losses in the brake cylinder and leverage system, lever ratio and brake shoe friction.

A concise version of the computation scheme is described in figure 5.2 below.
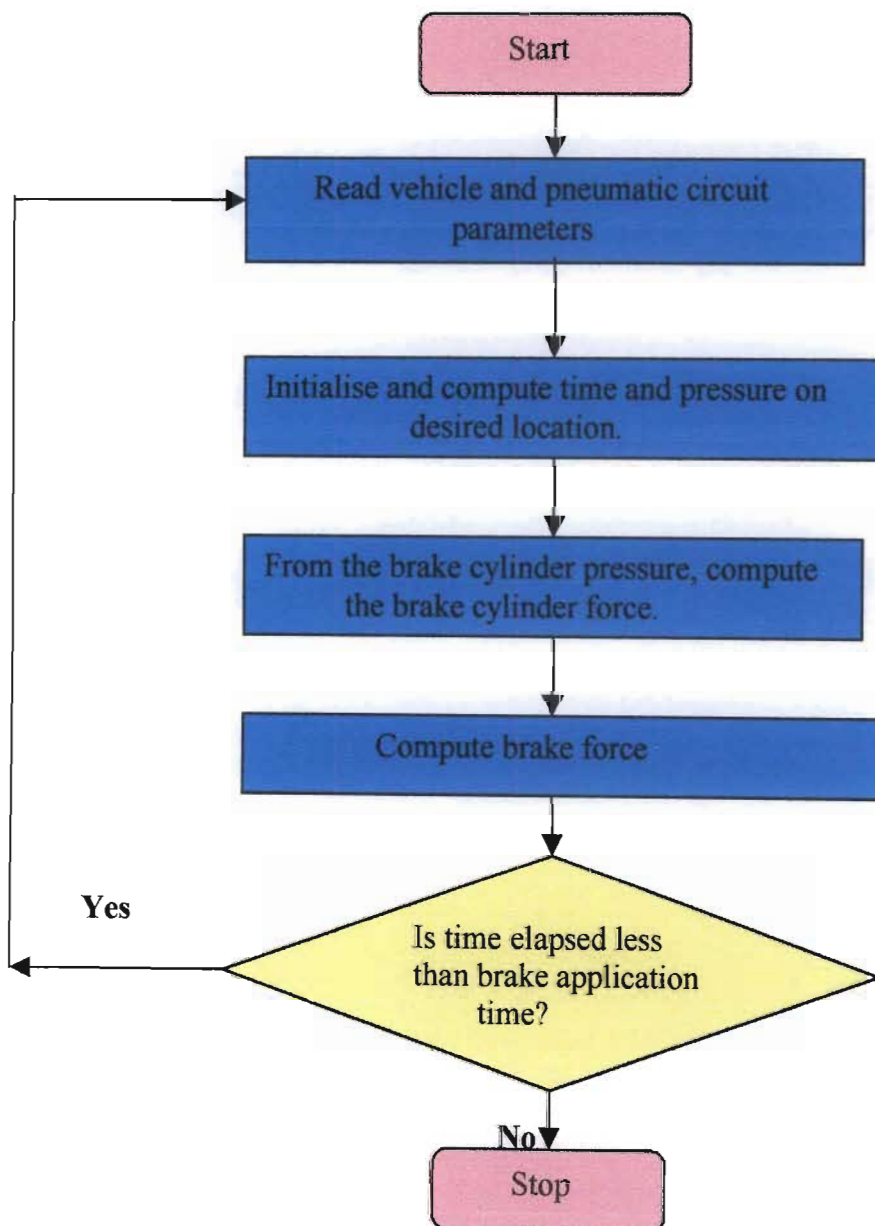
Figure 5.2 : Flowchart for Air Brake System

5.2.2 Bogies

The bogie can be considered as an independently articulated framework holding one or more wheelsets.

There are three basic kinds of bogies, namely :

- rigid bogies that hold axles parallel and in place laterally;
- radial bogies that allow axles to take up a radial position in a curve e.g. HS bogies;
- three piece bogies that hold axles parallel but allow them to move laterally.

The HS type bogie will be assumed for all vehicles in the system. When axles are allowed to take up a radial position in a curve, there is no force input from the head of the rails into the wheel tread and from the face of the rail into the flange as well in sharper curves. Rigid and three piece bogies on the other hand have higher force inputs.

Rolling Resistance

Rolling resistance includes all resistive forces acting on a train including air resistance but excluding gradient and curve resistance. This resistance is made up of a constant component (A+B/W N/ton), a speed dependent component (C v), and a component which varies with the square of speed (D v^2/W).

A and B are constants for a given type of vehicle where the former is the rolling resistance (external friction) coefficient and the latter is the bearing resistance (internal friction) coefficient. External friction appears at the wheel-rail interface due to three factors:

deformation of the wheels and rails at the points of contact, the separation force due to rolling, and the energy loss from wheelslip.

C, the track resistance coefficient, is the constant resulting from the relative motion between the wheelsets, bearings and rails, surface roughness of wheel and rail, natural oscillation of the vehicle, the creep effect caused by the deformation in the wheel rail contact area and friction from skew running bogies.

D is the aerodynamic resistance coefficient. Aerodynamic resistance appears as both surface friction and normal pressure drag. It depends on vehicle dimensions, shape and surface roughness.

W is the axle load of the vehicle in tons.

The rolling resistance, Frr, is often determined by the modified Davis equation in which wind resistance is also included.

W. J. Davis Jr., developed a single equation to allow for differences in vehicle configuration based on the rolling resistance tests of Professor Edward C. Schmidt and Professor J. K. Tuthill [24].

The Davis formula as applicable to South African conditions in Metric units is:

$$Frr = (6.38 + 0.137v) \bullet mass/1000 + 0.028v^2$$

For worn wagons, 6.38 changes to 62.88 .

5.2.3 Gradient Resistance

Gradient resistance is the resistance that has to be overcome by the locomotive consist to move the train up a gradient. The component of the weight, mg, in the direction parallel and down the gradient is the gradient resistance force, Fgrad.

$$Fgrad = -mg \bullet \sin \theta$$

$$But \quad \sin \theta = \frac{y}{r}$$

The gradient is normally represented as the ratio 1: h, hence :

$$\sin \theta = \frac{1}{\sqrt{1+h^2}}$$

$$\therefore \quad Fgrad = -mg \bullet \frac{1}{\sqrt{1+h^2}}$$

5.2.4 Curve Resistance

Many rolling and sliding contact theories have been formulated to account for the complex processes involved in as far as curve negotiation is concerned, but it is sufficient to understand that curving forces give rise to resistance in a curve. Track

curvature represents extra work done in overcoming frictional forces between the wheel flanges and treads, and the rail head and gauge corners. It depends on the wheel-rail friction coefficient, the track gauge, and the distance between the axles in each bogie. Curve alignment resistance, Fc, is generally derived experimentally and approximated by the empirical expression below.

$$Fc = -0.00035mg \bullet D$$

$$D = \frac{1745}{Curve\_Radius}$$

This representation is applicable to South African practice (only) possibly to allow for the narrower gauge (1065mm). The US uses an equivalent gradient of 0.04% for every degree of curvature instead of 0.035%.

5.2.5 Draw-gears

Draw-gears are the predominant mechanical devices which would have the greatest influence on the system response in studies involving longitudinal train dynamics. The draw-gear sub-system comprises the following :-

• coupler;

• yoke;

• draft-gear element;

• loose rear stops and front follower.

Draw-gears comprise of spring-damping elements of various designs and materials. The spring elements absorb, store energy and restore the gear to its neutral position i.e. draw-gears deflect under load to absorb impacts between railway vehicles. The cardinal feature of a draw-gear for train action is to limit the generation of slack. This make the requirement of a high pre-load mandatory, so that the unit does not stroke on slow variation of the train forces but reacts to a high rate of change of force or jerk value.

At the end of the rakes, the Miner SL-76 draw gear is used. The characteristic of this draw gear is shown in figure 5.3 and the performance specifications are listed below.

Performance Specifications:

- Construction   - Wedge friction-rubber draw-gear
- Certification   - AAR M-901E
- Official Capacity   - 64.8 kJ
- Official rating travel   - 77.5 mm
- Reaction Force @ rating travel   - 2 270 kN
- Pre-load Force   - 100 kN
- Gear Mass   - 142 kg
- Efficiency   - 36.8 %
- Maximum capacity @ rating travel   - 73.1 kJ

The draw-gear model used in all simulations is based on an analysis of the spring and damping elements of each individual draw-gear, and is described and developed by Desmorat [23].
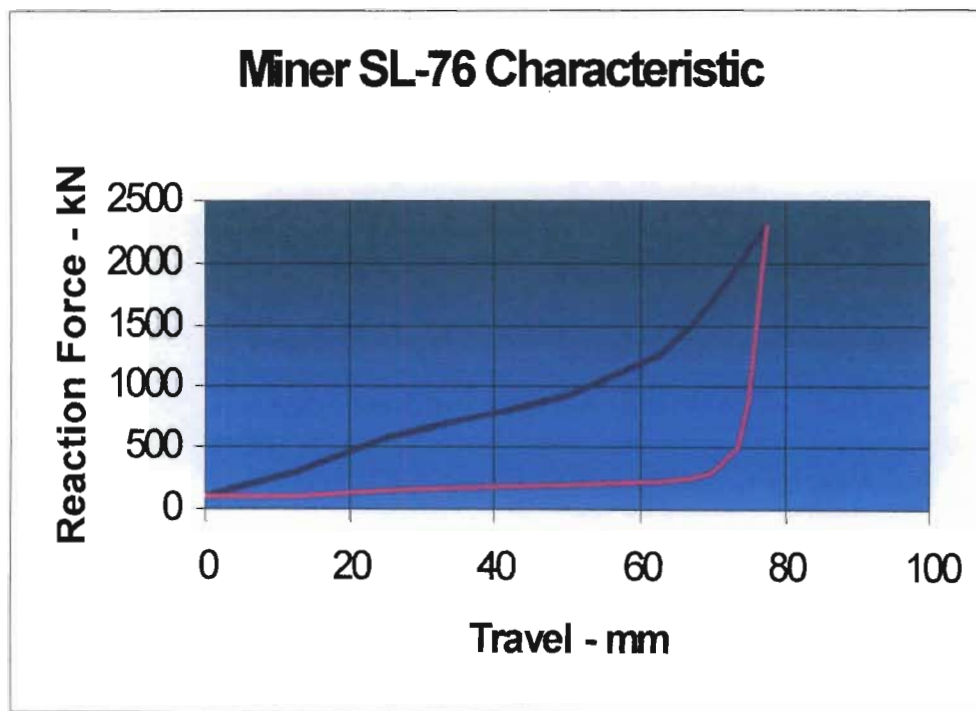
Figure 5.3 : The Miner SL-76 Characteristic

The Draw-gear Characteristic

The overall response of the draw-gear sub-system is symmetric in tension and compression since the combination is arranged such that the draw-gear element is compressed in both cases. The tensile half of the characteristic will suffice for illustration purpose. A schematic representation of the draw-gear arrangement and action is shown in figure 5.4 followed by the description and analytical treatment of the package.

Draw-gear Action

- The free slack region, [0], does not support any force and occurs due to clearances and wear within the draw-gear assembly. Once loaded outside this region, the draw-gear element is compressed.
- The draw-gear is loaded within phases of increasing stiffness in the stroking zone, [1] and [2], due to the geometry of the arrangement. If the external load is reduced, the draw-gear is locked, [5], and a very high stiffness is observed.
- The draw-gear element relaxes along a line of relatively low stiffness during the unloading phase, [4]. This follows [5] provided the external load drops sufficiently for friction to be overcome in the direction opposite to that during loading.
- The response may exhibit hysterisis, moving up and down the locked region several times. This implies zero damping as far as the draw-gear element is concerned. Damping is offered by the structure of the couplers and the vehicle body.
- Under very high loading, the resistance of the spring-damping element is negligible and the stiffness is that of the structure, [3].
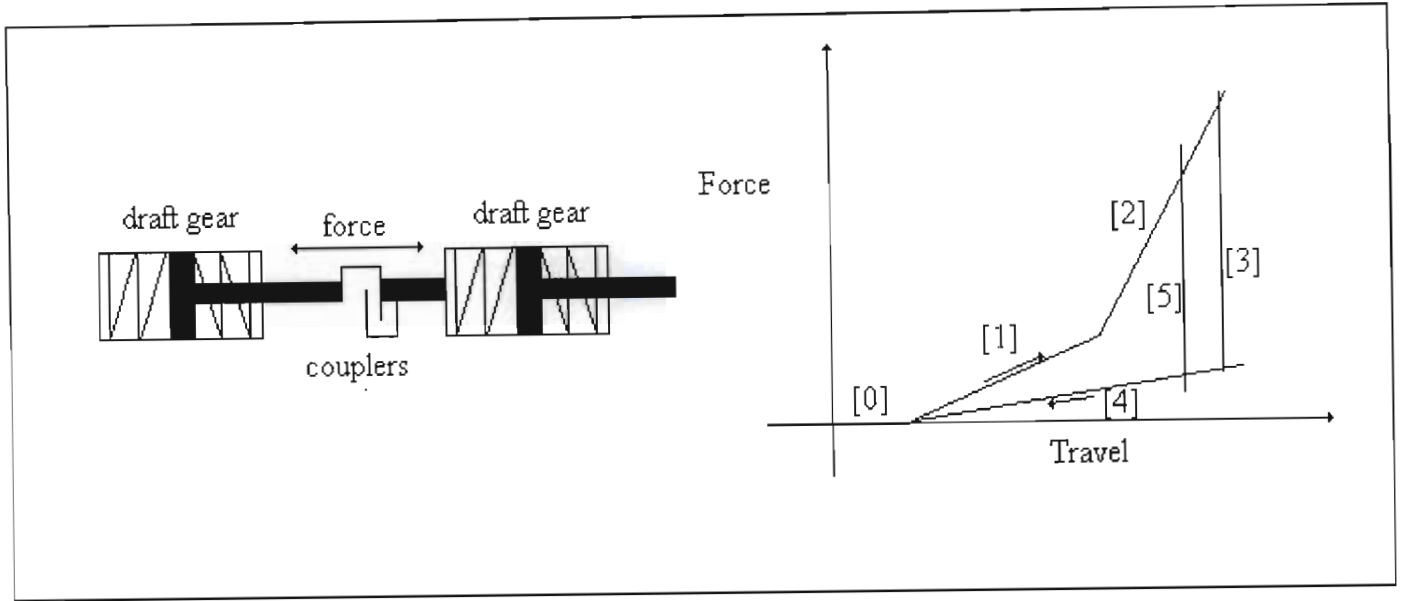
Figure 5.4 : Functional Draw gear and its Action

A general relationship, which is applicable to all types of draw-gear and is based upon empirical data is mathematically described as:

$$R(x) = Fp + (Fm - Fp)\left(1 - e^{a\frac{x}{s}}\right)\bigg/\left(1 - e^{a}\right) \qquad\qquad For \quad x \geq 0 \,\&\, \dot{x} \geq 0$$

$$R(x) = Fp + (Fm - Fp)\left(1 - e^{b\frac{x}{s}}\right)\bigg/\left(1 - e^{b}\right) \qquad\qquad For \quad x \geq 0 \,\&\, \dot{x} \prec 0$$

5.2.6   Locomotive Characteristics

As explained in depth in Chapter 4, the locomotive characteristics are developed in terms of plots for each throttle position. The tractive effort or dynamic force applied is given as a function of locomotive speed for each throttle (notch) position. The model uses lookup tables to set the respective force levels. The armature current levels for traction are also represented as lookup tables. The armature current is also a function of speed and notch setting. There is no need to monitor armature levels during dynamic braking since the locomotives are set to always operate below critical limits in dynamic brake mode.

5.3 Locomotives in Multiple

5.3.1 Required Number of Locomotives

The tractive effort that the locomotives must exert must be equal to or more than the total resistance that must be overcome. The number of locomotives of any one class that can work in multiple is limited (in practice) by a number of reasons, namely:

(1) Structure Strength.

Older locomotives (6E to 10E) are weaker and no more than 4 should be used in multiple except under special circumstances where up to 6 can be used.

(2) Control Circuitry.

The locomotive control circuitry is designed to control only a certain number of locomotives in multiple. The limit exists due to electrical loading and losses in the train lines and the number (not more than 6) is usually specified at design time.

(3) Substation Capacity.

Very heavy trains require high continuous ratings (15 MW typically) which may not be available since substation capacity is limited to about 6 MW per substation, typically.

(4) Electrical Interference.

Modern 3-phase locomotives generate large currents internally, with variable frequencies. If too many of these locomotives run on a line with track circuit components sensitive to the generated frequencies, the minute residual interference of each locomotive add up to the point where the signals may change their aspect thus distort the signalling system.

(5) Working Together of Locomotives.

Resistance controlled locomotives do not always work together properly. The more the locomotives that are put together, the less likely the chance that they will work satisfactorily.

(6) Maximum Demand.

In order to limit the peak energy demand, Eskom introduced the so-called Maximum Demand Tariff to encourage users to limit their usage maximums. This implies that very heavy trains would be discouraged if the benefit conceived is rendered not justified by the accompanying electrical consumption and expense.

(7) Coupler Strength.

A practical limitation to heavier trains exists, which is that the coupler strength of standard coal trucks will be exceeded if more than 4 coupled electric locomotives haul from the front of the train. E and F type couplers can be worked up to 1500kN to 1600kN on the Coal Line.

The problems mentioned above limit the number of locomotives that can be worked in multiple and hence the use of very heavy trains. Some of these problems could be overcome by the division of motive power to enable longer trains. Another factor to consider would be the use of mixed consist locomotives.

The Calculation Recipe

- Calculate the gradient resistance using the ruling grade (steepest gradient) of the section.
- Calculate the rolling resistance. It is customary to assume that the resistance of the locomotives is the same as that of the wagons.
- Add them together.
- Find the nominal tractive effort at balancing speed from the traction characteristic.
- Divide this tractive effort by the total resistance. This gives the load that the locomotive can move up the given gradient.
- Subtract the mass of the locomotive from this total.
- Divide the operational load by this amount to get the number of locomotives required.

The calculation recipe presented above is derived from Spoornet's Technical Operating Handbook [24].

5.3.2 Mixed Consist Operations

Different classes of locomotives can be used together in one consist provided they are compatible in all the speed ranges.

This is practical from the electrical power aspect but problems of control and train handling are introduced. The following locomotive combinations can be used in multiple :

- Locomotives having different power output but same axle loading. At a certain speed, the extra horsepower of the higher horsepower unit cannot be utilised and must be reduced to that of the lower horsepower unit.
- Locomotives having different power output but same minimum continuous speed. Power reduction is not necessary in this case although the adhesion levels are different.

Since different locomotive types load up to characteristic amperages at different rates, to permit each unit in a mixed consist to load up properly to provide a consistent accelerating force, throttle changes should be made one notch at a time with a pause between throttle changes.

5.3.3 Remote Locomotives

Remotely controlled locomotives allow the tractive effort to be spread throughout the train enabling the full power potential of the additional locomotives to be realised without exceeding the maximum allowable draw bar pull. Draw bar pull is the force exerted on the coupler between the locomotive and the trailing vehicle which is equal to the locomotive tractive effort less the rolling resistance of the locomotive.

Other advantages of division of motive power include the following :

- increased train lengths are conceivable. Longer trains are also preferred because they average grades over a greater distance;
- faster brake application and release times are achievable hence improvement of the performance of the air-brake system;
- power efficiency can be increased;
- reduced impact forces in the last half to two-thirds of the train by introducing a means of controlling slack between vehicles in this region.

5.4 Results

5.4.1 Objectives

The objectives of the simulations were to :-

• determine the most appropriate train configuration for train operations;

• quantify the merits of operating with the optimum train configuration by

monitoring:-

- in-train forces;

- energy consumption;

- running time;

- temperature rise of the motors;

- jack knifing displacement.

5.4.2 In-train Forces

The simulations were based on the train configurations presented in Table 5.1.

Simulation	Configuration
1	4 × 11E head-end locomotives; 200× CCL-9 wagons
2	2× 11E head-end locos, 2× 11E remote locos; 200× CCL-9 wagons
3	2× 11E head-end locos, 3× 7E head-end locos; 200× CCL-9 wagons
4	2× 11E head-end locos, 3× 7E remote locos; 200× CCL-9 wagons

Table 5.1 : The Train Configurations

The most appropriate method of illustrating the effect of in-train forces is to consider the maximum, mean and minimum forces measured at specific positions for each train consist on the track. The comparative track is an adaptation of a section of the actual terrain on the Coal Line.

The selected positions were 1, 36, 72, 84, 108 and 162, coinciding with coupler positions since rakes of 4 wagons were used and there are no couplers within rakes because of the slackless drawbars.

Tables 5.2 to 5.5 and Figures 5.5 to 5.8 illustrate the results obtained.

Table 5.2

Force (kN)	Position					
	1	36	72	84	108	164
Fmean	58.479	17.418	82.436	8.167	503.931	306.408
Fmin	-379.23	-356.9	-442.89	-434.38	-323.69	-830.75
Fmax	496.19	391.74	607.82	450.71	1332	1444

Table 5.3

Force (kN)	Position					
	1	36	72	84	108	164
Fmean	54.109	-29.108	-61.097	-29.285	1.776	42.54
Fmin	-191.56	-513.75	-519.04	-512.81	-518.06	-937.85
Fmax	299.78	455.54	396.84	454.24	521.613	1023

Table 5.4

Force (kN)	Position					
	1	36	72	84	108	164
Fmean	148.02	80.34	-7.018	-49.159	-59.443	-7.109
Fmin	-301.2	-561.53	-844.43	-853.33	-991.88	-555.23
Fmax	597.24	722.21	830.395	755.01	873	541.01

Table 5.5

Position						
Force (kN)	1	36	72	84	108	164
Fmean	30.696	-95.528	-8.789	12.143	13.623	-12.113
Fmin	-259.89	-997.849	-657.53	-374.83	-406.56	-565.24
Fmax	321.28	806.79	639.93	399.12	433.81	541.01

Figure 5.5

Figure 5.6

Remote Operation

Figure 5.7

Mixed Operation (head-end)

Figure 5.8

Mixed Operation (remote)
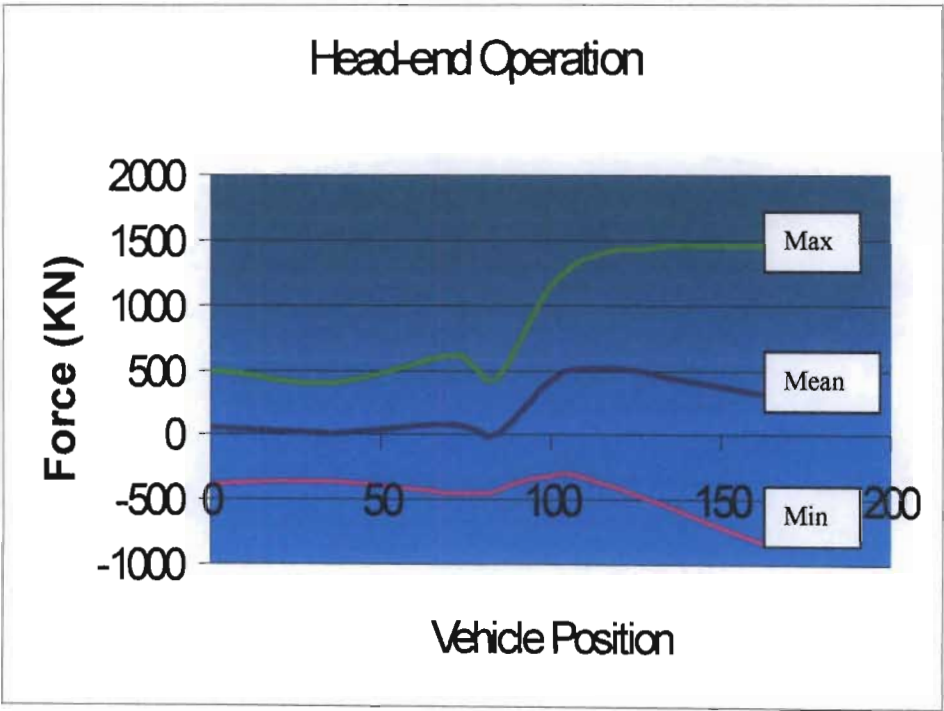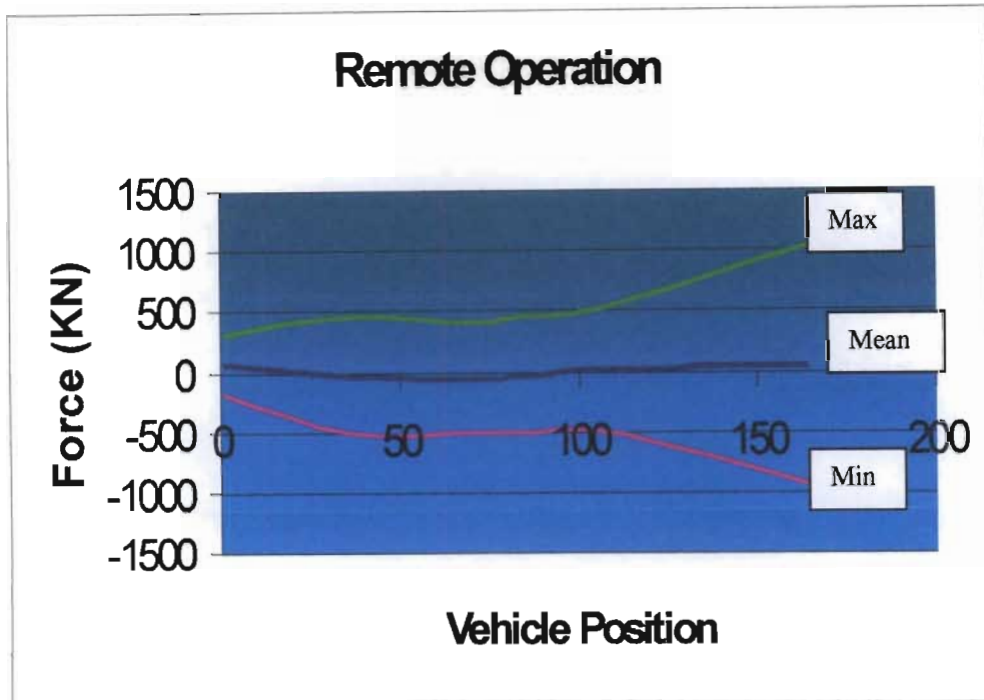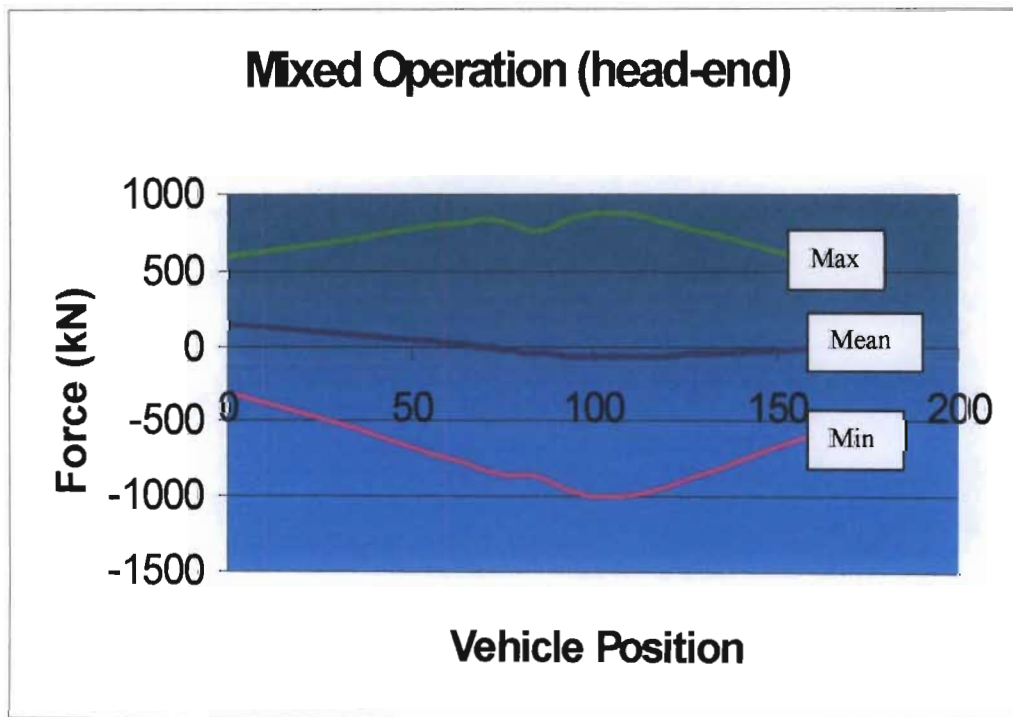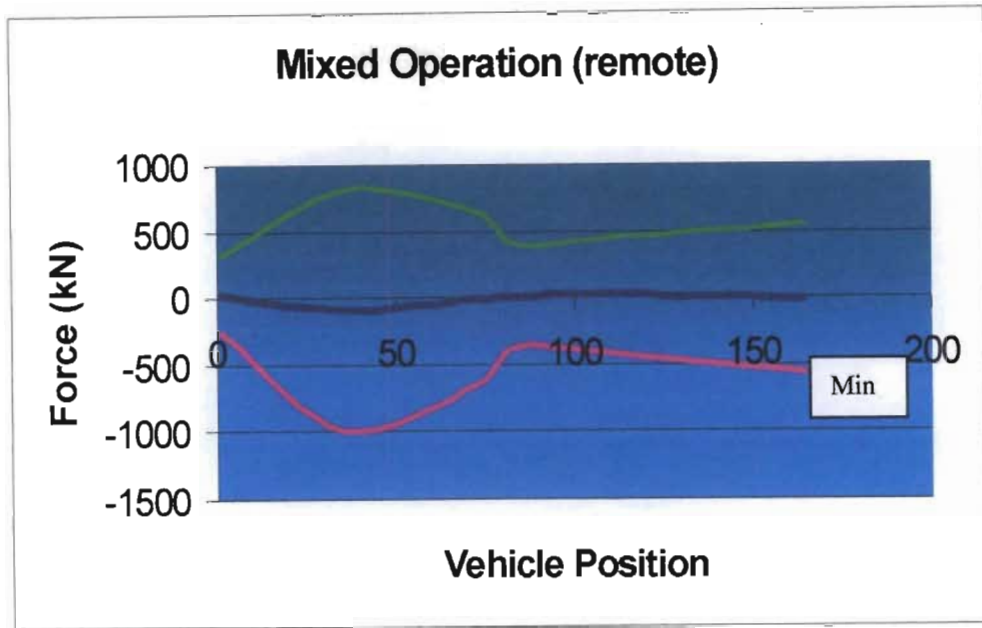
Discussion

From the results above, the following can be observed :

• with head-end operation, a tensile mean is dominant over the entire length of the train regardless of the locomotive consist;

• the simulation with four head-end locomotives clearly shows the position of the minimum effective longitudinal in-train force at a position near the middle of the train consist and hence suggests this position as most suitable for remote locomotives;

• remote operation yields a mean that is approximately zero through the train consist. This is a favourable result as far as the fatigue life of the system and sub-system components is concerned;

• in three of the above four cases, the force response is oscillatory implying increased fatigue damage unlike the case of working 2 head-end locomotives and 2

100

remote locomotives in the middle of the train consist;

- it is possible to work different class locomotives in one locomotive consist when electrical interface limitations are not considered, yielding an improved force spectrum compared to that obtained from the simulation with same class locomotives.

5.4.3   Optimisation of Train Make-up

Figures 5.9 to 5.29   illustrate the results obtained from simulations 1 to 3 respectively
in terms of critical draw gear forces, energy consumption, running time, armature
current, velocity profile and jack knifing displacement. A summary of the critical
parameters observed in the simulation is presented in section 5.4.3.1 below.
Figures 5.9 to 5.16 represent a standard train consist with 4 head-end locomotives.
Figures 5.17 to 5.24 represent a train consist with remote locomotives.
Figures 5.25 to 5.29 represent mixed consist operation.
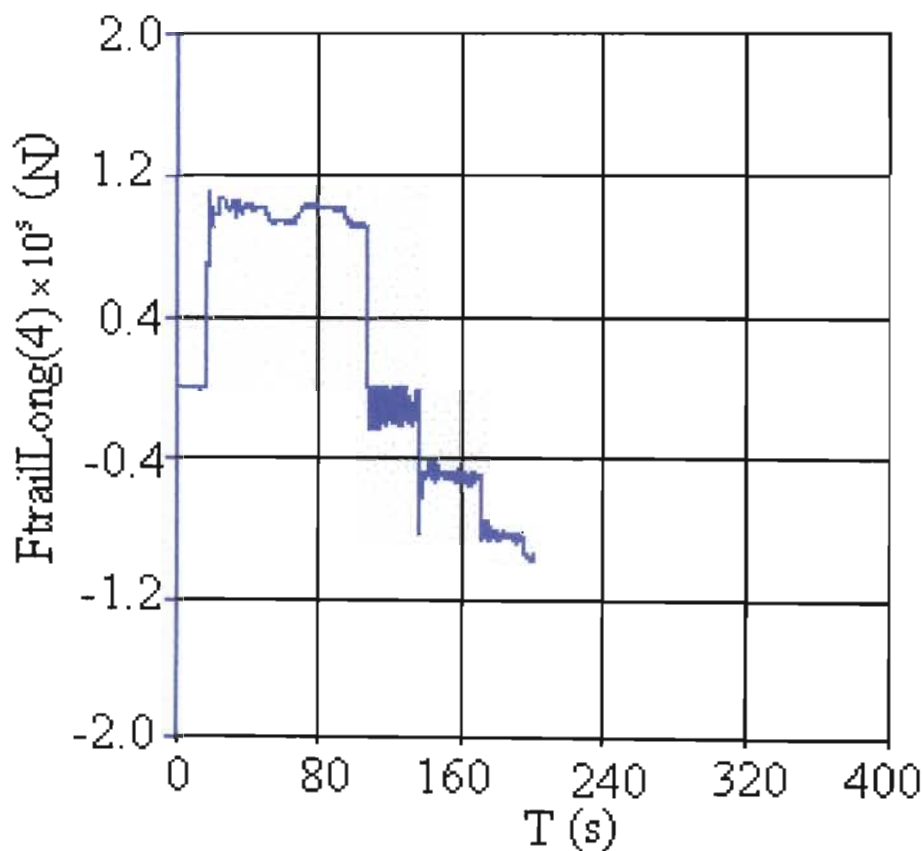
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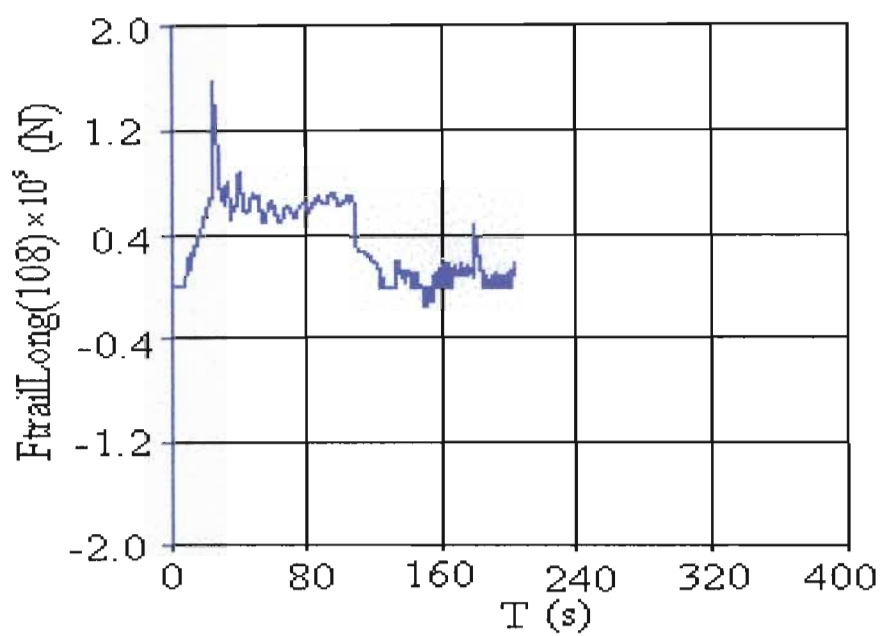
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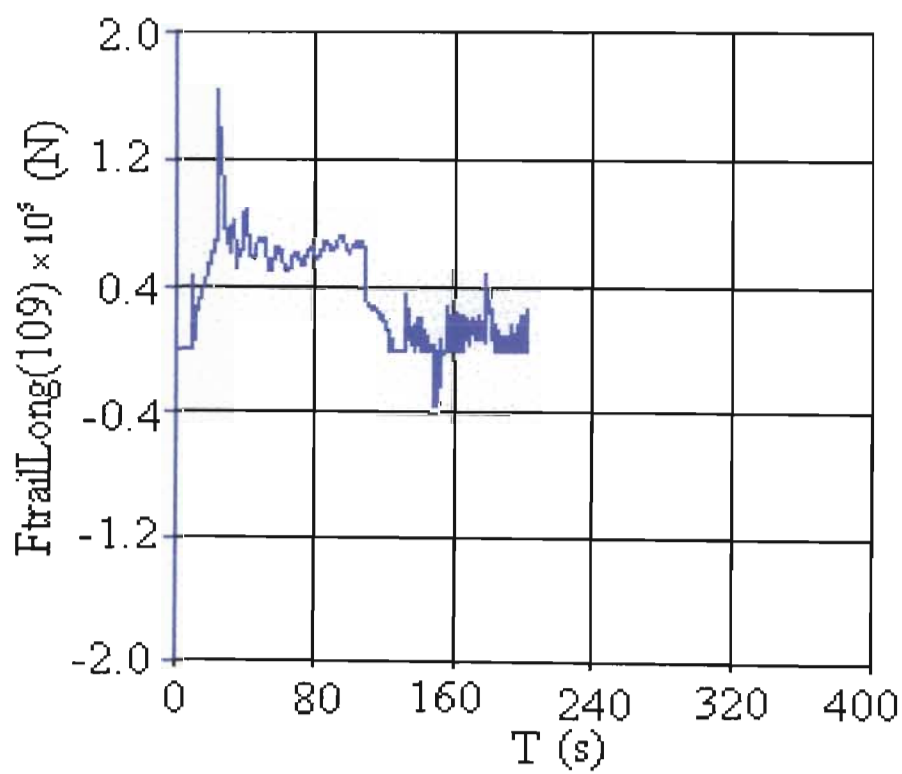
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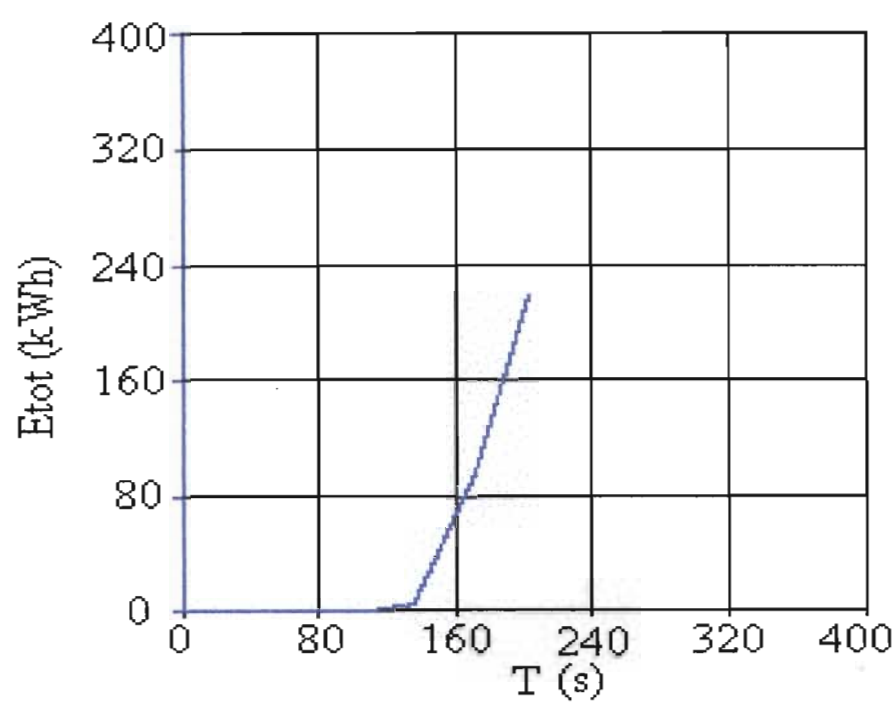
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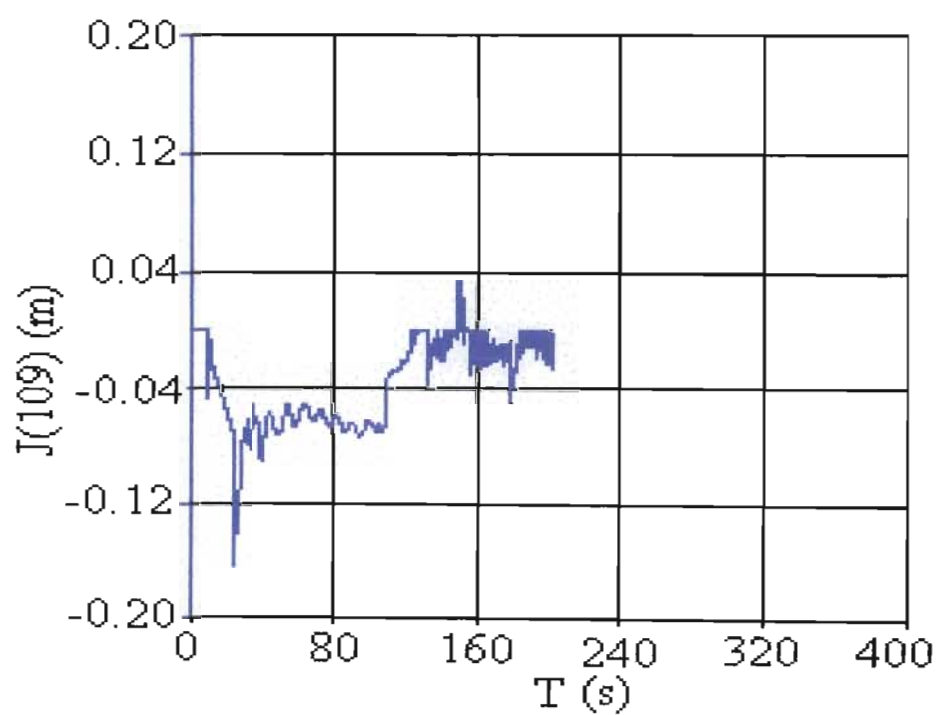
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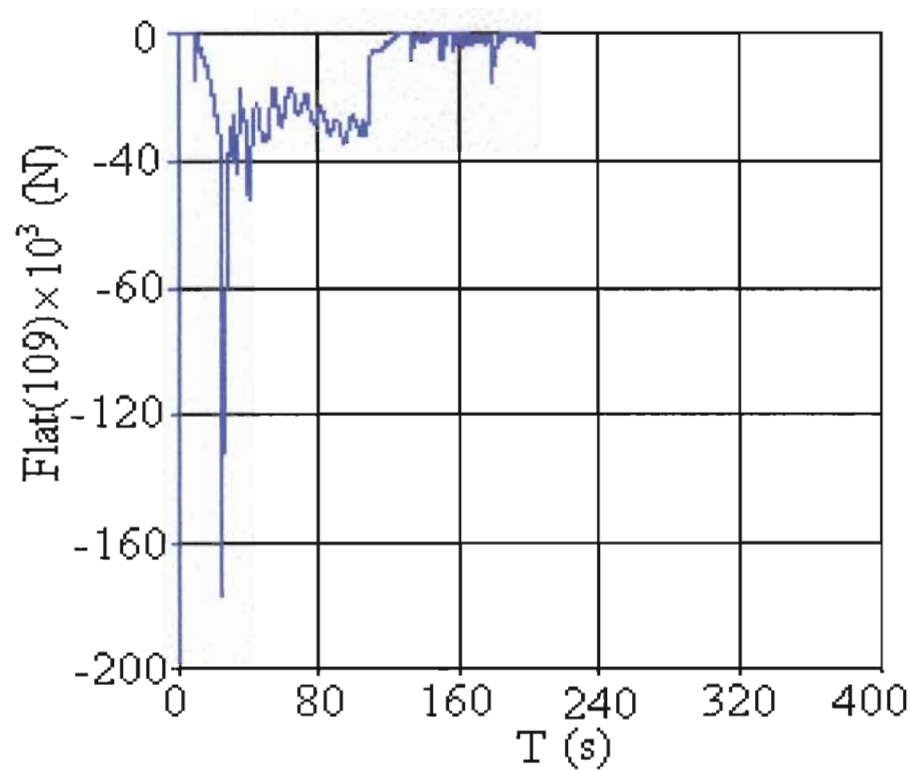
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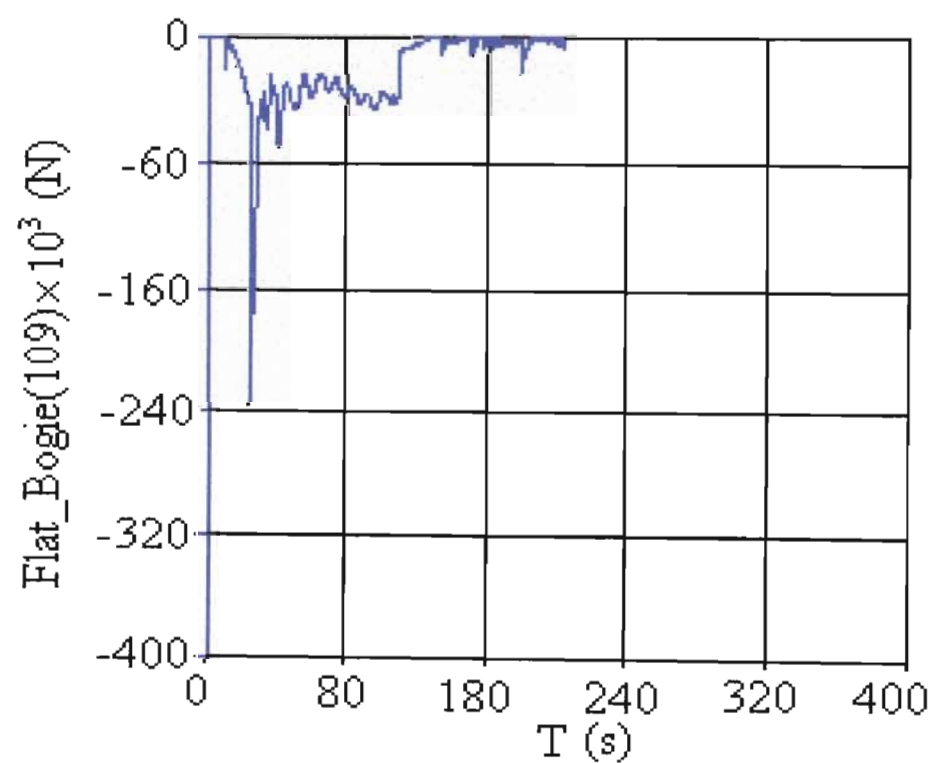
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Figure 5.16
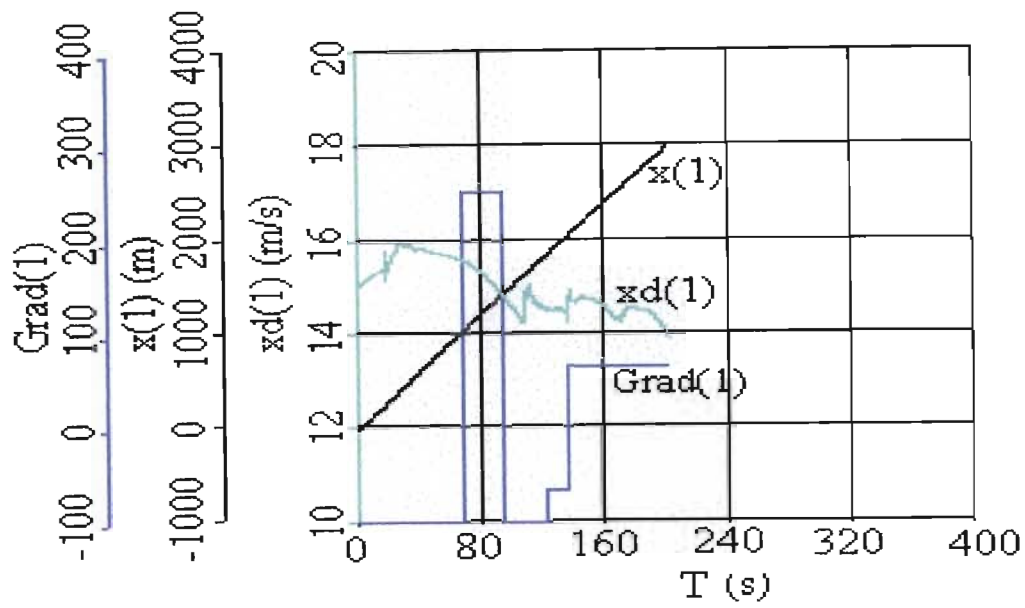
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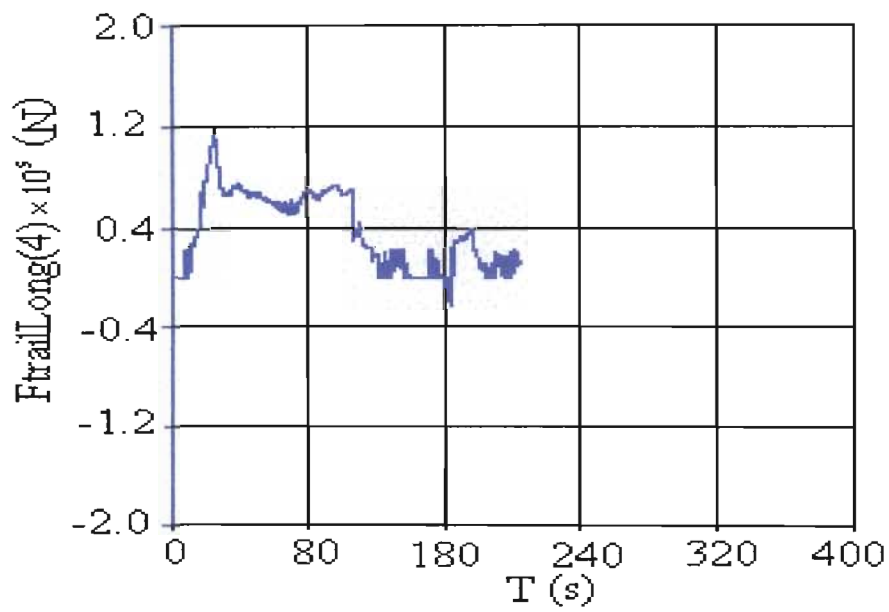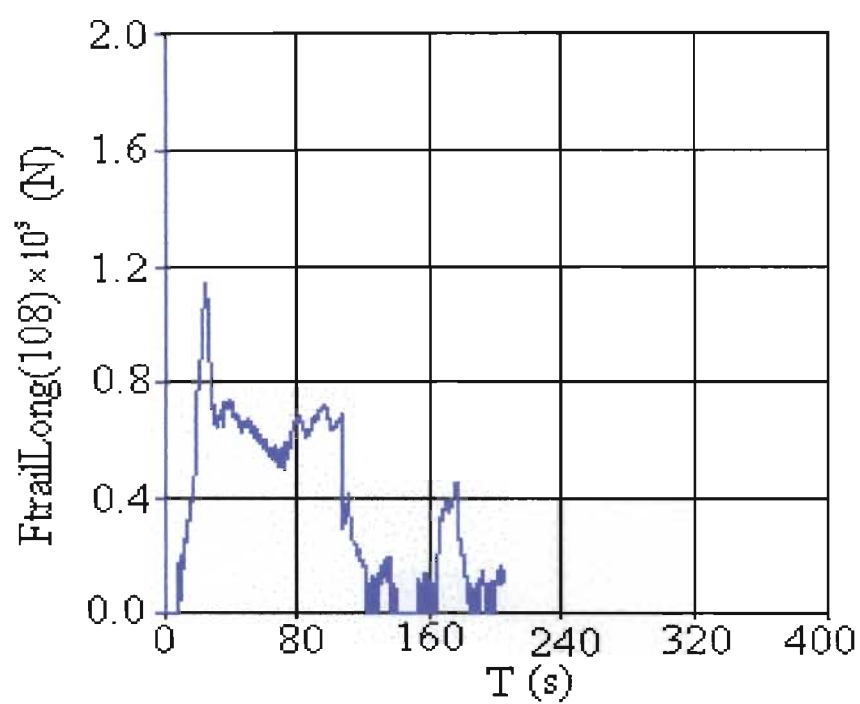
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Figure 5.19
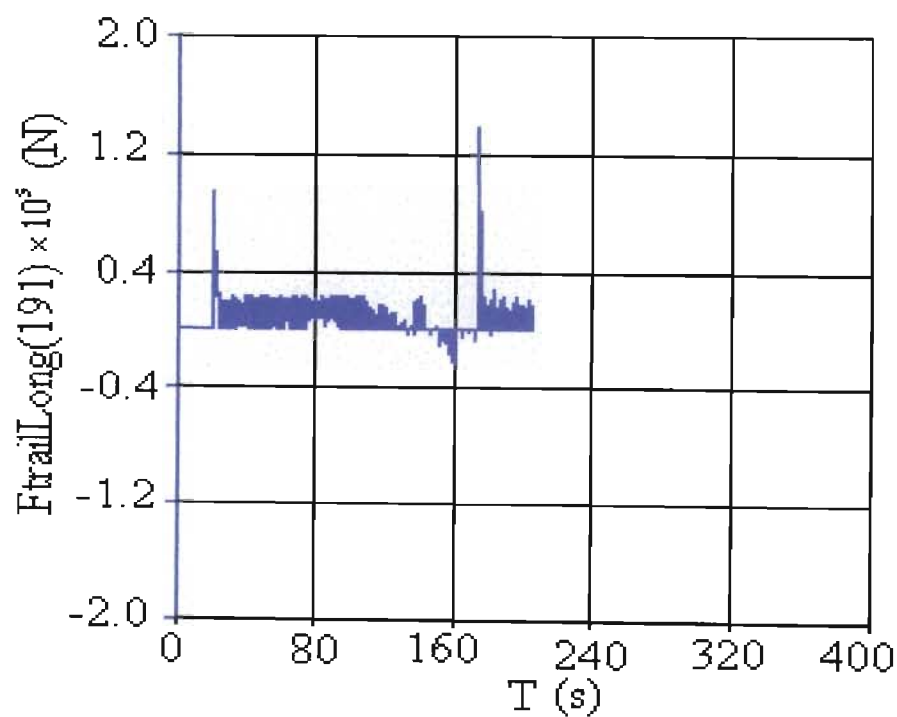
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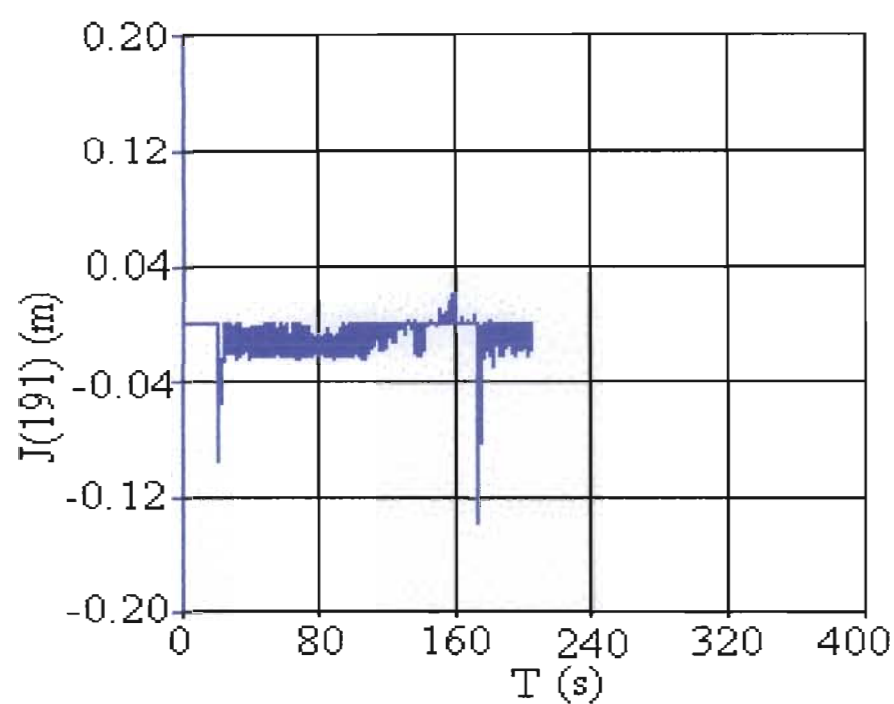
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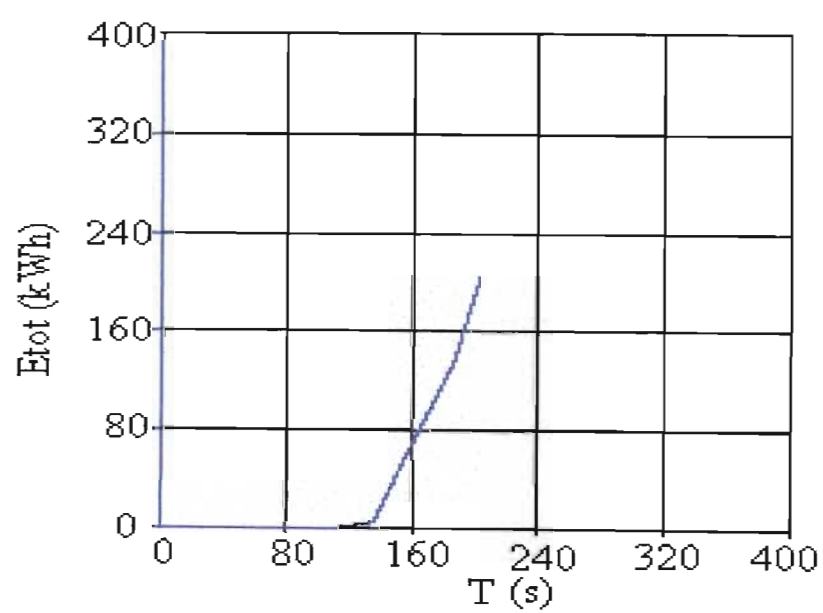
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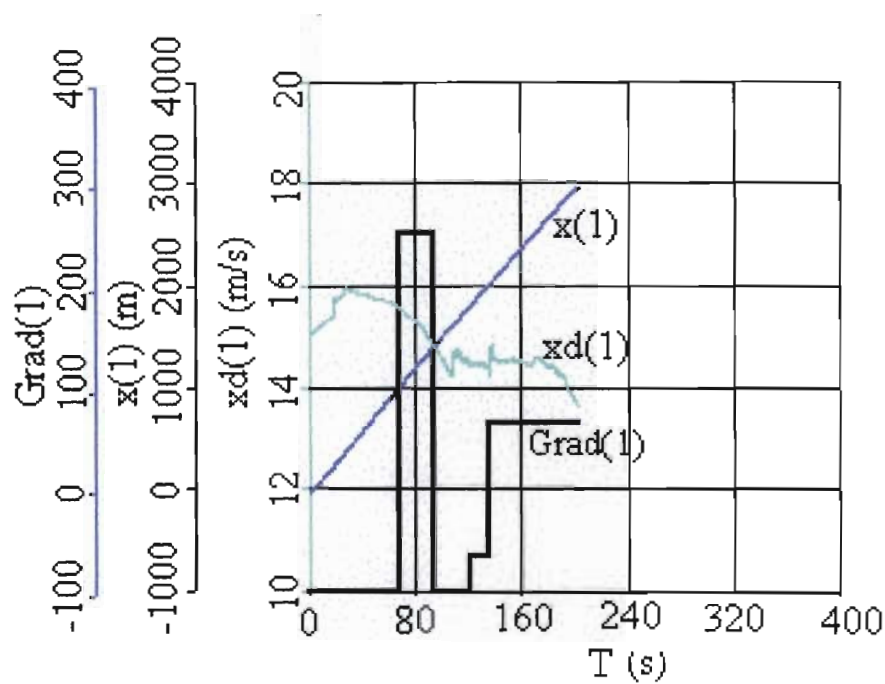
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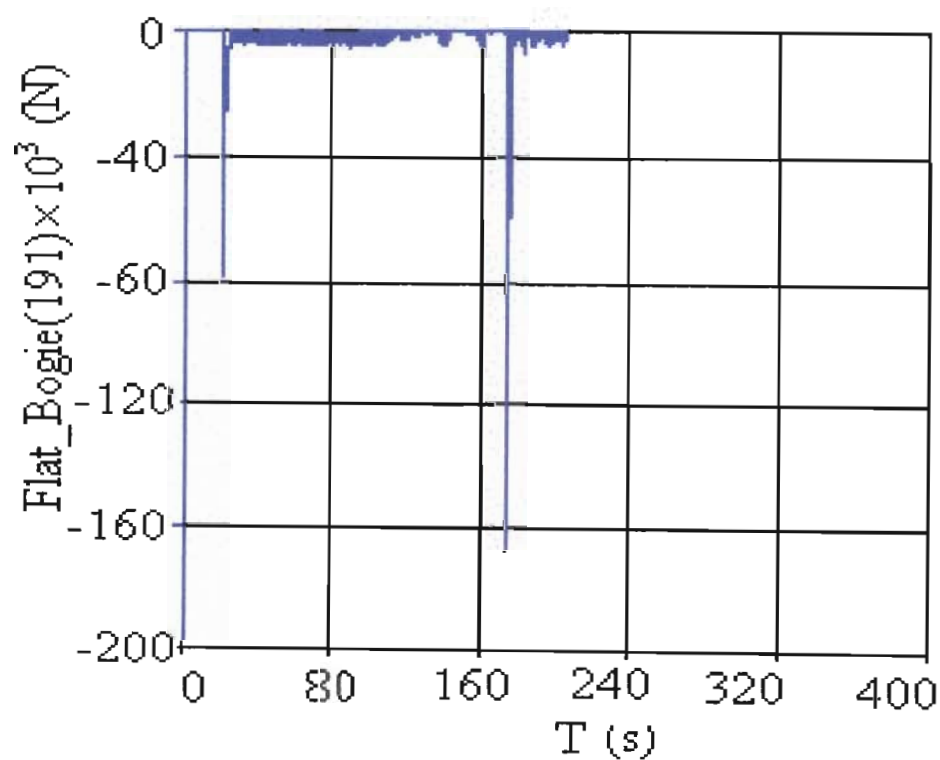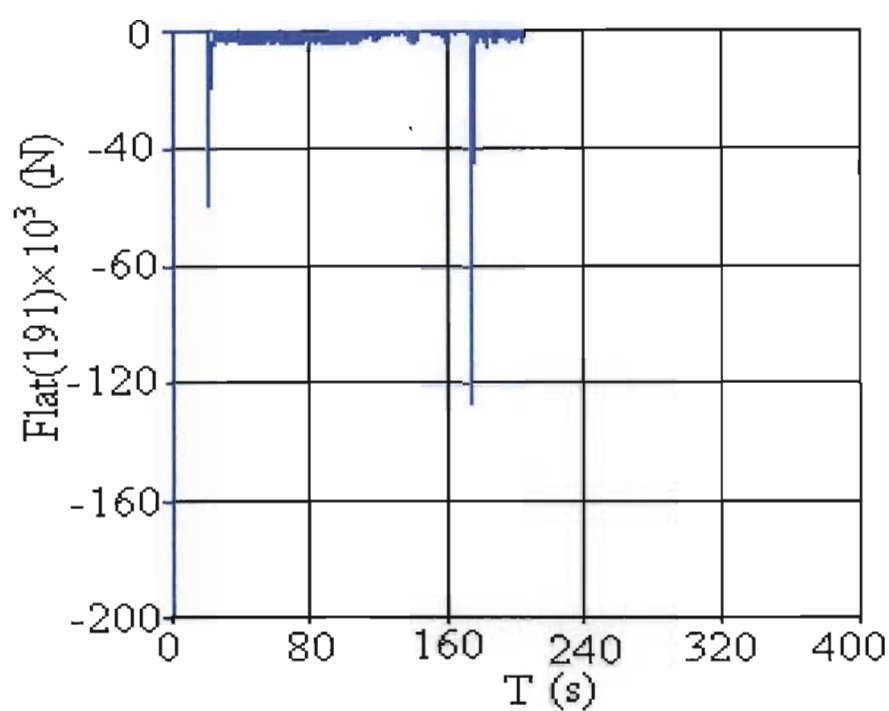
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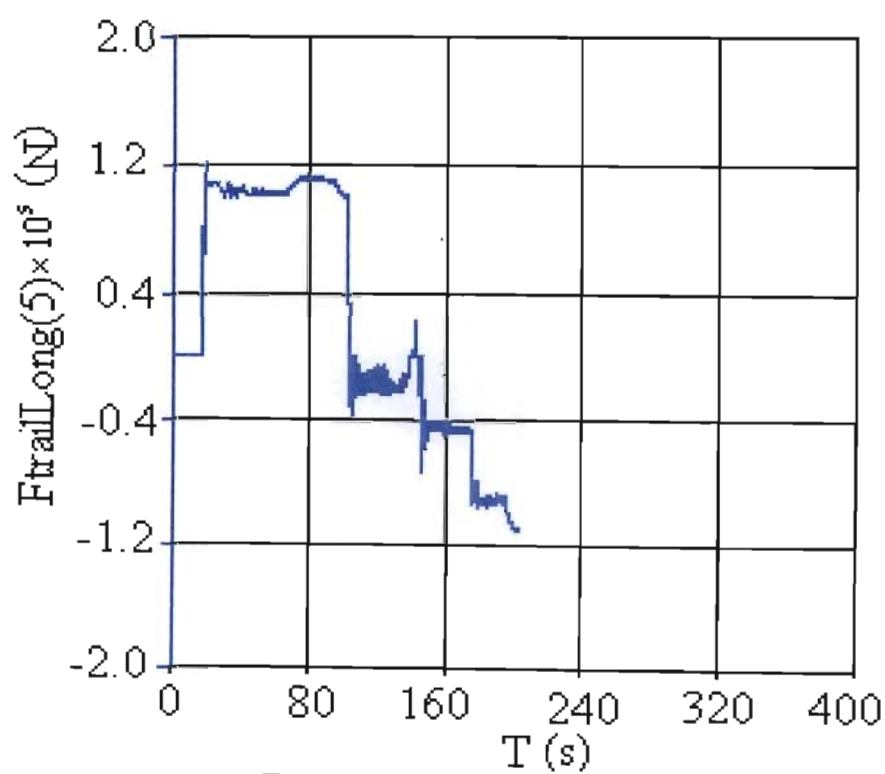
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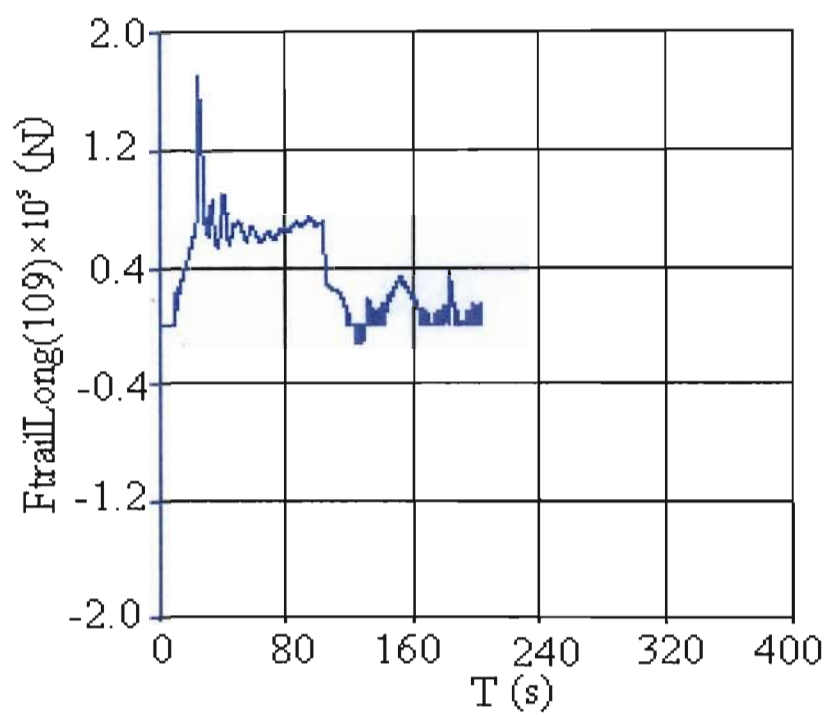
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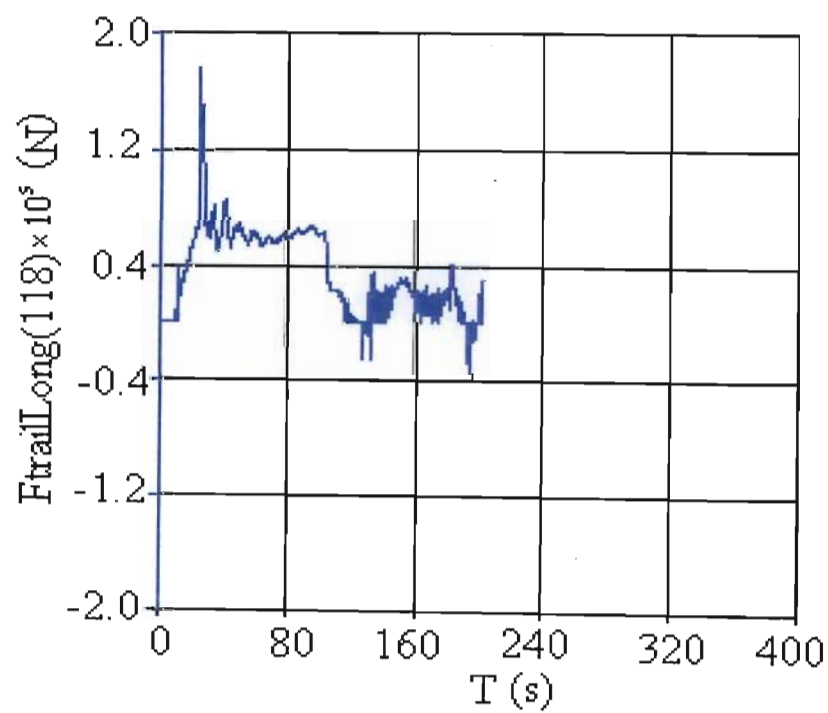
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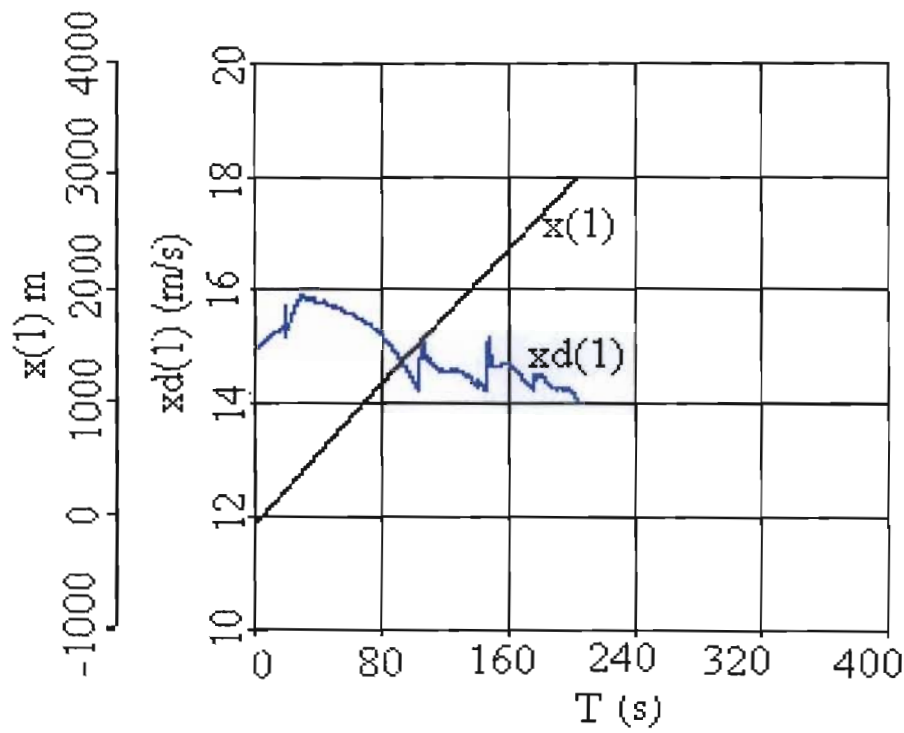
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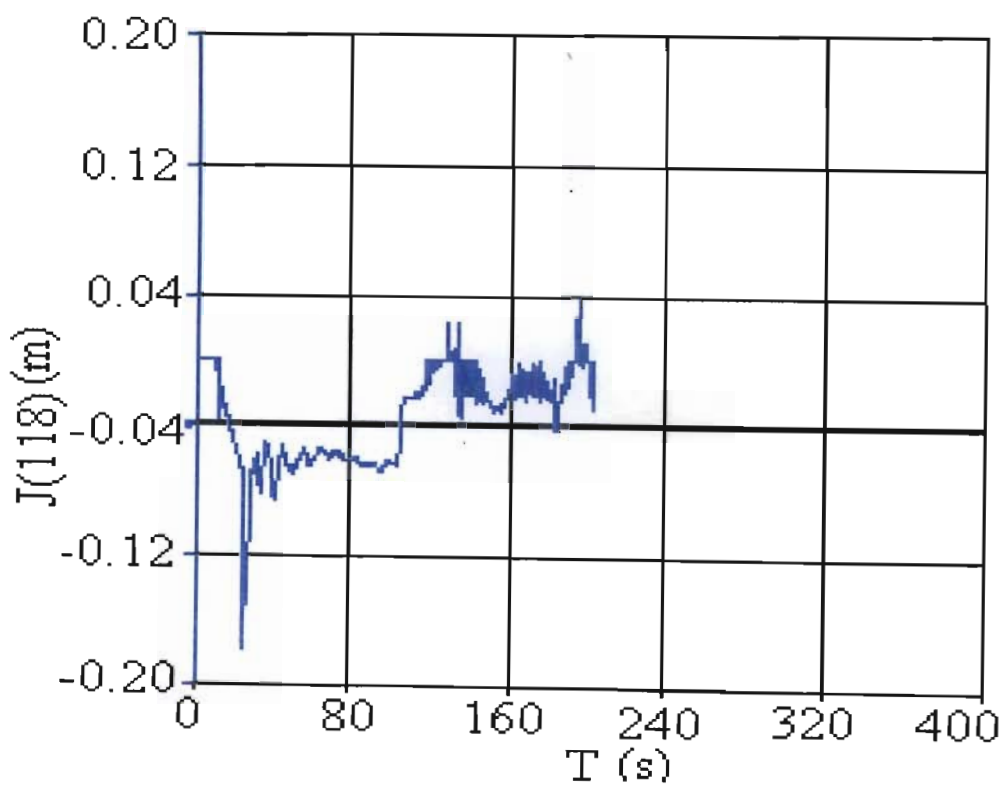
5.4.3.1 Critical Parameters

Head-end Operation

Maximum Longitudinal coupler force = 1650 kN

Maximum Armature Current   = 795 A

Total Energy Consumption   = 222 kWh

Running Time   = 204 s

Maximum Traction   = 280 kN

Maximum Lateral coupler force   = 180 kN

Max. Lateral load on bogie centre   = 240 kN

Max. jack knifing displacement   = 164 mm

Position of largest longitudinal force   = 109

Based on the results for a standard consist with 4 head-end locomotives, the maximum draw gear force was noted in position 108 and the maximum drawbar force was observed in position 109. This suggests harsh slack action in the last half of the train consist and hence the appropriate location of the in-train locomotives to introduce a means of controlling the slack. This is also a suitable position for the remote locomotives from the operation point of view during wagon loading and unloading. The discharge mechanism is a tandem rotary dumper which uses an electro-hydraulic power unit to index the wagons through the tippler. The tippler has the capacity to dump a consist of 100 wagons at a time.

The results of simulating a consist with 2 head-end locomotives and 2 remote (in-train) locomotives after 100 wagons are presented below.

Remote Operation

Maximum longitudinal coupler force = 1459 kN

Maximum Armature Current   = 795 A

Total Energy Consumption   = 206 kWh

Running Time   = 204 s

Maximum Traction   = 280 kN

Maximum Lateral coupler force   = 128 kN

Max. lateral load on bogie centre   = 168 kN

Max. jack knifing displacement   = 135 mm

Position of largest longitudinal force = 191

Availability is an important factor to consider in providing a reliable and predictable service hence the need to investigate the intricacies of working different classes of locomotives in one train consist. A locomotive consist of 2 class 11E locomotives and 3 class 7E locomotives was set up and the critical parameters are shown below.

Mixed Consist Operation

Maximum Longitudinal coupler force = 1773 kN

Maximum Armature Current   = 795 A and 665 A

Total Energy Consumption   = 217 kWh

Running Time   = 204 s

Position of largest longitudinal force = 118

Max. jack knifing displacement   = 178 mm

Discussion

- Inspection of Figures 5.9 to 5.24 suggests that the introduction of remote locomotives in a standard train consist improves the force spectrum;

- Slack run-ins and run-outs occur when either the air brake is applied or the mode of operation is changed from powering to dynamic braking and vice versa;

- The current rating for the class 11E locomotive is 815 A and the maximum observed current of 795 A suggests that the temperature rise of the motors is within acceptable limits throughout the simulation;

- Remote operation also suggests a 7% improvement in the energy consumption while comparing standard operation with mixed consist operation shows no significant change on this figure (2%). Train configuration has little influence on energy consumption unlike train handling or driving strategy. This suggests a need for an optimum train handling algorithm;

- Running time is only affected by the train handling strategy and is independent of the train make-up when trailing locomotives are controlled by the leading locomotive and their response passive;

- In both cases of head-end operation, the maximum allowable load of 1600 kN on the knuckle of the draw gear is exceeded. However, in not one of the 3 cases considered, do the lateral forces seem sufficiently high to shift a wheel on an axle. To press a wheel onto or off an axle requires approximately 1200 kN;

- The 135 mm, 164 mm and 178 mm jack knifing displacements seem excessive when compared to the specifications for lateral bogie displacement. A logical means of reducing lateral effects due to in-train force is by decreasing the maximum in-train force. This is achieved by distributing the tractive effort evenly through the 200 wagon train by introducing remote locomotives.

5.4.3.2 Knuckle Failure

Investigation of critical draw gear forces is important in that draw gear problems are responsible for more than 12% of the wagon incidents in South Africa. Further statistical analyses of draw gear problems indicate that failures of knuckles are responsible for the largest percentage of draw gear problems i.e. 40.64% and about 69% of these failures occur on the Ermelo-Richards Bay Coal Line [29].
One of the major reasons for knuckle failures is abnormal in-train forces.
A knuckle is a draw gear component which is designed to work only under tension loading in service. Spoornet uses the so-called F-type knuckles on the Coal Line. The knuckle has two main purposes:
- to couple train wagons to one another;
- it is designed to fail if the in-train forces exceed a certain limit (1600 kN) to protect other more expensive draw gear components.

The replacement cost for a new F-type knuckle as used on the Coal Line is about R900. In 1996, for example, there were 65 incidents involving failed knuckles in a period of 9 months. The cost to replace failed knuckles was R58 500 ,excluding labour and time.

The gross income per coal train is about R500 000 and there are 12 trains working the line daily. The total time delayed as a result of knuckle failures in this period was 8231 minutes (6 days).

The total loss of income over the 9 month period was :

$$A = B[C \times D]$$
$$= 6[12 \times 500000]$$
$$= R36000000 \text{ i.e. R36 million}$$

where:

A = Estimated cost as a result of time delayed;

B = Total time delayed (days)

C = Number of coal trains per day

D = Gross income per coal train

Although knuckles are relatively cheap and easy to replace, the cost due to the time delayed is worth notice.

6 TRAIN HANDLING

6.1 Introduction

When trains encompass more than 100 heavy vehicles equipped with ARR-type couplers and roller journal bearings, speed differentials between the various parts of the train become an important consideration. These speed differentials caused by variations in track gradients, curvature, throttle and braking conditions, in turn cause slack changes. Slack changes cannot be prevented but can be controlled. Uncontrolled slack action can cause damage ,train parting and in extreme cases, derailment and hence must be avoided. The concept of controlling slack involves allowing time for unavoidable slack changes to occur slowly - the art of good train handling.

The basis for good train handling requires that :

- the throttle of brake is advanced one notch at a time;
- motoring and electric braking do not occur simultaneously i.e. when motoring, the dynamic brake must be off and where braking, traction must be off;
- in the initial starting mode, the throttle is at as low a setting as possible. This allows slack to stretch out slowly and minimises the total tractive effort exerted;
- since heavy head-end braking causes high compression forces behind the locomotives which can cause derailment when negotiating sharp curves, it must be avoided;
- power changes are not made unnecessarily since they cause surges down the length of the train.

Slack changes are inevitable whenever a train passes over reverse grade changes, i.e. level to up, level to down, up to level, down to level, down to up and up to down. The most practicable method of avoiding harsh slack action is to keep the locomotive speed as constant as possible, only with a minimum variation. Further, having a minimum train brake application in effect should lessen the harsh slack action. This ensures an acceptable force spectrum so that the fatigue life of the components of the system is not severely reduced.

Variables Affecting Train Handling

(1) Weather - cold, hot, rain, dry, calm or wind etc.

(2) Adhesion between the locomotive and rail as influenced by condition of the rail and track conditions.

(3) Speed, train length, tonnage, starts and stops.

(4) Character and make-up of the train.

(5) Effectiveness of train brakes.

(6) Normal slack between vehicles in the train consist.

(7) Grade - level, ascending, descending, undulating or a combination thereof.

6.2 Optimisation

The algorithm for train handling on straight tangent track and ascending grade is presented in Appendix 9.3. The simulations thus far have been based on the assumption that steady state conditions have been reached and the investigations are based on the steady state or maximum recommended speed.

In this case, the train starts with a certain initial velocity, 36 km/h for straight track and 54 km/h for ascending grade under the assumption that momentum is carried from the previous grade. The results are presented in Figures 6.1 to 6.4 where the drawbar pull and velocity profile are monitored. Only the train configuration with 4 head-end locomotives of the same class was investigated.

In the first set of results, the train accelerates uniformly to the maximum speed of 60 km/h and then maintains that speed.

In the second set of results, the train decelerates due to lack of power and momentum because of the degree of the grade.

The case of automatic train handling is a complex one and this chapter only serves as an introduction to the traction duty cycle. Only three cases have been considered independently, namely :

(1) tangent track;

(2) ascending grade;

(3) descending grade.

Figure 6.1
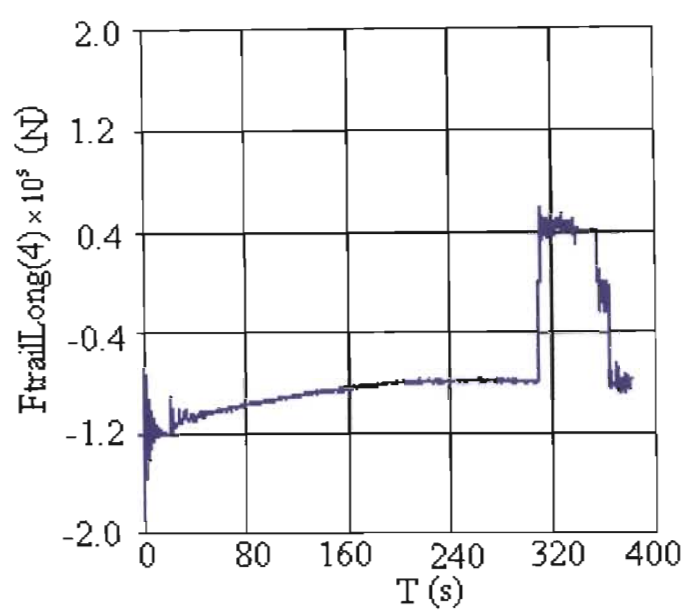
Figure 6.2
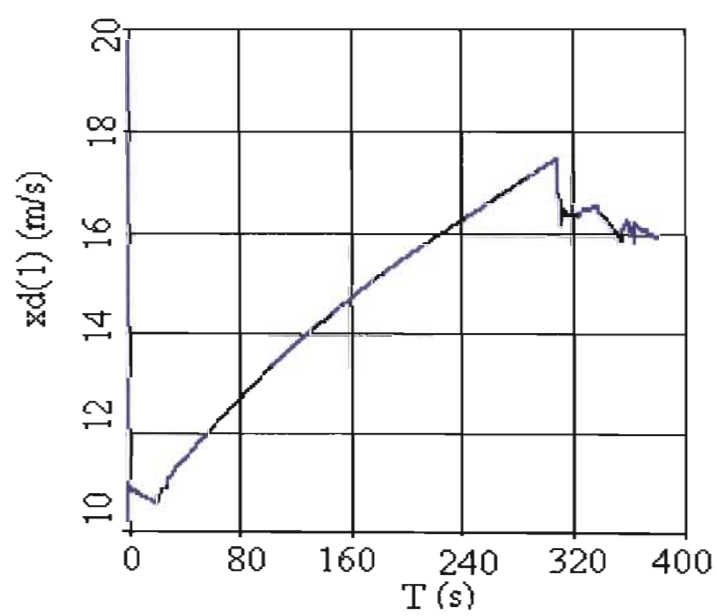
Figure 6.3
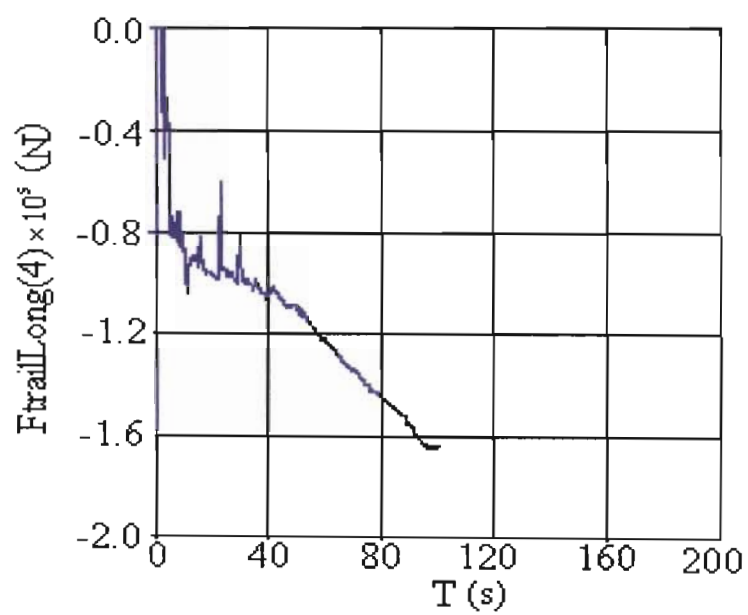
Figure 6.4
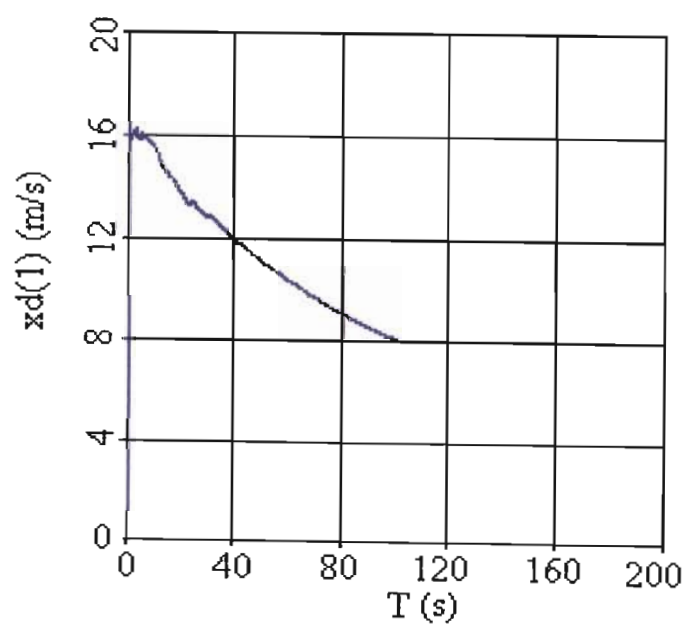
In the case of descending grade, several parameters are introduced and these are :

(1) balancing the grade;

(2) effecting the braking routine.

Appendix 9.3 defines the concept of balancing the grade. The speed that is set to be maintained is the balancing speed for that gradient as defined by the gradient and rolling resistance.

In order to effect the air brake routine, a macro defining the air brake required for each grade is introduced and presented below.

```
Macro BrakeLimit(v,GGrad,vd)
If((GGrad.GE.-33.0).AND.(GGrad.LT.0.0))then
Brake_Reduction=16
else if ((GGrad.LT.-33.0).AND.(GGrad.GE.-40.0))then
Brake_Reduction=14
else if ((GGrad.LT.-40.0).AND.(GGrad.GE.-50.0))then
Brake_Reduction=12
else if ((GGrad.LT.-50.0).AND.(GGrad.GE.-66.0))then
Brake_Reduction=10
else if ((GGrad.LT.-66.0).AND.(GGrad.GE.-100.0))then
Brake_Reduction=7
Endif
Macro End
```

The Macro above directs the program to the subroutine that calculates the braking force since different brake pipe reductions have different characteristic curves and behaviour. The program code will only effect dynamic braking if there is insufficient air brake i.e. the air brake is the primary braking mode.

7. TRAIN PERFORMANCE PROGRAM

At each point in the simulation, the total resistance to motion, motoring effect and couplers is calculated. This takes into account the gradient and the fact that the load is spread over the length of the train and may be on more than one gradient at any one time. This is also the case with curvature. The available tractive effort at any particular train speed is then obtained from the locomotive characteristic. The difference between the available tractive effort and the resistance to motion determines whether the train is to accelerate if the speed is below the ruling speed restriction, or decelerate due to lack of power. Newton's Second Law of motion is applied to establish the train speed at the next point in the simulation.

The new speed is used to calculate the power demand from the overhead line. At this point, the program returns to calculate the resistance to motion at the next point in the run and in this way, the train performance is calculated at finite intervals from start to finish. If the train resistance to motion is negative, indicating that the train is on a downgrade, then a braking routine is used to effect a smooth change of speed to the speed restriction for the grade.

7.1 Program Control

The execution of the program is controlled from a master menu window which directs the user to the main functional components and controls of the model (see [3] and[4]). Figure 7.1 shows the custom controls which the user clicks on to either enter user details, facilitate input, execute run, review output for further processing and terminate operation. Data entry requires the user to enter only those data values that are unique to the particular simulation.All the program control was developed using the Visual Basic Macros presented in the Appendices.

Figure 7.1 : Master Menu

7.2 Input Data

7.2.1 Reference Details

The required data is entered through a menu driven dialogue box and the data is organised as follows :

⇒ Reference Details : Title, Requester, Date, Aim (of simulation), Operator.

7.2.2 Input Detail

The program input option buttons allow the user to define train consists from various vehicles stored in standard libraries specific for locomotives and wagons, routes and simulation control variables. The data is organised in Excel worksheets building databases for various elements of the train being simulated. The input is saved and stored for future reference. These files must be converted to text files to be read by ACSL using FORTRAN commands during the simulation.

The data is organised as follows :

⇒ Wagons : Name, Type, Length, Width, Weight, parameters for braking, brake pipe

diameter and reaction times, number of axles, parameters for train resistance. The parameters for train resistance are assumed constant for all vehicle types and are thus represented as constants in the simulation. Table 7.1 shows a typical vehicle data input field where the 'type' column is read as vehicle class and the 'vehicle' column represents the type of vehicle. The 'position' column is used for indexing, "i".

Type	Vehicle	Position	Number	Length(m)	Weight(N)	Total Weight(N)	Axles
11E	Loco	1	1	19.2	174000	174000	6
	Loco	2	1	19.2	174000	174000	6
11E	Loco	3	1	19.2	174000	174000	6
	Loco	4	1	19.2	174000	174000	6
CCL-9	Wagon	5	1	12.07	84000	104000	4
	Wagon	6	1	12.07	84000	104000	4
	Wagon	7	1	12.07	84000	104000	4
	Wagon	8	1	12.07	84000	104000	4
	Wagon	9	1	12.07	84000	104000	4
	Wagon	10	1	12.07	84000	104000	4
	Wagon	11	1	12.07	84000	104000	4
	Wagon	12	1	12.07	84000	104000	4
	Wagon	13	1	12.07	84000	104000	4
	Wagon	14	1	12.07	84000	104000	4
	Wagon	15	1	12.07	84000	104000	4
	Wagon	16	1	12.07	84000	104000	4
	Wagon	17	1	12.07	84000	104000	4
	Wagon	18	1	12.07	84000	104000	4
	Wagon	19	1	12.07	84000	104000	4
	Wagon	20	1	12.07	84000	104000	4
	Wagon	21	1	12.07	84000	104000	4
	Wagon	22	1	12.07	84000	104000	4

Table 7.1 Wagon Detail

Figure 7.2 : Locomotive Data Menu

⇒ Locomotives. In addition to the data listed for wagons, the locomotive data
includes the following variables, as shown in Figure 7.2 and Tables
7.2 and 7.3 :

1. Tractive Effort Data. Tractive effort characteristics as look up tables for various notch positions (1 to 14) at various speeds (1 to maximum locomotive speed in increments of 1 km/h). Only a selection of the data is shown.

2. Motor Data - motor characteristics showing armature current as a notch versus speed matrix. Motor data is used to predict the temperature rise on the motors as a result of dynamic braking or motoring.

3. Dynamic Brake Effort Data. Dynamic brake data appears similar to tractive effort data except for the difference in the available notch range.

Table 7.2 : Tractive Effort Data

speed	notch1	notch2	notch3	notch4	notch5	notch6	notch7
0	40	83	124	165	208	248	290
1	38.8024	81.4985	122.8	163.56	206.3908	246.4	288.2862
1.67	38.00001	80.4925	121.996	162.5952	205.3126	245.328	287.138
2	34.61834	79.997	121.6	162.12	204.7816	244.8	286.5724
3	22.50503	78.4955	120.4	160.68	203.1724	243.2	284.8586
3.33	20.14383	78.00001	120.004	160.2048	202.6414	242.672	284.293
4	16.57991	69.4036	119.2	159.24	201.5632	241.6	283.1448
5	13.0814	56.61509	118	157.8	199.954	240	281.431
6	10.77844	47.93619	98.77988	156.36	198.3448	238.4	279.7172
6.25	10.3211	46.18303	94.8918	156	197.9425	238	279.2888
7	9.150641	41.64484	84.88148	144.8693	196.7356	236.8	278.0034

Speed	notch1	notch2	notch3	notch4	notch5	notch6	notch7
0	5.6727	7.8182	6.4167	6.2143	4.7619	2.4	15.2
1	6.24	9.5534	9.5798	10.7214	10.9048	10.6	24.48
2	6.8073	11.2886	12.7429	15.2285	17.0477	18.8	33.76
3	7.3746	13.0238	15.906	19.7356	23.1906	27	43.04
4	7.9419	14.759	19.0691	24.2427	29.3335	35.2	52.32
5	8.5092	16.4942	22.2322	28.7498	35.4764	43.4	61.6
6	9.0765	18.2294	25.3953	33.2569	41.6193	51.6	70.88
7	9.6438	19.9646	28.5584	37.764	47.7622	59.8	80.16
8	10.2111	21.6998	31.7215	42.2711	53.9051	68	89.44
9	10.7784	23.435	34.8846	46.7782	60.048	76.2	98.72
10	11.3457	25.1702	38.0477	51.2853	66.1909	84.4	108

Table 7.3 : Dynamic Brake Effort Data

⇒ Coupler Data : Name, Type, Pre-load force, Maximum force, Draw-gear characteristics, Maximum travel, Free slack.

Fp	Fm	a	k or b	xm	xs
220	2300	2.5	5000000	0.035	0.05
100	2270	1.5	2000000	0.075	0.05
220	2500	1.1	5.5	0.0145	0.025

Table 7.4 : Coupler Data

⇒ Consist Data : As applicable to the program, a consist may include up to 400 wagons and 12 locomotives in any combination of positions. The consist file is a standalone record defining the train to be simulated. Each record includes the position of each vehicle on the consist and entire data record of the referenced vehicle. See Table 7.1 with wagon/vehicle data.

⇒ Track Data : The track data defines the grade and degree of curvature at each section of the track. Plans exist to include information on special situations such as signal positions, signal spacing and speed restrictions. Track irregularities and their effects are ignored.

Table 7.5 : Track Data

Distance (m)	Grade
-1.20E+04	6.60E+01
-1.00E+02	-6.60E+01
1.00E-02	-1.00E+02
1.00E+03	-1.00E+02
1.10E+03	2.50E+02
1.40E+03	2.50E+02
1.45E+03	-1.00E+02
1.80E+03	-1.00E+02
1.85E+03	-6.60E+01
2.00E+03	-6.60E+01
2.05E+03	6.60E+01
3.00E+03	6.60E+01

The degree of curvature is not shown on the track data table since it was not used in the simulations since only the response on straight track was investigated.

⇒ Driver Command Data : The driving mode of each locomotive is controlled by the

commands on the leading locomotive. In the case of braking, the trailing locomotives brake actively with a delay for the start time of the braking mode specified. Manual train handling data is edited and stored in this file that serves as an alternative to the automatic train handling algorithm incorporated in ACSL. For each position on the track, the particular notch setting (either for dynamic brake or traction) is read for use in the locomotive characteristics.

Table 7.6 : Train Handling Data

Distance (m)	Notch
-2.97E+00	39
-2.24E+00	40
-1.32E+00	40
-1.22E+00	40
-7.90E-01	39
-7.15E-01	39
-6.90E-01	38
-6.15E-01	38
-5.90E-01	37
-5.40E-01	37
-4.90E-01	36

⇒ Braking System : This file contains part of operating data related to the air brake, namely the brake pipe reduction to be used in the braking routine. In the case of the simulations run, the brake is either off (0) or there is a minimum service reduction (1).

Table 7.7 : Brake Data

Distance (m)	Brake Status
4.14E+00	0
1.46E+01	1
2.01E+01	0
5.71E+01	1
7.80E+01	0
8.21E+01	1
8.72E+01	0
9.66E+01	1

7.3 Output Records

The required output from the simulation is stored in a data file on ACSL and exported in tabular form to Excel. The user then has the ability to generate graphical output desired other than the set output fields of cumulative energy consumption, running time, train speed and acceleration, displacement, train handling parameters, maximum coupler force and its position.

8. CONCLUSIONS

8.1 Operation Improvements and Efficiency

Spoornet's recent past has been characterised by the need to meet the challenges placed on the business by its markets, customers, competition, and shareholders. The business, however, operates on limited capital rendering the process of re-engineering existing assets in order to obtain cost and productivity improvements, more feasible. This search for productivity improvements and cost reduction inevitably led to the interest of applying alternative train configurations viz. mixed consist and distributed power technology, to the coal train operation. Chapter 1 is dedicated to the discussion of the parameters that seek to address the improvement of current railway operations.

Labour and power cost escalations necessitate the operation of longer and heavier trains more efficiently without replacing available rolling stock.

8.1.1. Recommendations
- From a business management point of view, what is required is a market-oriented rail freight service with improved efficiency and effectiveness required to remain economically viable. The marketing of the services should be seen in a more comprehensive context than merely "selling" of the services as per Section 1.3.1.

8.2 Longitudinal Train Dynamics

The longitudinal train dynamics simulation model presented describes the behaviour of a train as a system of semi-rigidly coupled rakes of slackless wagons, with semi-rigidly coupled locomotives. A global idea of how the resultant in-train forces influence the lateral response of wagons in a long train as well as derailment potential is illustrated (Figure 2.8).

8.2.1 Recommendations

From the static system response, the following conclusion was drawn:

- It is not advisable to run trains at low speeds around sharp curves since low speed operation promotes high tractive forces and hence wheel unloading with an increased risk of derailment.

8.3 Solution Techniques

The dynamic model of a train can be solved by analytical techniques but the because of the system complexity, such calculations are time consuming, expensive and prone to error. It is mandatory to use the direct differential equation formulation approach with solutions obtained by means of software packages for digital computers. Chapter 3 discusses these solution techniques in detail and lists possible software packages. The simulation tool has been made user-friendly by interfacing ACSL with Microsoft Excel where inputs are facilitated and outputs generated in sequence by clicking on custom controls as discussed in Chapter 7.

8.4 Management of Train Operations

An essential element of railroad heavy haul asset management is the use of computer models for operations planning. This thesis presented, in Chapter 5, the development of a one-dimensional system model for dynamic train performance studies that would serve as an invaluable tool for heavy haul asset management to Spoornet. Applications include optimisation of train make-up and train-handling, schedule and capacity planning, vehicle evaluation and maximising the productivity of each train configuration. It will now be possible to run various tests in a very short time and reduced cost without any risk regarding staff, infrastructure and rolling stock. Substantial improvements in the railway's efficiency appear possible by improved train handling techniques.

8.4.1 Recommendations

From the system dynamic response, the following conclusions were drawn :-

- The concept of introducing remote locomotives in the middle of a train consist is favoured from the force spectrum perspective, implying reduced fatigue damage and hence improved overall vehicle life cycle expectancies. From the energy consumption point of view, remote operation is favoured especially when one considers the price of electricity and Eskom tariffs. Furthermore, current loading and dumping operations favour this position of in-train locomotives. However, as train configurations change, problems related to train handling are also introduced. The use of remote locomotives can introduce further improvements when coupled to ECP (electronic controlled pneumatic) technology as applicable to brake systems for both the railway operator, Spoornet , and its customers through improved safety, shorter stopping distances, improved train handling, fewer derailments, reduced slack action, fewer break-in-twos, reduced lading damage, reduced maintenance due to fewer wheel replacements, reduced break shoe wear, reduced draft component replacement, reduced train delays, better train braking, reduced dynamic braking, and improved equipment utilisation.

- It is possible to work different class locomotives in one locomotive consist when electrical interfacing limitations are ignored and this has positive implications in terms of improving availability figures. This means that normal operations could proceed even if less than 100% availability of any one given class of locomotives is met without any damage being incurred by the system.

- In-train forces are to a large extent affected by the driving strategy and so are the energy consumption and running time figures. This introduces a need for an optimum train handling algorithm. Driving strategy should vary with train configuration under the constraint of traction duty cycle.

- An introduction to the automatic train handling algorithm was presented but an artificial intelligence model is required to represent a recommendable real-life strategy.

9. FURTHER WORK

The above recommendations and conclusions suggest that further research is required with focus on the following subjects :-

• With the introduction of new train configurations, various other parameters could be investigated e.g. increased train length. It is standard practice to operate trains with 200 wagons on the Coal Line but with remote locomotives, train lengths could be increased to prevent line congestion as envisaged with capacity increases. A further constraint of air brake system response could be coupled with that of in-train force response. Another alternative would be developing a model with an ECP brake system and quantifying the merits of such an operation.

• An optimum train handling strategy with course artificial intelligence is required to represent the optimum operation of the train. It would be interesting to model a train with the trailing locomotives operated actively i.e. each locomotive operated independently.

• The energy consumption algorithm presented in this thesis does not consider regeneration and hence variations in supply line receptivity. In order to obtain accurate figures of energy consumption, regeneration that occurs as power is fed back to the overhead line during dynamic braking would have to be considered. An electrical power system model is required.

• The means of monitoring heat damage on the motors by armature current could be improved by the direct calculation of temperature across the motors.

• In putting together different train configurations, there is a need to determine whether active or passive draw gear units would be required for the locomotive consists especially during the starting phase of the traction duty cycle. Also, an evaluation would have to be done on system components that would need to have modified designs e.g. draw gears.

The differences in the dynamic behaviour of the different class locomotives in one consist causes in-train shocks. An evaluation is required to ensure that safe and reliable conditions will be guaranteed.

- From a control system perspective, the dynamic effect resulting from wheel slip correction on the train system would also have to be investigated.

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11. APPENDICES

Contents

Labels on drawing:

No. 1 END / ENT

No. 2 END / ENT

19 200

11 940 CENTRES OF PANTOGRAPHS / HARTLYNE VAN PANTOGRAWE

4 200

3 962

1 700

890

2 850

MAX. PERMISSIBLE AXLE MASS LOAD MAKS. TOELAAT-BARE ASMASSA-BELASTING (FIRST 12 LOCOS. ONLY) (SLEGS EERSTE 12 LOKOS.)

29 000kg 29 000kg 29 000kg 29 000kg 29 000kg 29 000kg

2 200 2 200 2 200 2 200

400 10 760 400 635

3 820 PIVOT CENTRES, 11 560/SPILHARTAFSTAND 3 820

AND LIFTING BRACKETS/EN HYSSTEUNE

20 470 OVER COUPLERS / TUSSEN KOPPELAARS
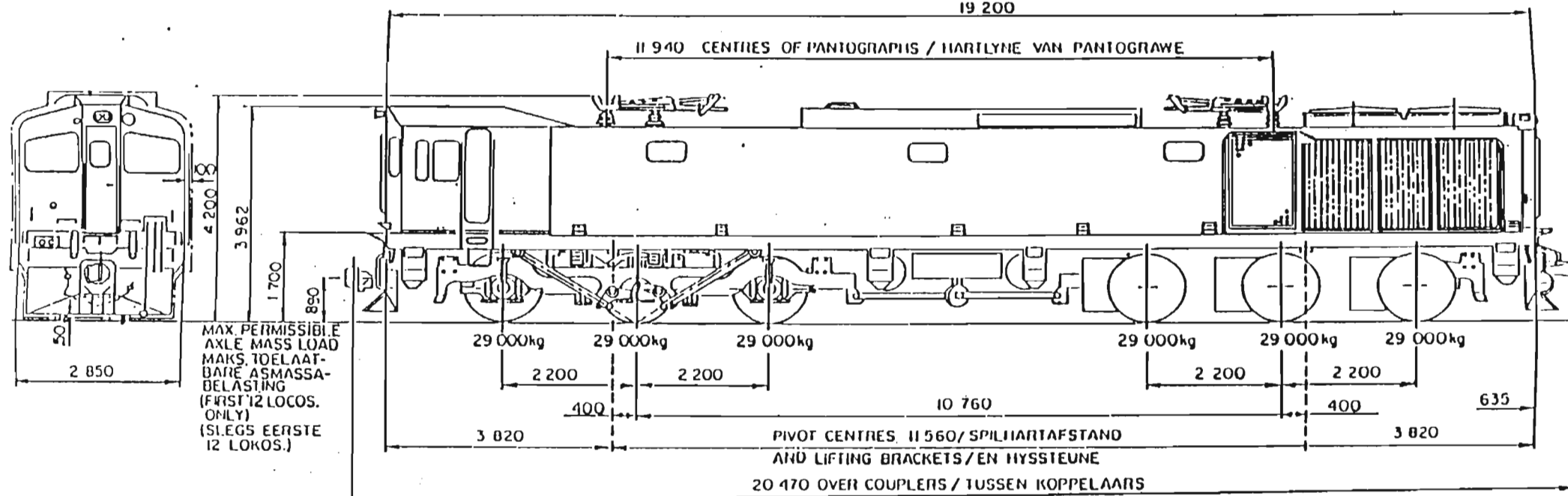
25kV AC ELECTRIC LOCOMOTIVE
25kV WS ELEKTRIESE LOKOMOTIEF

TOTAL MASS OF LOCOMOTIVE
TOTALE MASSA VAN LOKOMOTIEF E11001 – E11012 IS 172 200kg AND/EN E11013 — E11045 IS 168 000kg IN WORKING ORDER/IN WERKENDE TOESTAND

TRACTIVE FORCE TREKKRAG	STARTING AANSIT	ONE HOUR EEN UUR	CONTINUOUS DEURLOPEND	SERIES REEKS	LOCO LOKO Nos.	DATE IN SERVICE DATUM IN DIENS	MECH. DRG. Nos. MEG. TEK.	ELEC. DRG. Nos. ELEK. TEK.
	580kN	425kN	400kN	1	E11001 – E11045	1985–1987	T –20110–	T 22011

TRACTION MOTORS: TREKKRAGMOTORS: SIX - LJM 540 – 1								
MOTOR RATING, PER MOTOR: MOTORKENWAARDE PER MOTOR: ONE HOUR: EEN UUR: 690kW CONTINUOUS: DEURLOPEND: 650kW								
MOTOR-RATING TOTAL: MOTORKENWAARDE TOTAAL: ONE HOUR: EEN UUR: 4140kW CONTINUOUS: DEURLOPEND: 3900kW								
GEAR RATIO: RATVERHOUDING: 16/71								
DESIGNED MAX. SPEED: ONTWERPTE MAKS. SPOED: 90km/h								
WHEEL ARRANGEMENT: WIELSAMESTEL: Co – Co	WHEEL DIAMETER: WIELDIAMETER: 1 220							

Draagtoestel Equipment - Trekvoerkultrusting

KK Coupler Hydraulic Cushioning Device
Koppelaar Hidroliese Kussinginrigting

SSC Centre Sill Hydraulic Cushioning Device
Middelbalk Hidroliese Kussinginrigting

Brake System - Remotelsel

A Dual Power - Automatic
  Twookrag - Outomaties

R Slack Adjuster
  Reeverateller

D Dual Power - Manually Operated
  Twookrag - Handbediening

Y Vacuum
  Vakuum

L Air
  Lug

3493

1830   1830
488   1392   8310   1392
OVER PUSHER PADS
11094 OOR DRUKKUSSINGS

976 BETWEEN PUSHER PADS
    TUSSEN DRUKKUSSINGS

OUTSIDE BUITE 3000
INSIDE BINNE 2800

INSIDE
10946 BINNE
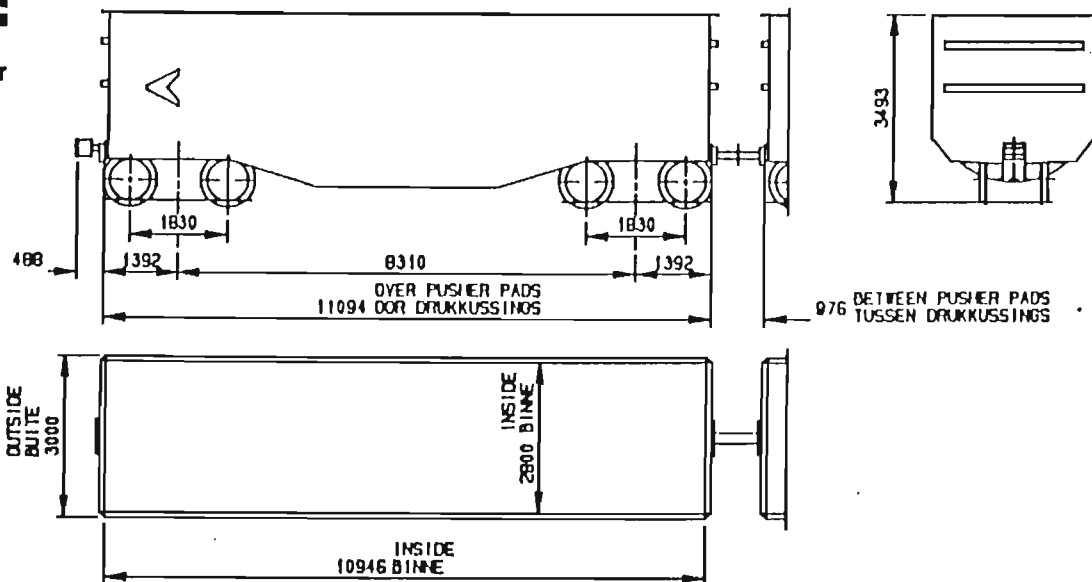
ARROW INDICATES ROTARY COUPLER/DRAWBAR END. OPPOSITE END FITTED WITH NON-ROTARY COUPLER/DRAWBAR
PYL DUI DRAAIKOPPELAAR/-TREKSTANG ENT AAN. TEENOORGESTELDE KANT PEPAS MET NIE-DRAAIENDE KOPPELAAR/-TREKSTANG
FITTED WITH "HOLDING BRAKE"

Remarks
Opmerkings 1- GEPAS MET "VASHOUREM"

SET OF 6 WAGONS WITH SEMI-PERMANENT DRAWBAR
STEL VAN 6 TROKKE MET HALFPERMANENTE TREKSTANG

*1 4.5:1 BRAKE RATIO Ø 915 WHEEL
         REMVERHOUDING   WIEL

*2 LOADED 841 LEVEL WITH TOP : 1 824mm
    841 GELYK GELAAI TOT BO : 1 824mm

*3 TOP 76.2mm³ BATH 9.46mm³
    BO   BAD

*4 PER WAGON
    PER TROK

Converted from Omskep van	Date Datum

				Centre of Gravity (Empty) Swaartepunt (Leeg)	933 *2	Tare (Average) Tarre (Gemiddeld) kg	20820 *4
Drawing Number Tekeningnommer	W001/D030					Load Vrag	84000 *4
Bogie Type Draaistelltpe	HS Mk V *1					Load (Coal) Vrag (Steenkool) kg	84000 *4
Bearing Size Laergroette	F					Floor Area Vloeroppervlakte m²	
Springs per Bogie Outer / Inner Vere per Draaistel Bulte / Binne	12/8					Capacity Inhoudsvermoe m³	85.66 *3
Brake System Remstelsel	L/R			Design Limit - Mass on Rail Ontwerplimiet - Massa op Spoor kg	104000 PER WAGON PER TROK		
Brake Cylinders Remsillinders	(V)	(L) 2/7x12		Originally designed for Oorspronklik ontwerp vir	COAL STEENKOOL		
Train Pipe / Treinpyp Brake Pipe / Rempyp	(V)	(L) 32		Converted for Omskep vir			
Brake Percentage Empty / Loaded Rempersentasie Leeg / Met Vrag	(V)	(L) 68.5 / 13.3		Revision Hersiening			
Drawgear Equipment Trekvoerkultrusting	AAR W901 E			Date Datum			
Coupler / Yoke Koppelaar / Juk	F/F						

CCL-9

11 E Tractive Effort

Appendix 11.1.4

11 E Dynamic Brake Effort
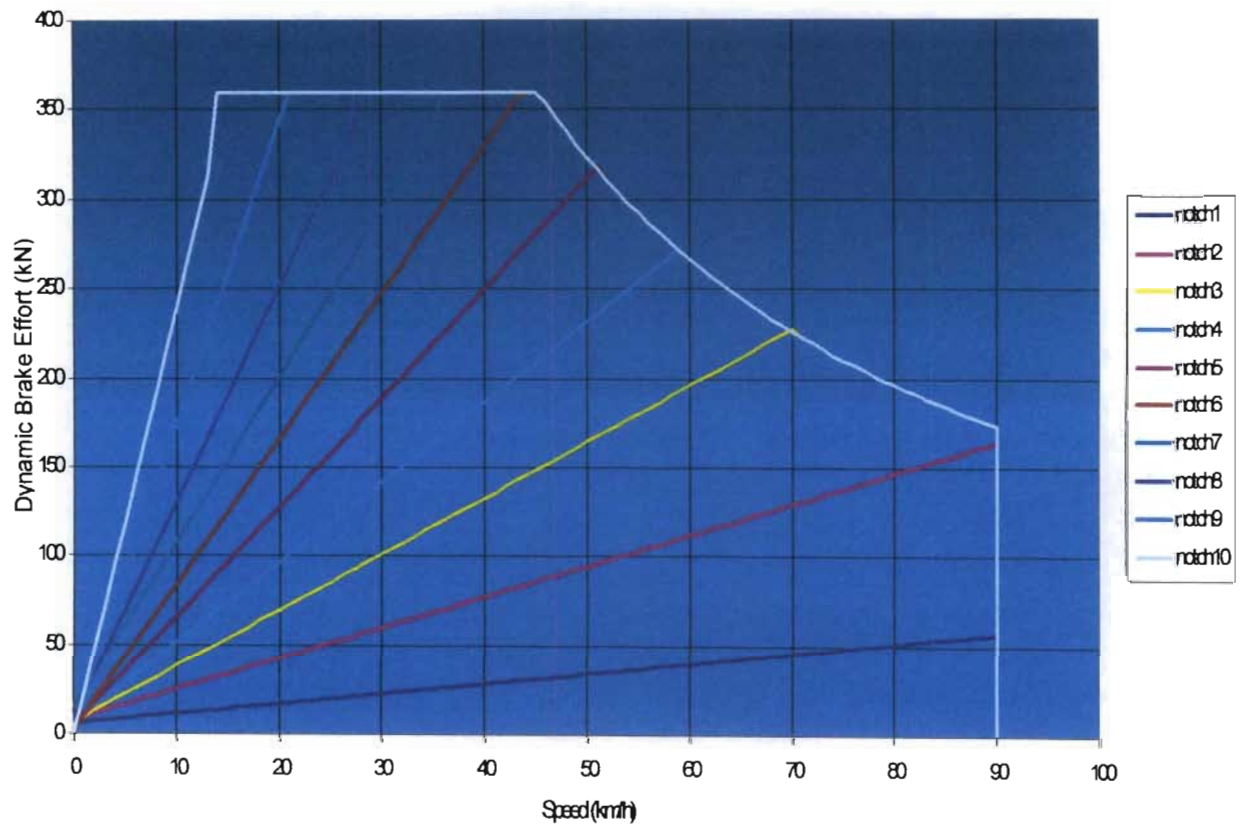
11E Armature Current
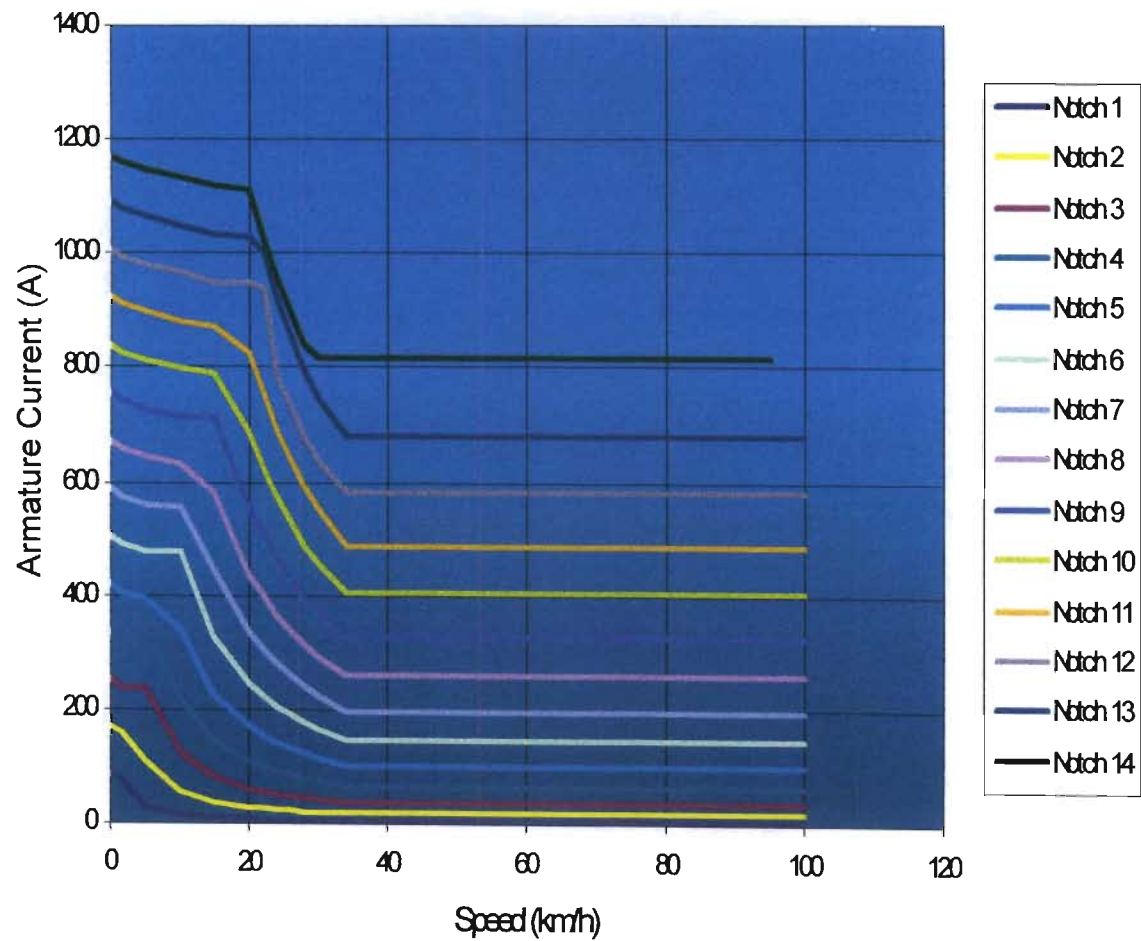
7 E Tractive Effort
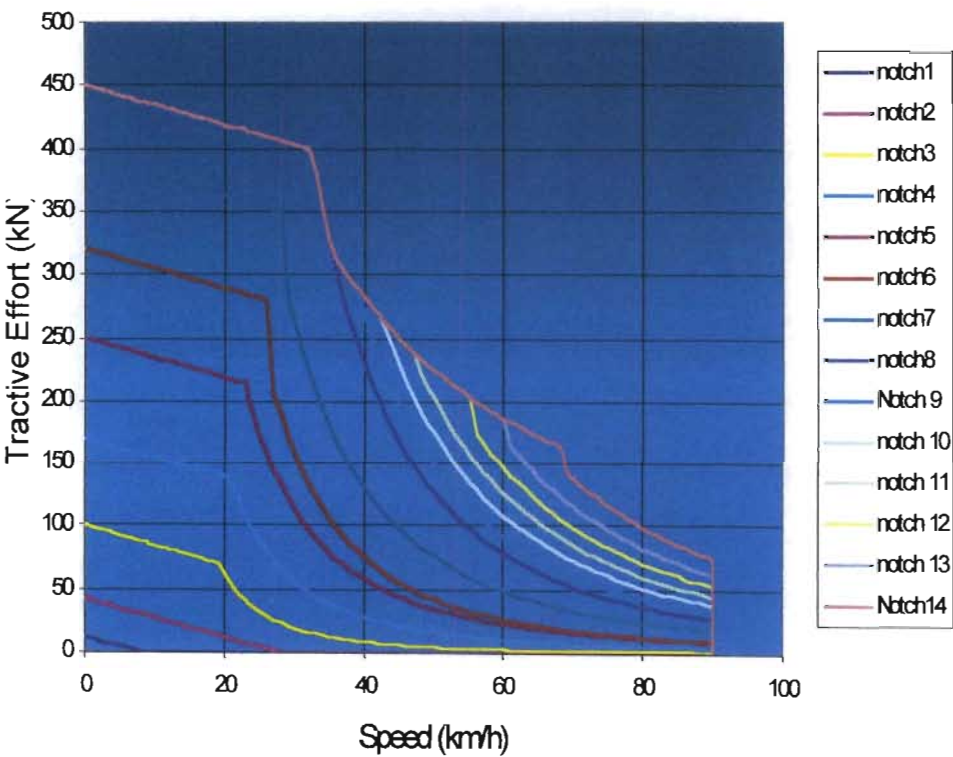
7 E Dynamic Brake
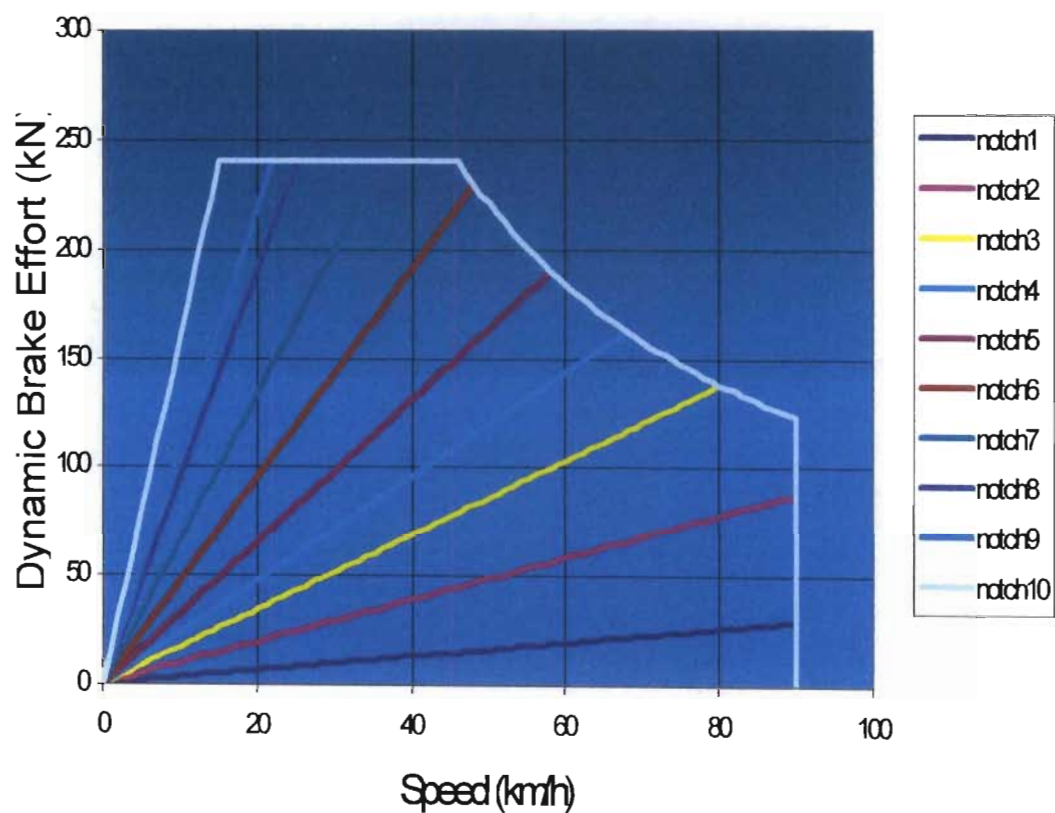
Appendix 11.1.8

7 E Armature Current
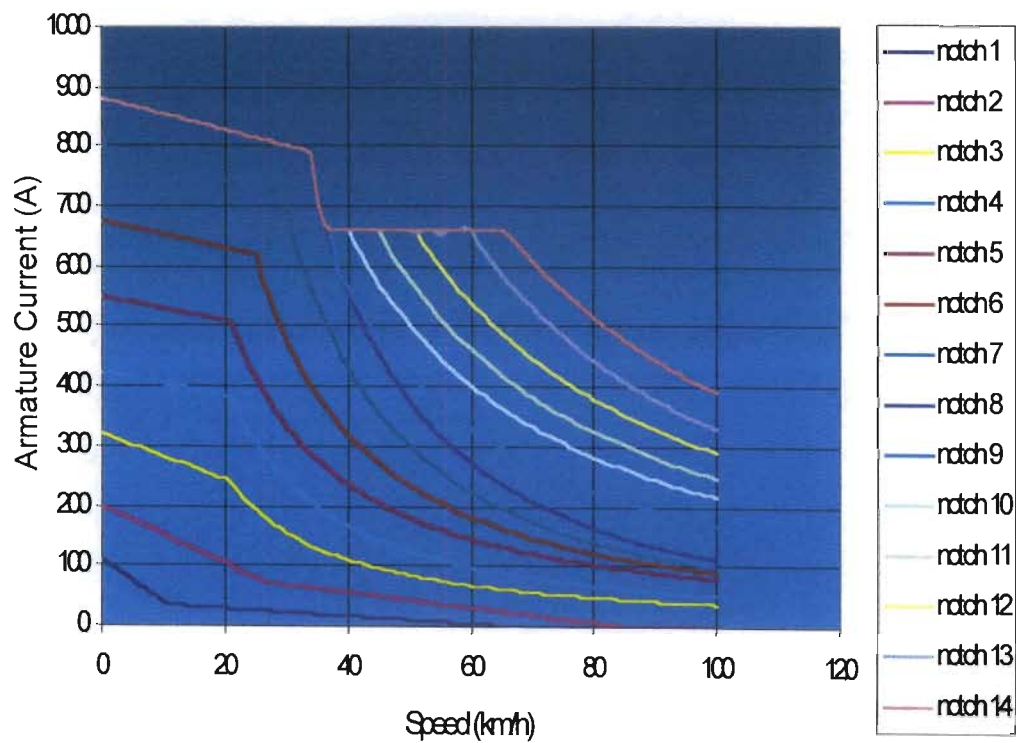
Appendix 11.2

PROGRAM complete

```
!.. program for nl locos in front (default=4)
!.. and nw wagons (default=200)
!...............................
!... Definition of the constants  ..
!...............................


dv = 0.1*vfin
!......................................................
!.. Constants used for the testing phase of the program
!......................................................


!.....for x
integer lastlocox
double precision xsref,Lref

!....... definition of pi :

 CONSTANT pi=3.14159265359d0

!.. Gravity

 CONSTANT g=9.805d0     ! gravity (m.s^-2)


!.............................................
!.. Characteristics of the different types of Draw gears :
!.............................................

integer cc3,Fpb1,Fmb1
 double precision Fpb,Fmb,ab,xmb,xsb,bb
open(19,file='trial3.txt',access = 'direct', recl=29,&
        form = 'formatted')

cc3=1
Read(19,1930,rec=cc3)Fpb1,Fmb1,ab,bb,xmb,xsb
Fpb=Fpb1*1000
Fmb=Fmb1*1000
1930..format(i3,1x,i4,1x,f3.1,1x,f3.1,1x,f6.5,1x,f5.4)

! xsb is half of the total free slack in the slackless connection

integer cc2,Fpg1,Fmg1,kg
 double precision Fpg,Fmg,ag,xmg,xsg
open(18,file='trial2.txt',access = 'direct', recl=31,&
        form = 'formatted')
    cc2=1
Read(18,1935,rec=cc1)Fpg1,Fmg1,ag,kg,xmg,xsg
Fpg=Fpg1*1000
Fmg=Fmg1*1000
```

1935..format(i3,1x,i4,1x,f3.1,1x,i7,1x,f5.3,1x,f4.2)

! xsg is half of the total free slack in the miner SL76 connection


```
 integer cc1,Fpl1,Fml1,kloco
 double precision Fpl,Fml,al,xml,xsl
open(60,file='trial.txt',access = 'direct', recl=31,&
        form = 'formatted')
     cc1=1
Read(60,1940,rec=cc1)Fpl1,Fml1,al,kloco,xml,xsl
Fpl=Fpl1*1000
Fml=Fml1*1000
1940..format(i3,1x,i4,1x,f3.1,1x,i7,1x,f5.3,1x,f4.2)
```


! xsl is half of the total free slack in the loco draw gear connection
! because of the lack of information , one assumed the same value of
! the length of the draw gear bar and total free slack than this of the
! Miner SL76


```
 CONSTANT  slope=5.d+8,xhi=0.5d0,  &! phase 2 of the draw gear
        slope5=1.d+8

 CONSTANT ks = 40000000,Lcb=1.508, & ! jack-knifing parameters
        bc=4.155,pc=5.547
!.......................................................
!.. Position from where the simulation will be started
!.......................................................

CONSTANT xdebut=0.d0

CONSTANT xstp=2999.d0
!...........................................................
!.. Characteristics of the loco, wagon and train configuration :
!...........................................................
```


! dd is the distance between the bolster and the pin point
! of the draw gear

! The values above are given values of total free slack of 50mm
! in a slackless connection,
! and 100mm of total free slack in a draw gear connection

! dgb reference is the length of the draw bar for the slackless
! connection, for the wagon connection and for the loco connection.

```
 CONSTANT  mrake=4     & ! rake size


!.......................................
!.. Characteristics of the simulation :
!.......................................
```

```
      CONSTANT  tstp=10. ,  & ! time limit for the simulation
              xdini=0.d0    ! initial speed of the locos and wagons
   !....................................................
   !.. Used for the definition of the Rolling resistance :
   !...................................................

      CONSTANT  Frr0=6.38d0   ! Rolling resistance per tonne (N/tonne)
                        ! for 1 truck
      CONSTANT  RollCoeff=5.d0 ! used for the static rolling resistance


   !.................................................
   !.. Constants used for the air brake
   !.................................

   integer cc5
    double precision   tbst,tbst1,tbst2,tbst3,tb,tnext,Dia,sf
   open(17,file='brake.txt',access = 'direct', recl=38,&
           form = 'formatted')
        cc5=1
   Read(17,1915,rec=cc5)tbst,tbst1,tbst2,tbst3,tb,tnext,Dia,sf
   1915..format(f3.1,1x,f3.1,1x,f3.1,1x,f3.1,1x,f4.1,1x,f4.2,1x,&
           f6.5,1x,f4.1)


   !.........................
   !..Beginning of initial section..
   !...............................
   INITIAL
   integer nn
   Parameter(nn=205)


   !...............................................
   !.. File which opens the in-out files
   !.........................................

    character*5 vehicle(nn)
     character*3 type(nn)
      integer cc,masse1(nn),naxle(nn)
      double precision masse(nn),Length(nn),width(nn)

   Procedural
   Do cons1 i=1,nn
   open(15,file='consist5.txt', access = 'direct', recl=23,&
           form = 'formatted')
       cc=i
   Read(15,1950,rec=cc)vehicle(i),masse1(i),naxle(i),Length(i),&
               width(i)

   masse(i)=masse1(i)*1000
   1950..format(a5,1x,i3,1x,i1,1x,f6.4,1x,f4.2)

   cons1..continue
   End!..of procedural

   !........locomotive consist definition....
```

```
Procedural
Do cons5 i=1,nn

 If (vehicle(i).eq.'locom')then
   If(i.le.4)then
     type(i)='11E'
else
     type(i)='7E1'
   endif
   endif
cons5..continue
End!...of procedural


!................................................
!...Definition of Lengths used in relative motion....
!................................................
!Procedural
!Do relm1 i=1,nn
!Lloco(i)=bolster(i)+dd(i)+dd(i+1)+(dgbreference(i)+xsl)
!Llocowagon(i)=bolster(i)+dd(i)+dd(i+1)+(dgbreference(i)+xsl)
!Lg(i)=bolster(i)+dd(i)+dd(i+1)+(dgbreference(i)+xsg)
!Lb(i)=bolster(i)+dd(i)+dd(i+1)+(dgbreference(i)+xsb)


 Open(3,File='result2.dat')

!.. For the gradient :


open(55,file='xgrad5.txt', access = 'direct', recl=10, &
        form = 'formatted')

open(60,file='grad5.txt', access = 'direct', recl=9,  &
        form = 'formatted')


!......................................
!.. Definition of all variables types ..
!......................................

!.. Variables for the wagons themselves :

!Double Precision        L(nn),dd(nn),width(nn),length(nn),    &
               ! d1(nn),d2(nn)

Double precision J(nn),Flat(nn),Flat_bogie(nn)

Integer         m

Logical         Stand(nn)

Double precision        x(nn), x0(nn), xd(nn), xd0(nn),      &
               interxd(nn),xdd(nn),              &
               test(nn)
```

!.. Variables for the links between trucks :

```
Integer          etat(nn),flag(nn)
Double Precision     y(nn),yd(nn),                    &
                e(nn),em(nn),elim(nn),          &
                Fa(nn),Fb(nn),F(nn),F2(nn),     &
                Fp(nn),p(nn)


Double precision     eb,el,eg,     &      ! To calculate elim(i)
          c     ! damping coefficient for the etat=2
                ! of a draw gear


integer          testFS(nn)
```

!..
!.. External forces acting on the trucks :
!..

!.. For the draw gear Forces :

!.. Remarks : (with nn=204 and nl=3 or 4)
! - one will not use
!   * FTrailLong(nn) and FTrailLat(nn) if nl=4
!   * FTrailLong(nn-1) and FTrailLat(nn-1)
!   and FTrailLong(nn) and FTrailLat(nn) if nl=3
! - one will not use
!   * FLeadLong(1) and FLeadLong(1)if nl=4
!   * FLeadLong(1) and FLeadLong(1)
!   and FLeadLong(nn) and FLeadLong(nn) if nl=3


```
Double precision     FTrailLong(nn),Fmean(nn)

Double Precision  FLeadLong(nn),For(nn),Fmax(nn),Fmin(nn)
Double precision     Fmaxloco , Fmaxdraw , Fmaxbuff, &
             Fmaxloco2 , Fmaxdraw2 , Fmaxbuff2, &
                   Xloco,Xdraw,Xbuff
Integer   posloco, posdraw, posbuff, &
      posloco2, posdraw2, posbuff2
```

!.. For the gradient force :

```
Double Precision  Fgrad(nn),Grad(nn),xchange(nn)
Integer          count(nn),count1(nn)
```

!.. For the rolling resistance :

```
Double Precision Frr(nn), rollzerowagon
```

! Rollzerowagon is the dynamic rolling resistance for the speed equal to zero
! it will be calculated in the initial section
! the static rolling resistance will be (Rollcoeff * Rollzerowagon)

!.. for the air brake :

```
! Remark :
!   - one will not use Fbrk(1,2,3,4) if nl=4,
!             Fbrk(1,2,3) and Fbrk(nn) if nl=3


Double Precision   Fbrk(nn),Pr(nn),BrkCylF(nn)

!.. for the locos forces (tractive effort+dynamic brake)and energy consumption :

Integer        NotchtNew,NotchdNew,  &
            NotchtNow,NotchdNow,NotchtUp,NotchdUp,  &
            Notchtrac,Notchdyn,NotchtLo,NotchdLo

Double Precision   Floco(nn),NotchtNew1,NotchdNew1,  &
            NotchtUp1,NotchdUp1,  &
            Notchtrac1,Notchdyn1,NotchtLo1,NotchdLo1,  &
            Power(nn),Pec(nn),Ener(nn),Ener0(nn), &
            Energy(nn),Etot,Armature(nn),  &
            FtracNew1(nn),FtracNew(nn),FdynNew1(nn),&
            Fte(nn),Fdb(nn),FdynNew(nn),FtLow,FdLow,&
            FtUp,FdUp,Armcrit(nn)

Logical Tracon,Dynon,Tracdn,Dyndn

!..................................................
!.. file which initialise some variables in the INITIAL section ..
!..................................................
!..................................................
!.. Definition of all the macros used in the program : ..
!..................................................
Macro loading(ff,ee,eelim,ii)
  if (vehicle(i).eq.'locom') then
    FF=Fpl+(Fml-Fpl)*((1-exp(al*(ee-eelim)/xml))/(1-exp(al)))
  else if(vehicle(i).ne.'locom')then
    if (Mod(ii-lastlocox,m).eq.0) then
        FF=Fpg+(Fmg-Fpg)*((1-exp(ag*(ee-eelim)/xmg))/(1-exp(ag)))
    else
        FF=Fpb+(Fmb-Fpb)*((1-exp(ab*(ee-eelim)/xmb))/(1-exp(ab)))
    endif
  endif
Macro end

Macro unloading(ff,ee,eelim,ii)
  if (vehicle(i).eq.'locom') then
    FF=kloco*(ee-eelim)+Fpl
  else if(vehicle(i).ne.'locom')then
    if (Mod(ii-lastlocox,m).eq.0) then
        FF=kg*(ee-eelim)+Fpg
    else
        FF=Fpb+(Fmb-Fpb)*((1-exp(bb*(ee-eelim)/xmb))/(1-exp(bb)))
    endif
  endif
Macro end

!..................................
```

```
!.. Gradient force calculation
!...............................

! Fgrad is > 0 when the truck goes uphill

Macro Hill(FFgrad,GGrad,mass)
    FFgrad=sign(1.0,GGrad)*(mass*g/(sqrt(1+(GGrad**2))))
Macro end


!...............................
!.. Rolling resistance calculation :
!...............................

! The Rolling resistance calculated is always positive
! the minus sign will be handled in the definition of the acceleration

Constant coefftest=1.0
Macro RollResistance(FFrr,vel,mass,numaxle)
   FFrr=coefftest*((Frr0+0.137*vel)*mass/1000.  &
        +(129.3+0.028*vel**2)*numaxle)
Macro end
!...............................
!.. Air brake force calculation :
!...............................

Macro BrakeP(Pr,t)
        If (t.lt.tbst1) then
                Pr=0
        else if ((t.ge.tbst1) .AND. (t.lt.tbst2)) then
                Pr=2*t-2
        else if ((t.ge.tbst2) .AND. (t.lt.tbst3)) then
                Pr=0.33*t + 1.34
        else if ((t.ge.tbst3) .AND. (t.lt.tb)) then
          Pr=-21.4480 + (5.0655*t) - (0.2682*t**2) + (0.0048*t**3)
        else if (t.ge.tb) then
                Pr=-21.4480 + (5.0655*tb) - (0.2682*tb**2) + (0.0048*tb**3)
        endif
Macro end

!.............Speed Restriction..........

Macro Speedres(v,GGrad,vd)

If(GGrad.GE.(0.0))then
v=60/3.6
else if ((GGrad.GE.-50.0).AND.(GGrad.LT.0.0))then
  v=30/3.6
else if ((GGrad.LE.-51.0).AND.(GGrad.GE.-65.0))then
  v=40/3.6
else if ((GGrad.LE.-66.0).AND.(GGrad.GE.-80.0))then
  v=45/3.6
else if ((GGrad.LE.-81.0).AND.(GGrad.GE.-100.0))then
v=50/3.6
else if (GGrad.LT.-100.0)
v=60/3.6
```

```
Endif
Macro End

! number of loco and wagon (which must be defined as integers)

m=mrake


!...................................................
!.. Parameters for a loco or a wagon  :
!...................................................

! geometric parameters +masse
! + Inertia of a loco or a wagon in the middle of itself :
! (defined for a shorter listing of the program!)

Tracon=.false.
Tracdn=.false.
Dynon=.false.
Dyndn=.false.


!...................................................
!.. values to be initialised for the calculation   ..
!.. of the lateral force to work properly :         ..
!...................................................

Fmaxloco2 = 0.d0
Fmaxdraw2 = 0.d0
Fmaxbuff2 = 0.d0


!...................................................
!.. Initial values for variables relative to the link between wagons
!...................................................

eb=Fpb/slope5
eg=Fpg/slope5
el=Fpl/slope5

Procedural
  Do init330 i=1,nn
If(vehicle(i).eq.'locom'.AND.vehicle(i+1).eq.'wagon')then
   lastlocox=i
   endif
init330..continue
End!..of procedural


Procedural

  do INIT0 i=1,nn
   If(vehicle(i).eq.'locom')then
         Fp(i)=Fpl
        elim(i)=el
   else if(vehicle(i).eq.'wagon')then
     If(Mod(i-lastlocox,m).eq.0)then
      Fp(i)=Fpg
```

```
      elim(i)=eg
     else
       Fp(i)=Fpb
       elim(i)=eb
     endif
    endif
INIT0.. continue

End!.....of procedural

!.. Initial values of some coefficient useful for the draw gears

PROCEDURAL

Do INIT2 i=1,nn-1
     em(i)=0.
     etat(i)=0
     F(i)=0.
     Fa(i)=0.
     Fb(i)=0.
     p(i)=0.

INIT2.. continue

END !.. of PROCEDURAL

!.. Definition of the damping coefficients

!.. For the straight configuration :
Procedural
Do damp1 i=1,nn
If(vehicle(i).eq.'wagon')then
 c=xhi*sqrt(slope*masse(i))
endif
damp1..continue
End!...of procedural

  !.........................................................
  !.. definition of the initial position, speed of the wagons ..
  !.........................................................

Procedural
    x0(1)=xdebut
    xd0(1)=xdini
    x(1)=x0(1)
    xd(1)=xd0(1)
    Do  init3 i=2,nn

   If(vehicle(i).eq.'locom'.AND.vehicle(i-1).eq.'locom')then
      Lref=Lloco
   else if(vehicle(i).ne.vehicle(i-1))then
       Lref=Llocowagon
   elseif(vehicle(i).eq.'wagon'.AND.vehicle(i-1).eq.'wagon')then
      If(Mod(i-lastlocox-1,m).eq.0)then
      Lref=Lg
```

```
      else
        Lref=Lb
        endif
      endif
  x0(i)=x0(i-1)-Lref
  x(i)=x0(i)
  xd0(i)=xdini
  xd(i)=xd0(i)
init3.. Continue

End !...of procedural...


!...........................................
!.. definition of the initial configuration of the wagons :
!...........................................


!.. standing or moving :
! (useful for the calculation of the rolling resistance
!  during the starting phase)

Procedural

do init5 i=1,nn
  If(vehicle(i).eq.'locom')then
    stand(i)=.false.
    else
    stand(i)=.true.
  Endif
init5.. continue

end ! of procedural


!...........................................
!..Initialisation of some values
!.. for the equation of dynamics to be valid for each truck
!...........................................
! this part is important because the eq. of dynamics calculates
! every forces for every truck.
! => eg, the loco forces must be put to zero for the wagons !
! ( here, with 4 locos in front Floco(i=5 to 204)=0. )
! We put at zero all the values, the one which are not going to be calculated
! will stay equal to zero, and the calculus of xdd(i) will be ok.

Procedural

Do init100 i=1,nn

NotchtNew1=0
 NotchtNew=0
 Notchtrac1=0
 Notchtrac=0
 NotchtUp1=0
 NotchtUp=0
```

```
NotchtLo=0
NotchtLo1=0
NotchtNow=0
NotchdNew1=0
NotchdNew=0
Notchdyn1=0
Notchdyn=0
NotchdUp1=0
NotchdUp=0
NotchdLo=0
NotchdLo1=0
NotchdNow=0

Floco(i)=0.d0
 Ener0(i)=0.d0
Energy(i)=0.d0
Armature(i)=0.d0
Armcrit(i)=0.d0
FLeadLong(i)=0.d0
FTrailLong(i)=0.d0

Fmax(i)=0.d0
Fmean(i)=0.d0
Fmin(i)=0.d0
 init100.. continue

 Etot=0.d0

end ! of procedural

!...........................................
!.. Relative to the rolling resistance force :  ..
!...........................................

! Rollzerwagon is the dynamic rolling resistance for the speed equal to zero
! the static rolling resistance will be ( Rollcoeff * Rollzerowagon )
 Procedural
Do init20 i=1,nn
If(vehicle(i).eq.'wagon')then
 RollResistance(RollZeroWagon=0.d0,masse(i),naxle(i))
 else
 RollResistance(RollZeroWagon=vfin*3.6,masse(i),naxle(i))

Endif
init20..continue
End!...of procedural

!.................................
!.. Relative to the gradient force :  ..
!.................................

Procedural

Do init8 i=1,nn
```

```
count(i)=1
read(55, 99, rec=count(i)) xchange(i)
99.. format(d9.5)
xchange(i)=xchange(i)*1000.
count1(i)=1
read(60, 97, rec=count1(i)) Grad(i)
97.. format(d9.4)


init8..continue

end ! of procedural

END !.. OF INITIAL ..


!.................................
!.. Beginning of the dynamic section ..
!.................................


DYNAMIC

!.....define simulation environment

  CINTERVAL cint=0.01
  ALGORITHM ialg=4
  MAXTERVAL maxt=0.01
  NSTEPS   nstp=1

!.. Definition of the tables for the calculation of the tractive
!.. and the dynamic brake

!........tractive effort for 11E..........
Table Traction,2,15,10                          &
      /  0,1,2,3,4,5,6,7,8,9,10,11,12,13,14              &
      , 0, 10, 20, 30, 40, 50, 60, 70, 80 ,90             &
      , 0,40,80,125,164,210,245,290,330,370,415,458,495,540,580 &
      , 0,5,34,60,110,170,230,275,310,355,400,440,480,520,560   &
      , 0,0,10,30,55,90,125,170,210,280,330,420,460,510,545     &
      , 0,0,2,15,30,40,80,110,140,185,220,280,320,380,440       &
      , 0,0,0,8,20,35,60,80,105,135,170,208,245,290,335         &
      , 0,0,0,2,12,28,50,60,85,110,135,165,190,230,270          &
      , 0,0,0,2,8,20,40,40,70,94,110,139,160,192,220            &
      , 0,0,0,2,5,12,32,30,60,80,95,118,140,164,180             &
      , 0,0,0,2,3,12,30,28,52,68,84,100,120,140,130             &
      , 0,0,0,2,2,12,25,28,48,60,74,90,105,105,105/

Table ForctLow,1,15          &
/0,1,2,3,4,5,6,7,8,9,10,11,12,13,14   &
,0,0,0,2,2,12,25,28,48,60,74,90,105,105,105/

Table ForctUpper,1,15                       &
/0,1,2,3,4,5,6,7,8,9,10,11,12,13,14              &
,0,40,80,125,164,210,245,290,330,370,415,458,495,540,580/
```

```
!........dynamic brake effort for 11E..........

Table DynBrake,2,11,10                    &
  /0,   1,   2,   3, 4,   5, 6,   7,  8,  9, 10,    &
   0,  10,  20,  30,40,  50,60,  70, 80, 90,       &
   0,   0,   0,   0, 0,   0, 0,   0,  0,  0, 0,    &
   0,  12,  25,  42,54,  70,88, 112,137,180,240,   &
   0,  20,  45,  70,100, 130,166, 212,268,340,360,    &
   0,  25,  62, 104,142, 190,248, 320,3*360,          &
   0,  30,  82, 136,188, 250,330, 4*360,              &
   0,  35,  98, 165,236, 310,5*325,                 &
   0,  40, 114, 195, 7*270,                     &
   0,  45, 130, 225, 7*230,                     &
   0,  50, 143, 8*200,                          &
   0,  55, 160, 8*0/

Table ForcdLow,1,11          &
/0,1,2,3,4,5,6,7,8,9,10   &
,0,0,0,8*0/

Table ForcdUpper,1,11                        &
/0,1,2,3,4,5,6,7,8,9,10                  &
,0,55,160,225,270,320,360,360,360,360,360/


!........Table of armature current for 11E.........

Table Current,2,15,10                         &
        / 0,1,2,3,4,5,6,7,8,9,10,11,12,13,14      &
        , 0, 10, 20, 30, 40, 50, 60, 70, 80 ,90     &
        , 0,75,165,245,330,410,490,570,650,730,815,900,980,1065,1130 &
        , 0,10,65, 120,220,335,450,540,620,700,790,870,940,1030,1100   &
      , 0,0, 20, 55, 80, 160, 280,340,435,560,680,800,905,1000,1065 &
      , 0,0, 5, 25, 60, 105, 160,230,300,395,460,575,650,780,860  &
      , 0,0, 2, 20,  50, 90, 140, 200,260,330,400,500,580,680,795 &
      , 0,0, 2, 20,  50, 90, 140, 200,260,330,400,500,580,680,795 &
      , 0,0, 2, 20,  50, 90, 140, 200,260,330,400,500,580,680,795 &
      , 0,0, 2, 20,  50, 90, 140, 200,260,330,400,500,580,680,795 &
      , 0,0, 2, 20,  50, 90, 140, 200,260,330,400,500,580,680,795 &
      , 0,0, 2, 20,  50, 90, 140, 200,260,330,400,500,580,680,795/

!.. Definition of the tables for the calculation of the tractive
!.. and the dynamic brake

!........tractive effort for 7E..........
Table Traction_2,2,15,10                         &
        / 0,1,2,3,4,5,6,7,8,9,10,11,12,13,14               &
        , 0, 10, 20, 30, 40, 50, 60, 70, 80 ,90            &
        , 0,12,42,100,170,250,320,396,450,450,450,450,450,450,450 &
        , 0,0,28,84,154,234,305,380,430,430,430,430,430,430,430   &
        , 0,0,12,62,140,219,290,364,420,420,420,420,420,420,420    &
        , 0,0,0,22,62,116,180,300,406,406,406,406,406,406,406      &
        , 0,0,0,10,30,60,98,140,214,240,275,280,280,280,280        &
        , 0,0,0,2,15,32,54,86,120,140,185,210,230,230,230          &
```

```
        , 0,0,0,2,10,22,34,52,76,90,120,130,140,190,190        &
        , 0,0,0,2,10,22,24,36,52,75,90,95,100,140,160          &
        , 0,0,0,2,10,22,24,34,38,60,75,75,75,105,120           &
        , 0,0,0,2,10,22,24,20,20,45,40,50,50,80,90/

Table ForctLow_2,1,15          &
/0,1,2,3,4,5,6,7,8,9,10,11,12,13,14  &
,0,0,0,2,10,22,24,20,20,45,40,50,50,80,90/

Table ForctUpper_2,1,15                            &
/0,1,2,3,4,5,6,7,8,9,10,11,12,13,14                &
,0,12,42,100,170,250,320,396,450,450,450,450,450,450,450/


!........dynamic brake effort for 7E...........

Table DynBrake_2,2,11,10                    &
  /0,  1,  2,  3, 4,  5, 6,  7,  8,  9, 10,   &
  0, 10, 20,  30, 40,  50, 60,  70, 80, 90,        &
  0,  0,  0,  0, 0,  0, 0,  0,  0,  0,  0,   &
  0,  3, 10,  18, 24, 33, 48,  66, 84, 110, 160,   &
  0,  6, 20,  35, 48, 65, 95, 200, 165, 220, 240,    &
  0, 10, 30,  52, 72, 98,145, 240, 240,240,240,       &
  0, 13, 40,  70, 95, 132,191, 220,240, 240,240,      &
  0, 16, 48,  87,120, 165, 220,185,220,220,220,       &
  0, 20, 58, 103,143, 185,185,185, 185,185,185,        &
  0, 23, 68, 120, 7*158,                      &
  0, 25, 78, 8*138,                    &
  0, 29, 88, 8*0/

Table ForcdLow_2,1,11          &
/0,1,2,3,4,5,6,7,8,9,10   &
,0,0,0,8*0/

Table ForcdUpper_2,1,11                    &
/0,1,2,3,4,5,6,7,8,9,10                  &
,0,29,88,138,158,185,220,240,240,240,240/


!........Table of armature current for 7E.........

Table Current_2,2,15,10                          &
        / 0,1,2,3,4,5,6,7,8,9,10,11,12,13,14        &
        , 0, 10, 20, 30, 40, 50, 60, 70, 80 ,90      &
        , 0,113,200,328,438,555,678,794,7*885        &
        , 0,38,170, 294,406,535,655,768,7*857        &
      , 0,28, 113, 245, 388, 510,633,743,7*829      &
      , 0,21, 82, 158, 244, 340, 465,717,7*801      &
      , 0,16, 53, 114,174,238, 320, 392,520,565,5*665 &
      , 0,12, 40,85,  133, 175, 235,294,360,413,493,585,3*665 &
      , 0,9, 30, 64, 101, 142, 183, 231,280,330,392,460,543,2*665 &
      , 0,7, 22, 48, 77, 115, 149, 186,220,275,323,383,451,530,615 &
      , 0,5, 17, 36, 58, 91, 119, 155,182,228,279,325,380,445,518 &
      , 0,4, 12, 27, 45, 71, 94, 126,153,197,245,290,330,381,446/
```

DERIVATIVE

```
!...................................................
!.. Calculation of the stroke
!...................................................

!.... Determination of testFS(i)=-1,0,1
!.... -1 : compression zone
!....  0 : free slack zone
!....  1 : tension zone



Procedural

Do  strk1 i=1,nn-1

   If(vehicle(i).eq.'locom'.AND.vehicle(i+1).eq.'locom')then
     Lref2=Lloco
     xsref=xsl
   else if(vehicle(i).ne.vehicle(i+1))then
       Lref2=Llocowagon
       xsref=xsl
   elseif(vehicle(i).eq.'wagon'.AND.vehicle(i+1).eq.'wagon')then
       If(Mod(i-lastlocox,m).eq.0)then
       Lref2=Lg
       xsref=xsg
       else
       Lref2=Lb
       xsref=xsb
       endif
     endif
   y(i)=x(i)-x(i+1)-Lref2
   e(i)=(abs(y(i))-xsref)/2.

if (e(i).le.0.d0) then
   testFS(i)=0
   e(i)=0.d0
else
   testFS(i)=sign(1.0,y(i))
endif

 strk1.. continue

end ! of procedural


!...................................................
!.. Calculation of the longitudinal forces inside the link
!.. (via the draw gear state)
!...................................................


Procedural
```

```
Do longf1 i=1,nn-1

yd(i)=xd(i)-xd(i+1)

if (etat(i).eq.0) then
  if (e(i).gt.0.) then
    if (e(i).gt.elim(i)) then
      etat(i)=1
      em(i)=e(i)
    else
      etat(i)=5
      em(i)=0.
    endif
  else
    etat(i)=0
  endif

else

  if (etat(i).eq.5) then
    if (e(i).le.0.) then
      etat(i)=0.
    else
      if (e(i).gt.elim(i)) then
        etat(i)=1
        em(i)=e(i)
      else
        etat(i)=5
      endif
    endif

  else

    if (etat(i).eq.1) then
      if (e(i).ge.em(i)) then
        etat(i)=1
        em(i)=e(i)
      else
        if (e(i).gt.elim(i)) then
          loading(Fa(i)=em(i),elim(i),i)
          p(i)=Fa(i)-slope*em(i)
          unloading(Fb(i)=e(i),elim(i),i)
          if ((slope*e(i)+p(i)).lt.Fb(i)) then
            etat(i)=3
            em(i)=e(i)
          else
            etat(i)=21
            flag(i)=1
          endif
        else
          if (e(i).gt.0.) then
            etat(i)=5
            em(i)=0.
          else
```

```
            etat(i)=0
           em(i)=0.
         endif
       endif
      endif


else

    if (etat(i).eq.3) then
      if (e(i).gt.em(i)) then
        unloading(Fb(i)=em(i),elim(i),i)
        p(i)=Fb(i)-slope*em(i)
        loading(Fa(i)=e(i),elim(i),i)
        if ((slope*e(i)+p(i)).gt.Fa(i)) then
          etat(i)=1
          em(i)=e(i)
        else
          etat(i)=21
          flag(i)=3
        endif
      else
        if (e(i).lt.elim(i)) then
          if (e(i).gt.0.) then
            etat(i)=5
            em(i)=0.
          else
            etat(i)=0
            em(i)=0.
          endif
        else
          etat(i)=3
          em(i)=e(i)
        endif
      endif
    endif

  else

    if ((etat(i).eq.21).or.(etat(i).eq.22)) then
      if (e(i).lt.elim(i)) then
        if (e(i).gt.0.) then
          etat(i)=5
          em(i)=0.
          flag(i)=0
        else
          etat(i)=0
          em(i)=0.
          flag(i)=0
        endif
      else
        if (flag(i).eq.1) then
          F2(i)=slope*e(i)+p(i)
          loading(Fa(i)=em(i),elim(i),i)
          if ((F2(i)+TestFS(i)*c*yd(i)).gt.Fa(i)) then
            etat(i)=1
            em(i)=e(i)
```

```fortran
                  flag(i)=0
              else
                unloading(Fb(i)=e(i),elim(i),i)
                if ((F2(i)+TestFS(i)*c*yd(i)).lt.Fb(i)) then
                    etat(i)=3
                    em(i)=e(i)
                    flag(i)=0
                else
                    etat(i)=22
                endif
              endif
            else
              if (flag(i).eq.3) then
                F2(i)=slope*e(i)+p(i)
                unloading(Fb(i)=em(i),elim(i),i)
                if ((F2(i)+TestFS(i)*c*yd(i)).lt.Fb(i)) then
                    etat(i)=3
                    em(i)=e(i)
                    flag(i)=0
                else
                  loading(Fa(i)=e(i),elim(i),i)
                  if ((F2(i)+TestFS(i)*c*yd(i)).gt.Fa(i)) then
                    etat(i)=1
                    em(i)=e(i)
                    flag(i)=0
                  else
                    etat(i)=22
                  endif
                endif
              endif
            endif
          endif
        else
          flag(i)=9
    endif
   endif
  endif
 endif
endif

!.... trailing force function of TestFS(i)
! (TestFS(i) has been calculated in stroke.inc)

if (etat(i).eq.0) then
   FTrailLong(i)=0.
else
 if (etat(i).eq.5) then
   FTrailLong(i)=-TestFS(i)*(slope5*e(i))
 else
  if (etat(i).eq.1) then
    loading(F(i)=e(i),elim(i),i)
    FTrailLong(i)=-TestFS(i)*F(i)
  else
    if (etat(i).eq.21) then
      FTrailLong(i)=-TestFS(i)*(slope*e(i)+p(i))
```

```
   else
     if (etat(i).eq.22) then
       FTrailLong(i)=-(TestFS(i)*(slope*e(i)+p(i))+c*yd(i))
     else
       unloading(F(i)=e(i),elim(i),i)
       FTrailLong(i)=-TestFS(i)*F(i)
     endif
   endif
 endif
endif
endif

!..... leading force FLeadLong(i+1)

FLeadLong(i+1)=-FTrailLong(i)

longf1.. continue

end ! of procedural

!.........................................
!.. Definition of Locoforce ..
!.........................................

  !............Test and increase/decrease traction as required

    Procedural
Do lf2 i=1,nn
  If(vehicle(i).eq.'locom')then
    If(xd(1).LT.vfin-dv/2)then
 Tracon=.true.
 If(Tracon)Fdb(i)=0.
 Dynon=.NOT.Tracon
 Dyndn=.NOT.Tracon
 NotchdNew1=0
 NotchdNew=0
 Notchdyn1=0
 Notchdyn=0
 NotchdUp1=0
 NotchdUp=0
 NotchdLo=0
 NotchdNow=0
 NotchtUp=NotchtNow+1
  NotchtUp1=NotchtUp
   NotchtNew=RSW(NotchtUp1.LE.14.0,NotchtUp1,14.0)
    NotchtNew1=NotchtNew
     If(type(i).eq.'11E')then
         If (xd(1) .LE. 15/3.6)then
Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)
         else If (xd(1) .GT. 15/3.6) then
         Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)
         else If (xd(1) .GT. 30/3.6)then
         Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)
```

```fortran
         else If (xd(1) .GT. 55/3.6) then
            Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
   Endif
    Notchtrac1=Notchtrac
  FtracNew1(i)=Traction(Notchtrac1,xd(i)*3.6)
  FtLow=ForctLow(Notchtrac1)
  FtUp=ForctUpper(Notchtrac1)
 FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
 FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
 Fte(i)=FtracNew(i)*1000
 Floco(i) =Fte(i)
 Armature(i)=Current(Notchtrac1,xd(i)*3.6)
else
         If (xd(1) .LE. 8/3.6)then
Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)

         else If (xd(1) .GT. 8/3.6) then
            Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)

         else If (xd(1) .GT. 30/3.6)then
            Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)

         else If (xd(1) .GT. 55/3.6) then
            Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
   Endif
    Notchtrac1=Notchtrac
  FtracNew1(i)=Traction_2(Notchtrac1,xd(i)*3.6)
  FtLow=ForctLow_2(Notchtrac1)
  FtUp=ForctUpper_2(Notchtrac1)
 FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
 FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
 Fte(i)=FtracNew(i)*1000
 Floco(i) =Fte(i)
 Armature(i)=Current_2(Notchtrac1,xd(i)*3.6)
Endif
 Power(i)=Floco(i)*xd(i)
 Pec(i)=Power(i)

 NotchtNow=Notchtrac
 Tracdn=.NOT.Tracon

else If(Tracon.AND.xd(1).GE.vfin-dv/2)then
  Tracdn=.true.
 If(Tracdn)Fdb(i)=0.
  Dynon=.NOT.Tracdn
  Dyndn=.NOT.Tracdn

NotchdNew1=0
 NotchdNew=0
 Notchdyn1=0
 Notchdyn=0
```

```
NotchdUp1=0
NotchdUp=0
NotchdLo=0
NotchdNow=0


NotchtLo=NotchtNow-1
 NotchtLo1=NotchtLo
  NotchtNew=RSW(NotchtLo1.GE.0.0,NotchtLo1,0.0)
   NotchtNew1=NotchtNew
If(type(i).eq.'11E')then
        If (xd(1) .LE. 15/3.6)then
Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)
        else If (xd(1) .GT. 15/3.6) then
          Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)
        else If (xd(1) .GT. 30/3.6)then
          Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)
        else If (xd(1) .GT. 55/3.6) then
          Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
   Endif
    Notchtrac1=Notchtrac
  FtracNew1(i)=Traction(Notchtrac1,xd(i)*3.6)
  FtLow=ForctLow(Notchtrac1)
  FtUp=ForctUpper(Notchtrac1)
 FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
 FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
Fte(i)=FtracNew(i)*1000
 Floco(i) =Fte(i)
 Armature(i)=Current(Notchtrac1,xd(i)*3.6)
else
        If (xd(1) .LE. 8/3.6)then
Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)

        else If (xd(1) .GT. 8/3.6) then
          Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)
        else If (xd(1) .GT. 30/3.6)then
          Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)
        else If (xd(1) .GT. 55/3.6) then
          Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
   Endif
    Notchtrac1=Notchtrac
  FtracNew1(i)=Traction_2(Notchtrac1,xd(i)*3.6)
  FtLow=ForctLow_2(Notchtrac1)
  FtUp=ForctUpper_2(Notchtrac1)
 FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
 FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
Fte(i)=FtracNew(i)*1000
 Floco(i) =Fte(i)
 Armature(i)=Current_2(Notchtrac1,xd(i)*3.6)
Endif
```

```
Power(i)=Floco(i)*xd(i)
Pec(i)=Power(i)
NotchtNow=Notchtrac
Tracon=.NOT.Tracdn
Endif

elseif(vehicle(i).eq.'wagon')then
       Floco(i) = 0.
       Armature(i)=0.
       Power(i)=0.
       Pec(i)=0.
       Energy(i)=0.
 Endif
lf2.. continue


End!........of Procedural

!............Test and increase/decrease dynamic brake as required

    Procedural
Do lf3 i=1,nn
  If(vehicle(i).eq.'locom')then
  If(xd(1).GT.vfin+dv/2)then
  Dynon=.true.
  If(Dynon)Fte(i)=0.
Tracon=.NOT.Dynon
Tracdn=.NOT.Dynon

NotchtNew1=0
  NotchtNew=0
  Notchtrac1=0
  Notchtrac=0
  NotchtUp1=0
  NotchtUp=0
  NotchtLo=0
NotchtLo1=0
  NotchtNow=0

  NotchdUp=NotchdNow+1
  NotchdUp1=NotchdUp
   NotchdNew=RSW(NotchdUp1.LE.10.0,NotchdUp1,10.0)
   NotchdNew1=NotchdNew
    If(type(i).eq.'11E')then
   If (xd(1) .GT. 70/3.6)   then
   Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
   else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
   Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
   else If ((xd(1) .LE. 60/3.6).AND. (xd(1) .GT. 55/3.6))then
   Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
   else If ((xd(1) .LE. 55/3.6).AND.(xd(1) .GT. 45/3.6))then
   Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
   else If (xd(1) .LE. 45/3.6) then
   Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
  Endif
```

```
     Notchdyn1=Notchdyn
   FdynNew1(i)=DynBrake(Notchdyn1,xd(i)*3.6)

   FdLow=ForcdLow(Notchdyn1)
   FdUp=ForcdUpper(Notchdyn1)
 else
 If (xd(1) .GT. 80/3.6)   then
    Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
    else If ((xd(1) .LE. 80/3.6).AND. (xd(1) .GT. 70/3.6))then
    Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
    else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
    Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
    else If ((xd(1) .LE. 60/3.6).AND.(xd(1) .GT. 50/3.6))then
    Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
    else If ((xd(1) .LE. 50/3.6).AND.(xd(1) .GT. 46/3.6))then
    Notchdyn=RSW(Notchdnew1 .le. 6.0,Notchdnew1,6.0)

    else If (xd(1) .LE. 46/3.6) then
    Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
  Endif

    Notchdyn1=Notchdyn
   FdynNew1(i)=DynBrake_2(Notchdyn1,xd(i)*3.6)
 FdLow=ForcdLow_2(Notchdyn1)
   FdUp=ForcdUpper_2(Notchdyn1)

 Endif
  FdynNew(i)=RSW(FdynNew1(i).GE.FdLow,FdynNew1(i),FdLow)
  FdynNew(i)=RSW(FdynNew1(i).LE.FdUp,FdynNew1(i),FdUp)
  Fdb(i)=-sign(FdynNew(i),xd(i))*1000
  Floco(i)= Fdb(i)
  Armature(i)=0.d0
  Power(i)=Floco(i)*xd(i)
  Pec(i)=0.d0
  NotchdNow=Notchdyn
  Dyndn=.NOT.Dynon

 else If(Dynon.AND.xd(1).LE.vfin+dv/2)then
  Dyndn=.true.
 If(Dyndn)Fte(i)=0.
 Tracon=.NOT.Dyndn
 Tracdn=.NOT.Dyndn

 NotchtNew1=0
  NotchtNew=0
  Notchtrac1=0
  Notchtrac=0
  NotchtUp1=0
  NotchtUp=0
  NotchtLo=0
 NotchtLo1=0
  NotchtNow=0

  NotchdLo=NotchdNow-1
```

```
              NotchdLo1=NotchdLo
              NotchdNew=RSW(NotchdLo1.GE.0.0,NotchdLo1,0.0)
              NotchdNew1=NotchdNew
                If(type(i).eq.'11E')then
      If (xd(1) .GT. 70/3.6)   then
              Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
                else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
              Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
                else If ((xd(1) .LE. 60/3.6).AND. (xd(1) .GT. 55/3.6))then
              Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
                else If ((xd(1) .LE. 55/3.6).AND.(xd(1) .GT. 45/3.6))then
              Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
                else If (xd(1) .LE. 45/3.6) then
              Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
          Endif
                  Notchdyn1=Notchdyn
              FdynNew1(i)=DynBrake(Notchdyn1,xd(i)*3.6)
              FdLow=ForcdLow(Notchdyn1)
              FdUp=ForcdUpper(Notchdyn1)
      else
        If (xd(1) .GT. 80/3.6)   then
              Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
                else If ((xd(1) .LE. 80/3.6).AND. (xd(1) .GT. 70/3.6))then
              Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
                else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
              Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
                else If ((xd(1) .LE. 60/3.6).AND.(xd(1) .GT. 50/3.6))then
              Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
                else If ((xd(1) .LE. 50/3.6).AND.(xd(1) .GT. 46/3.6))then
              Notchdyn=RSW(Notchdnew1 .le. 6.0,Notchdnew1,6.0)
                else If (xd(1) .LE. 46/3.6) then
              Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
          Endif

                  Notchdyn1=Notchdyn
              FdynNew1(i)=DynBrake_2(Notchdyn1,xd(i)*3.6)
              FdLow=ForcdLow_2(Notchdyn1)
              FdUp=ForcdUpper_2(Notchdyn1)
      endif
       FdynNew(i)=RSW(FdynNew1(i).GE.FdLow,FdynNew1(i),FdLow)
       FdynNew(i)=RSW(FdynNew1(i).LE.FdUp,FdynNew1(i),FdUp)
       Fdb(i)=-sign(FdynNew(i),xd(i))*1000
       Floco(i)= Fdb(i)
       Armature(i)=0.d0
       Power(i)=Floco(i)*xd(i)
       Pec(i)=0.d0
       NotchdNow=Notchdyn
      Dynon=.NOT.Dyndn
      Endif

      elseif(vehicle(i).eq.'wagon')then
              Floco(i) = 0.
              Armature(i)=0.
              Power(i)=0.
              Pec(i)=0.
```

```
        Energy(i)=0.
  Endif
If3.. continue

End!........of Procedural

  !.....................................
  !.. Definition of the Rolling Resistance ..
  !.....................................


  !...........................................
  !.. File which calculates the rolling resistance
  !.. and handle the fact that the rolling resistance must
  !.. be zero if the truck is not moving ( variable stand(i) )
  !...........................................


  !..(the equations must handle that x(i)=0 if the wagon is standing)

  ! for the next procedural section below,
  ! one must assume the wagons on a straight track
  ! => the train must start on a straight track !

  ! The resistance to start the train is supposed to be 5 times greater
  ! than the resistance of a moving wagon at a very low speed ( Frr0 ).
  ! Frr0 is the rolling resistance when the speed tends towards zero.

  ! We can use at runtime the coefficient RollCoeff
  ! defined as a constant :
   Procedural

Do roll1 i=1,nn
 If(vehicle(i).eq.'wagon')then
    if (stand(i)) then
     if (xdini.eq.(0.d0)) then
     if ((-Fgrad(i)+FLeadLong(i)+FTrailLong(i) &
      -RollCoeff*Rollzerowagon).GT.(0.d0) ) then
     stand(i)=.false.
     test(i)=t
endif
else
stand(i)=.false.
test(i)=t

endif
endif
endif
roll1.. continue

End !..of procedural

  !.. Calculation of the Rolling Resistance :

  ! The Rolling resistance calculated is always positive
  ! the minus sign will be handled in the definition of the acceleration
```

Procedural

```
Do roll2 i=1,nn
If (stand(i)) then
   Frr(i)=0.d0
else
   RollResistance(Frr(i)=xd(i)*3.6,masse(i),Naxle(i))

endif
 roll2..continue
End!....of procedural

 ! the next  test (Frr(i)=0 or not) is not obligatory
 ! but it makes more sense to fix FRR(i)=0 if the train is not moving
 ! The calculation of the acceleration takes the fact standing/moving
 ! into account

 !.........The gradient force

Procedural
Do gradlp1 i=1,nn

If (x(i).ge.xchange(i)) then

20.. continue
   count(i) = count(i) + 1
   read(55, 90, rec=count(i)) xchange(i)
90.. format(d9.5)
   xchange(i)=xchange(i)*1000.
count1(i) = count1(i) + 1
   read(60, 91, rec=count1(i)) Grad(i)
91.. format(d9.4)
if (x(i).ge.xchange(i)) goto 20

 ! comment : the loop with label 20 is to take into account
 ! an initial position of the first loco which is not zero.

endif

 gradlp1..continue

End!... of procedural

Procedural
 Do gradlp2 i=1,nn
    Hill(Fgrad(i)=Grad(i),masse(i))
 gradlp2..continue

end ! of Procedural

 !.............................................................
 !..File which calculates the airbrake forces acting on the wagons
 !.............................................................
Procedural
```

```fortran
Do ab6 i=1,nn

    If (i.eq.1)then
        time1=t
      BrakeP(Pr(i)=time1)
    else
        time = time1-(i*tnext)-tbst1
        BrakeP(Pr(i)=time)
    endif

BrkCylF(i) = (6900*Pr(i)*pi*(Dia**2)/4) -sf

If (BrkcylF(i).le.0) then
  Fbrk(i)=0.d0
else
  Fbrk(i) = 2*(BrkCylF(i) * (680./305.) -1600)  &
        * (430./615.) * (320./230.) * 4.5
endif

If (Fbrk(i).lt.0) Fbrk(i)=0.d0

ab6..continue
end ! of procedural

!
!............Energy Consumption calculation


Procedural
Do enerlb1 i=1,nn
Energy(i)=Ener(i)*1/3.6e6
enerlb1..continue

Etot=Energy(1)+Energy(2)+Energy(3)+Energy(4)+Energy(5)+Energy(6)& ! Cum. energy
kWh
+Energy(7)+ Energy(8)+Energy(9)+Energy(10)+Energy(11)+Energy(12)&
+Energy(13)+Energy(14)+Energy(15)+Energy(16)+Energy(17)+Energy(18)&
+Energy(19)+Energy(20)+Energy(21)+Energy(22)+ Energy(23)+Energy(23)&
+Energy(24)+Energy(25)+Energy(26)+Energy(27)+Energy(28)+ Energy(29)&
+Energy(30)+Energy(31)+Energy(32)+Energy(33)+Energy(34)+Energy(35)&
+Energy(36)+Energy(37)+Energy(38)+Energy(39)+Energy(40)+Energy(41)&
+Energy(42)+Energy(43)+Energy(44)+Energy(45)+Energy(46)+Energy(47)&
+Energy(48)+Energy(49)+Energy(50)+Energy(51)+Energy(52)+Energy(53)&
+Energy(54)+Energy(55)+Energy(56)+Energy(57)+Energy(58)+Energy(59)&
+Energy(60)+Energy(61)+Energy(62)+Energy(63)+Energy(64)+Energy(65)&
+Energy(66)+Energy(67)+Energy(68)+Energy(69)+Energy(70)+Energy(71)&
+Energy(72)+Energy(73)+Energy(74)+Energy(75)+Energy(76)+Energy(77)&
+Energy(78)+Energy(79)+Energy(80)+Energy(81)+Energy(82)+Energy(83)&
+Energy(84)+Energy(85)+Energy(86)+Energy(87)+Energy(88)+Energy(89)&
+Energy(90)+Energy(91)+Energy(92)+Energy(93)+Energy(94)+Energy(95)&
+Energy(96)+Energy(97)+Energy(98)+Energy(99)+Energy(100)+Energy(101)&
+Energy(102)+Energy(103)+Energy(104)+Energy(105)+Energy(106)&
+Energy(107)&
+Energy(108)+Energy(109)+Energy(110)+Energy(111)+Energy(112)+Energy(113)&
+Energy(114)+Energy(115)+Energy(116)+Energy(117)+Energy(118)&
```

```
+Energy(119)&
+Energy(120)+Energy(121)+Energy(122)+Energy(123)+Energy(124)+Energy(125)&
+Energy(126)+Energy(127)+Energy(128)+Energy(129)+Energy(130)+Energy(131)&
+Energy(132)+Energy(133)+Energy(134)+Energy(135)+Energy(136)+Energy(137)&
+Energy(138)+Energy(139)+Energy(140)+Energy(141)+Energy(142)+Energy(143)&
+Energy(144)+Energy(145)+Energy(146)+Energy(147)+Energy(148)+Energy(149)&
+Energy(150)+Energy(151)+Energy(152)+Energy(153)+Energy(154)+Energy(155)&
+Energy(156)+Energy(157)+Energy(158)+Energy(159)+Energy(160)+Energy(161)&
+Energy(162)+Energy(163)+Energy(164)+Energy(165)+Energy(166)+Energy(167)&
+Energy(168)+Energy(169)+Energy(170)+Energy(171)+Energy(172)+Energy(173)&
+Energy(174)+Energy(175)+Energy(176)+Energy(177)+Energy(178)+Energy(179)&
+Energy(180)+Energy(181)+Energy(182)+Energy(183)+Energy(184)+Energy(185)&
+Energy(186)+Energy(187)+Energy(188)+Energy(189)+Energy(190)+Energy(191)&
+Energy(192)+Energy(193)+Energy(194)+Energy(195)+Energy(196)+Energy(197)&
+Energy(198)+Energy(199)+Energy(200)+Energy(201)+Energy(202)+Energy(203)&
+Energy(204)


End!........of procedural

!..........Jack knifing calculation......

Procedural
 Do jacklb1 i=1,nn-1
J(i)=(1/ks)*(-4*Ftraillong(i))
Flat(i)=(J(i)/Lcb)*(Ftraillong(i))
Flat_bogie(i)=Flat(i)*(pc/bc)

jacklb1..continue
End !......of procedural
 !...................................
 !.. Definition of the Accelerations ..
 !...................................

Procedural

DO acc1 i=1,nn
    For(i)=Floco(i)+Fleadlong(i)+Ftraillong(i)-Fgrad(i)&
        -Frr(i)-Fbrk(i)
    xdd(i)=RSW(stand(i),0.,(For(i)/masse(i)))

acc1..Continue
End!..of Procedural

!............Calculate max,min,mean
Procedural
 Do forcvec1 i=1,nn

  Fmin(i)=RSW(For(i).LT.Fmin(i),For(i),Fmin(i))
  Fmean(i)=(Fmax(i)+Fmin(i))/2
  Armcrit(i)=RSW(Armature(i).GT.Armcrit(i),Armature(i),&
            Armcrit(i))
 Fmax(i)=RSW(For(i).GT.Fmax(i),For(i), &
            Fmax(i))

forcvec1..continue
```

End!.....of procedural
!...........................
!..... Integration ....
!...........................

```
  xd=INTVC(xdd,xd0)
  Call XFERBR (interxd=xd,nn)
  x=INTVC(interxd,x0)
  Ener = INTVC(Pec,Ener0)

END !.. OF DERIVATIVE ..

! determination of the maximum force, and the position
! of the maximum force inside the train consist
! attention : one is using Ftraillong
! -> step integration interval

Procedural
posloco=1
Fmaxloco=Ftraillong(1)

 posdraw=lastlocox+m
  Fmaxdraw=Ftraillong(lastlocox+m)
   posbuff=lastlocox+1
   Fmaxbuff=Ftraillong(lastlocox+1)

Do post1 i=2,nn
If(i.GT.1.AND.vehicle(i).eq.'locom')then
  if ( (abs(Ftraillong(i))).gt.(abs(Fmaxloco)) ) then
     posloco=i
     Fmaxloco=Ftraillong(i)
   endif

else If(vehicle(i).eq.'wagon')then
 if (Mod(i-lastlocox,m).eq.0) then
    if ( (abs(Ftraillong(i))).gt.(abs(Fmaxdraw)) ) then
      posdraw=i
      Fmaxdraw=Ftraillong(i)
    endif

  else
    if ( (abs(Ftraillong(i))).gt.(abs(Fmaxbuff)) ) then
      posbuff=i
      Fmaxbuff=Ftraillong(i)
    endif
  endif
endif

If ((abs(fmaxloco)).gt.(abs(Fmaxloco2))) then
  posloco2=posloco
  Fmaxloco2=Fmaxloco
  Xloco=x(posloco2)
endif

If ((abs(fmaxdraw)).gt.(abs(Fmaxdraw2))) then
```

```
      posdraw2=posdraw
      Fmaxdraw2=Fmaxdraw
      Xdraw=x(posdraw2)
  endif


  If ((abs(fmaxbuff)).gt.(abs(Fmaxbuff2))) then
      posbuff2=posbuff
      Fmaxbuff2=Fmaxbuff
      Xbuff=x(posbuff2)
  endif
  post1.. continue
  end ! of procedural

  TERMT(t.GE.tstp,'time limit')
  TERMT(x(1).GE.xstp,'end of track')
  END !.. OF DYNAMIC ..

  TERMINAL

  close(40)
  close(45)
  close(55)
  close(60)
  close(65)
  close(70)

  write(3,1000)t,Etot
  1000..Format(1x(d14.6))

  !.. Call for debug dump
  !  gives the initial values + the values of the variables
  !  at the end of the run

  Logical  dump
  Constant  dump=.false.
  If (dump) Call Debug

  END !.. of TERMINAL

  END !.. of PROGRAM
```

Appendix 11.3

```
    Procedural
Do lf2 i=1,nn
Speedres(vmax(1)=Grad(1),xd(1))

 vref(1)=vmax(1)
 dv(1) = 0.1*vref(1)

  If(vehicle(i).eq.'locom')then
    If(xd(1).LT.vref(1)-dv(1)/2)then
  Tracon=.true.
 If(Tracon)Fdb(i)=0.
  Dynon=.NOT.Tracon
  Dyndn=.NOT.Tracon
  NotchdNew1=0
  NotchdNew=0
  Notchdyn1=0
  Notchdyn=0   .
  NotchdUp1=0
  NotchdUp=0
  NotchdLo=0
  NotchdNow=0
  NotchtUp=NotchtNow+1
   NotchtUp1=NotchtUp
   NotchtNew=RSW(NotchtUp1.LE.14.0,NotchtUp1,14.0)
    NotchtNew1=NotchtNew
     If(type(i).eq.'11E')then
          If (xd(1) .LE. 15/3.6)then
Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)

          else If (xd(1) .GT. 15/3.6) then
          Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
   14.0),NotchtNew1,2.0)

          else If (xd(1) .GT. 30/3.6)then
          Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
   14.0),NotchtNew1,3.0)

          else If (xd(1) .GT. 55/3.6) then
          Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
   14.0),NotchtNew1,4.0)
     Endif
     Notchtrac1=Notchtrac
   FtracNew1(i)=Traction(Notchtrac1,xd(i)*3.6)
   FtLow=ForctLow(Notchtrac1)
   FtUp=ForctUpper(Notchtrac1)
  FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
  FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
  Fte(i)=FtracNew(i)*1000
  Floco(i) =Fte(i)
  Armature(i)=Current(Notchtrac1,xd(i)*3.6)
 else
```

```
          If (xd(1) .LE. 8/3.6)then
Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)

          else If (xd(1) .GT. 8/3.6) then
          Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)

          else If (xd(1) .GT. 30/3.6)then
          Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)

          else If (xd(1) .GT. 55/3.6) then
          Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
     Endif
     Notchtrac1=Notchtrac
  FtracNew1(i)=Traction_2(Notchtrac1,xd(i)*3.6)
  FtLow=ForctLow_2(Notchtrac1)
  FtUp=ForctUpper_2(Notchtrac1)
 FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
 FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
  Fte(i)=FtracNew(i)*1000
  Floco(i) =Fte(i)
  Armature(i)=Current_2(Notchtrac1,xd(i)*3.6)
Endif
  Power(i)=Floco(i)*xd(i)
  Pec(i)=Power(i)

  NotchtNow=Notchtrac
  Tracdn=.NOT.Tracon

else If(Tracon.AND.xd(1).GE.vref(1)-dv(1)/2)then
  Tracdn=.true.
 If(Tracdn)Fdb(i)=0.
  Dynon=.NOT.Tracdn
  Dyndn=.NOT.Tracdn

NotchdNew1=0
  NotchdNew=0
  Notchdyn1=0
  Notchdyn=0
  NotchdUp1=0
  NotchdUp=0
  NotchdLo=0
  NotchdNow=0

  NotchtLo=NotchtNow-1
  NotchtLo1=NotchtLo
   NotchtNew=RSW(NotchtLo1.GE.0.0,NotchtLo1,0.0)
    NotchtNew1=NotchtNew
If(type(i).eq.'11E')then
        If (xd(1) .LE. 15/3.6)then
 Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)

        else If (xd(1) .GT. 15/3.6) then
```

```fortran
          Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)

          else If (xd(1) .GT. 30/3.6)then
          Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)

          else If (xd(1) .GT. 55/3.6) then
          Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
      Endif
      Notchtrac1=Notchtrac
    FtracNew1(i)=Traction(Notchtrac1,xd(i)*3.6)
    FtLow=ForctLow(Notchtrac1)
    FtUp=ForctUpper(Notchtrac1)
   FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
   FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
  Fte(i)=FtracNew(i)*1000
   Floco(i) =Fte(i)
   Armature(i)=Current(Notchtrac1,xd(i)*3.6)
  else
          If (xd(1) .LE. 8/3.6)then
  Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)

          else If (xd(1) .GT. 8/3.6) then
          Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)

          else If (xd(1) .GT. 30/3.6)then
          Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)

          else If (xd(1) .GT. 55/3.6) then
          Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
      Endif
      Notchtrac1=Notchtrac
    FtracNew1(i)=Traction_2(Notchtrac1,xd(i)*3.6)
    FtLow=ForctLow_2(Notchtrac1)
    FtUp=ForctUpper_2(Notchtrac1)
   FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
   FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
  Fte(i)=FtracNew(i)*1000
   Floco(i) =Fte(i)
   Armature(i)=Current_2(Notchtrac1,xd(i)*3.6)
  Endif
   Power(i)=Floco(i)*xd(i)
   Pec(i)=Power(i)

  NotchtNow=Notchtrac
  Tracon=.NOT.Tracdn
  Endif

elseif(vehicle(i).eq.'wagon')then
        Floco(i) = 0.
```

```
           Armature(i)=0.
           Power(i)=0.
           Pec(i)=0.
           Energy(i)=0.
      Endif
    lf2.. continue


End!........of Procedural


     Procedural
    Do lf3 i=1,nn
      If(vehicle(i).eq.'locom')then
      If(xd(1).GT.vref(1)+dv(1)/2)then
      Dynon=.true.
      If(Dynon)Fte(i)=0.
    Tracon=.NOT.Dynon
    Tracdn=.NOT.Dynon

    NotchtNew1=0
      NotchtNew=0
      Notchtrac1=0
      Notchtrac=0
      NotchtUp1=0
      NotchtUp=0
      NotchtLo=0
    NotchtLo1=0
      NotchtNow=0

      NotchdUp=NotchdNow+1
       NotchdUp1=NotchdUp
       NotchdNew=RSW(NotchdUp1.LE.10.0,NotchdUp1,10.0)
        NotchdNew1=NotchdNew
         If(type(i).eq.'11E')then
        If (xd(1) .GT. 70/3.6)   then
        Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
        else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
        Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
        else If ((xd(1) .LE. 60/3.6).AND. (xd(1) .GT. 55/3.6))then
        Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
        else If ((xd(1) .LE. 55/3.6).AND.(xd(1) .GT. 45/3.6))then
        Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
        else If (xd(1) .LE. 45/3.6) then
        Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
      Endif

        Notchdyn1=Notchdyn
      FdynNew1(i)=DynBrake(Notchdyn1,xd(i)*3.6)

      FdLow=ForcdLow(Notchdyn1)
       FdUp=ForcdUpper(Notchdyn1)
    else
    If (xd(1) .GT. 80/3.6)   then
        Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
```

```
else If ((xd(1) .LE. 80/3.6).AND. (xd(1) .GT. 70/3.6))then
Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
else If ((xd(1) .LE. 60/3.6).AND.(xd(1) .GT. 50/3.6))then
Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
else If ((xd(1) .LE. 50/3.6).AND.(xd(1) .GT. 46/3.6))then
Notchdyn=RSW(Notchdnew1 .le. 6.0,Notchdnew1,6.0)

 else If (xd(1) .LE. 46/3.6) then
 Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
Endif

   Notchdyn1=Notchdyn
  FdynNew1(i)=DynBrake_2(Notchdyn1,xd(i)*3.6)
FdLow=ForcdLow_2(Notchdyn1)
  FdUp=ForcdUpper_2(Notchdyn1)

Endif
 FdynNew(i)=RSW(FdynNew1(i).GE.FdLow,FdynNew1(i),FdLow)
 FdynNew(i)=RSW(FdynNew1(i).LE.FdUp,FdynNew1(i),FdUp)
 Fdb(i)=-sign(FdynNew(i),xd(i))*1000
 Floco(i)= Fdb(i)
 Armature(i)=0.d0
 Power(i)=Floco(i)*xd(i)
 Pec(i)=0.d0


 NotchdNow=Notchdyn
  Dyndn=.NOT.Dynon

else If(Dynon.AND.xd(1).LE.vref(1)+dv(1)/2)then
  Dyndn=.true.
 If(Dyndn)Fte(i)=0.
Tracon=.NOT.Dyndn
Tracdn=.NOT.Dyndn

NotchtNew1=0
 NotchtNew=0
 Notchtrac1=0
 Notchtrac=0
 NotchtUp1=0
 NotchtUp=0
 NotchtLo=0
NotchtLo1=0
 NotchtNow=0

 NotchdLo=NotchdNow-1
  NotchdLo1=NotchdLo
  NotchdNew=RSW(NotchdLo1.GE.0.0,NotchdLo1,0.0)
   NotchdNew1=NotchdNew
    If(type(i).eq.'11E')then
If (xd(1) .GT. 70/3.6)   then
  Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
  else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
```

```fortran
      Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
      else If ((xd(1) .LE. 60/3.6).AND. (xd(1) .GT. 55/3.6))then
      Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
      else If ((xd(1) .LE. 55/3.6).AND.(xd(1) .GT. 45/3.6))then
      Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
      else If (xd(1) .LE. 45/3.6) then
      Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
     Endif
        Notchdyn1=Notchdyn
     FdynNew1(i)=DynBrake(Notchdyn1,xd(i)*3.6)
     FdLow=ForcdLow(Notchdyn1)
     FdUp=ForcdUpper(Notchdyn1)
   else
    If (xd(1) .GT. 80/3.6)   then
      Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
      else If ((xd(1) .LE. 80/3.6).AND. (xd(1) .GT. 70/3.6))then
      Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
      else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
      Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
      else If ((xd(1) .LE. 60/3.6).AND.(xd(1) .GT. 50/3.6))then
      Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
      else If ((xd(1) .LE. 50/3.6).AND.(xd(1) .GT. 46/3.6))then
      Notchdyn=RSW(Notchdnew1 .le. 6.0,Notchdnew1,6.0)
      else If (xd(1) .LE. 46/3.6) then
      Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
     Endif

        Notchdyn1=Notchdyn
     FdynNew1(i)=DynBrake_2(Notchdyn1,xd(i)*3.6)
     FdLow=ForcdLow_2(Notchdyn1)
     FdUp=ForcdUpper_2(Notchdyn1)
   endif
    FdynNew(i)=RSW(FdynNew1(i).GE.FdLow,FdynNew1(i),FdLow)
    FdynNew(i)=RSW(FdynNew1(i).LE.FdUp,FdynNew1(i),FdUp)
    Fdb(i)=-sign(FdynNew(i),xd(i))*1000
    Floco(i)= Fdb(i)
    Armature(i)=0.d0
    Power(i)=Floco(i)*xd(i)
    Pec(i)=0.d0
    NotchdNow=Notchdyn
   Dynon=.NOT.Dyndn
   Endif

   elseif(vehicle(i).eq.'wagon')then
         Floco(i) = 0.
         Armature(i)=0.
         Power(i)=0.
         Pec(i)=0.
         Energy(i)=0.
    Endif
    lf3.. continue


End!........of Procedural
```

!.............Train Handling Algorithm for Descending Grade

If (xd(1).LT.vmax(1))then

```
 If(Fte(1).LE.(Fgrad(1)+Frr(1)+1.0).AND.Fte(1).GE.(Fgrad(1)+Frr(1)-1.0)) then
     xd(1)=vbal(1)
   If(vmax(1).GE.vbal(1))then
     vref(1)=vbal(1)
       else
     vref(1)=vmax(1)
   endif
If(xd(1).LT.vref(1)-dv/2) then
   Tracon=.true.
 If(Tracon)Fdb(i)=0.
  Dynon=.NOT.Tracon
  Dyndn=.NOT.Tracon
  NotchdNew1=0
  NotchdNew=0
  Notchdyn1=0
  Notchdyn=0
  NotchdUp1=0
  NotchdUp=0
  NotchdLo=0
  NotchdNow=0
  NotchtUp=NotchtNow+1
   NotchtUp1=NotchtUp
    NotchtNew=RSW(NotchtUp1.LE.14.0,NotchtUp1,14.0)
    NotchtNew1=NotchtNew

        If (xd(1) .LE. 15/3.6)then
Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)

        else If (xd(1) .GT. 15/3.6) then
        Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)

        else If (xd(1) .GT. 30/3.6)then
        Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)

        else If (xd(1) .GT. 55/3.6) then
        Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
    Endif
     Notchtrac1=Notchtrac
   FtracNew1(i)=Traction(Notchtrac1,xd(i)*3.6)
   FtLow=ForctLow(Notchtrac1)
   FtUp=ForctUpper(Notchtrac1)
  FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
  FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
  Fte(i)=FtracNew(i)*1000
  Floco(i) =Fte(i)
  Armature(i)=Current(Notchtrac1,xd(i)*3.6)
  Power(i)=Floco(i)*xd(i)
  Pec(i)=Power(i)
```

```
NotchtNow=Notchtrac
Tracdn=.NOT.Tracon

else If(Tracon.AND.xd(1).GE.vref(1)-dv/2)then
  Tracdn=.true.
If(Tracdn)Fdb(i)=0.
  Dynon=.NOT.Tracdn
  Dyndn=.NOT.Tracdn

NotchdNew1=0
 NotchdNew=0
 Notchdyn1=0
 Notchdyn=0
 NotchdUp1=0
 NotchdUp=0
 NotchdLo=0
 NotchdNow=0

 NotchtLo=NotchtNow-1
  NotchtLo1=NotchtLo
   NotchtNew=RSW(NotchtLo1.GE.0.0,NotchtLo1,0.0)
    NotchtNew1=NotchtNew

        If (xd(1) .LE. 15/3.6)then
Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)

        else If (xd(1) .GT. 15/3.6) then
        Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)

        else If (xd(1) .GT. 30/3.6)then
        Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)

        else If (xd(1) .GT. 55/3.6) then
        Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
    Endif
    Notchtrac1=Notchtrac
  FtracNew1(i)=Traction(Notchtrac1,xd(i)*3.6)
  FtLow=ForctLow(Notchtrac1)
  FtUp=ForctUpper(Notchtrac1)
 FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
 FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
Fte(i)=FtracNew(i)*1000
 Floco(i) =Fte(i)
 Armature(i)=Current(Notchtrac1,xd(i)*3.6)
 Power(i)=Floco(i)*xd(i)
 Pec(i)=Power(i)

 NotchtNow=Notchtrac
 Tracon=.NOT.Tracdn

 else If(xd(1).GT.vref(1)+dv/2)then
```

```fortran
      Dynon=.true.
      If(Dynon)Fte(i)=0.
      Tracon=.NOT.Dynon
      Tracdn=.NOT.Dynon

      NotchtNew1=0
       NotchtNew=0
       Notchtrac1=0
       Notchtrac=0
       NotchtUp1=0
       NotchtUp=0
       NotchtLo=0
      NotchtLo1=0
       NotchtNow=0

       NotchdUp=NotchdNow+1
        NotchdUp1=NotchdUp
         NotchdNew=RSW(NotchdUp1.LE.10.0,NotchdUp1,10.0)
          NotchdNew1=NotchdNew

          If (xd(1) .GT. 70/3.6)   then
          Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
          else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
          Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
          else If ((xd(1) .LE. 60/3.6).AND. (xd(1) .GT. 55/3.6))then
          Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
          else If ((xd(1) .LE. 55/3.6).AND.(xd(1) .GT. 45/3.6))then
          Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
          else If (xd(1) .LE. 45/3.6) then
          Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
       Endif

          Notchdyn1=Notchdyn
        FdynNew1(i)=DynBrake(Notchdyn1,xd(i)*3.6)

        FdLow=ForcdLow(Notchdyn1)
        FdUp=ForcdUpper(Notchdyn1)
       FdynNew(i)=RSW(FdynNew1(i).GE.FdLow,FdynNew1(i),FdLow)
       FdynNew(i)=RSW(FdynNew1(i).LE.FdUp,FdynNew1(i),FdUp)
       Fdb(i)=-sign(FdynNew(i),xd(i))*1000
       Floco(i)= Fdb(i)
       Armature(i)=0.d0
       Power(i)=Floco(i)*xd(i)
       Pec(i)=0.d0

       NotchdNow=Notchdyn
        Dyndn=.NOT.Dynon

      else If(Dynon.AND.xd(1).LE.vref(1)+dv/2)then
        Dyndn=.true.
       If(Dyndn)Fte(i)=0.
      Tracon=.NOT.Dyndn
      Tracdn=.NOT.Dyndn

      NotchtNew1=0
```

```
  NotchtNew=0
  Notchtrac1=0
  Notchtrac=0
  NotchtUp1=0
  NotchtUp=0
  NotchtLo=0
NotchtLo1=0
  NotchtNow=0


  NotchdLo=NotchdNow-1
  NotchdLo1=NotchdLo
   NotchdNew=RSW(NotchdLo1.GE.0.0,NotchdLo1,0.0)
   NotchdNew1=NotchdNew

If (xd(1) .GT. 70/3.6)   then
   Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
   else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
   Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
   else If ((xd(1) .LE. 60/3.6).AND. (xd(1) .GT. 55/3.6))then
   Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
   else If ((xd(1) .LE. 55/3.6).AND.(xd(1) .GT. 45/3.6))then
   Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
   else If (xd(1) .LE. 45/3.6) then
   Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
  Endif
      Notchdyn1=Notchdyn
  FdynNew1(i)=DynBrake(Notchdyn1,xd(i)*3.6)
  FdLow=ForcdLow(Notchdyn1)
  FdUp=ForcdUpper(Notchdyn1)
   FdynNew(i)=RSW(FdynNew1(i).GE.FdLow,FdynNew1(i),FdLow)
 FdynNew(i)=RSW(FdynNew1(i).LE.FdUp,FdynNew1(i),FdUp)
 Fdb(i)=-sign(FdynNew(i),xd(i))*1000
 Floco(i)= Fdb(i)
 Armature(i)=0.d0
 Power(i)=Floco(i)*xd(i)
 Pec(i)=0.d0
 NotchdNow=Notchdyn
Dynon=.NOT.Dyndn

 Endif

else if(Fte(1).LT.Fgrad(1)+Frr(1)-1.0)then
Tracon=.true.
 If(Tracon)Fdb(i)=0.
 Dynon=.NOT.Tracon
 Dyndn=.NOT.Tracon
 NotchdNew1=0
 NotchdNew=0
 Notchdyn1=0
 Notchdyn=0
 NotchdUp1=0
 NotchdUp=0
 NotchdLo=0
 NotchdNow=0
 NotchtUp=NotchtNow+1
```

```
  NotchtUp1=NotchtUp
   NotchtNew=RSW(NotchtUp1.LE.14.0,NotchtUp1,14.0)
    NotchtNew1=NotchtNew

        If (xd(1) .LE. 15/3.6)then
Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)

        else If (xd(1) .GT. 15/3.6) then
        Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)

        else If (xd(1) .GT. 30/3.6)then
        Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)

        else If (xd(1) .GT. 55/3.6) then
        Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
    Endif
     Notchtrac1=Notchtrac
   FtracNew1(i)=Traction(Notchtrac1,xd(i)*3.6)
   FtLow=ForctLow(Notchtrac1)
   FtUp=ForctUpper(Notchtrac1)
  FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
  FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
  Fte(i)=FtracNew(i)*1000
  Floco(i) =Fte(i)
  Armature(i)=Current(Notchtrac1,xd(i)*3.6)
  Power(i)=Floco(i)*xd(i)
  Pec(i)=Power(i)

  NotchtNow=Notchtrac
   Tracdn=.NOT.Tracon
Endif

else if (Fte(1).GT.Fgrad(1)+Frr(1)+1.0.AND.Tracon)then
Tracdn=.true.
 If(Tracdn)Fdb(i)=0.
   Dynon=.NOT.Tracdn
   Dyndn=.NOT.Tracdn

NotchdNew1=0
 NotchdNew=0
 Notchdyn1=0
 Notchdyn=0
 NotchdUp1=0
 NotchdUp=0
 NotchdLo=0
 NotchdNow=0

 NotchtLo=NotchtNow-1
  NotchtLo1=NotchtLo
   NotchtNew=RSW(NotchtLo1.GE.0.0,NotchtLo1,0.0)
    NotchtNew1=NotchtNew
```

```fortran
        If (xd(1) .LE. 15/3.6)then
Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)

        else If (xd(1) .GT. 15/3.6) then
        Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)

        else If (xd(1) .GT. 30/3.6)then
        Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)

        else If (xd(1) .GT. 55/3.6) then
        Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
    Endif
    Notchtrac1=Notchtrac
  FtracNew1(i)=Traction(Notchtrac1,xd(i)*3.6)
  FtLow=ForctLow(Notchtrac1)
  FtUp=ForctUpper(Notchtrac1)
 FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
 FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
Fte(i)=FtracNew(i)*1000
 Floco(i) =Fte(i)
 Armature(i)=Current(Notchtrac1,xd(i)*3.6)
 Power(i)=Floco(i)*xd(i)
 Pec(i)=Power(i)

 NotchtNow=Notchtrac
 Tracon=.NOT.Tracdn

 Endif

else if(xd(1).GE.vmax(1))then

If (Fdb(1).LE.(Fgrad(1)+Frr(1)+1.0).AND.Fdb(1).GE.(Fgrad(1)+Frr(1)-1.0))then
 xd(1)=vbal(1)
If (vmax(1).GE.vbal(1))then
  vref(1)=vbal(1)
else
 vref(1)=vmax(1)
endif

If(xd(1).LT.vref(1)-dv/2) then
  Tracon=.true.
If(Tracon)Fdb(i)=0.
 Dynon=.NOT.Tracon
 Dyndn=.NOT.Tracon
 NotchdNew1=0
 NotchdNew=0
 Notchdyn1=0
 Notchdyn=0
 NotchdUp1=0
 NotchdUp=0
 NotchdLo=0
 NotchdNow=0
```

```
    NotchtUp=NotchtNow+1
    NotchtUp1=NotchtUp
     NotchtNew=RSW(NotchtUp1.LE.14.0,NotchtUp1,14.0)
      NotchtNew1=NotchtNew

          If (xd(1) .LE. 15/3.6)then
Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)

          else If (xd(1) .GT. 15/3.6) then
             Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)

          else If (xd(1) .GT. 30/3.6)then
             Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)

          else If (xd(1) .GT. 55/3.6) then
             Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
    Endif
     Notchtrac1=Notchtrac
    FtracNew1(i)=Traction(Notchtrac1,xd(i)*3.6)
    FtLow=ForctLow(Notchtrac1)
    FtUp=ForctUpper(Notchtrac1)
FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
    Fte(i)=FtracNew(i)*1000
    Floco(i) =Fte(i)
    Armature(i)=Current(Notchtrac1,xd(i)*3.6)
    Power(i)=Floco(i)*xd(i)
    Pec(i)=Power(i)

    NotchtNow=Notchtrac
     Tracdn=.NOT.Tracon

else If(Tracon.AND.xd(1).GE.vref(1)-dv/2)then
    Tracdn=.true.
   If(Tracdn)Fdb(i)=0.
    Dynon=.NOT.Tracdn
    Dyndn=.NOT.Tracdn

NotchdNew1=0
 NotchdNew=0
 Notchdyn1=0
 Notchdyn=0
 NotchdUp1=0
 NotchdUp=0
 NotchdLo=0
 NotchdNow=0

 NotchtLo=NotchtNow-1
  NotchtLo1=NotchtLo
   NotchtNew=RSW(NotchtLo1.GE.0.0,NotchtLo1,0.0)
    NotchtNew1=NotchtNew
```

```
        If (xd(1) .LE. 15/3.6)then
Notchtrac=RSW((NotchtNew1 .Gt. 0.0) .and. (NotchtNew1 .LE. 14.0),NotchtNew1,0.0)

        else If (xd(1) .GT. 15/3.6) then
        Notchtrac=RSW((NotchtNew1.GE. 2.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,2.0)

        else If (xd(1) .GT. 30/3.6)then
        Notchtrac=RSW((NotchtNew1.GE. 3.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,3.0)

        else If (xd(1) .GT. 55/3.6) then
        Notchtrac=RSW((NotchtNew1.GE. 4.0) .and. (NotchtNew1.LE.
14.0),NotchtNew1,4.0)
   Endif
    Notchtrac1=Notchtrac
  FtracNew1(i)=Traction(Notchtrac1,xd(i)*3.6)
  FtLow=ForctLow(Notchtrac1)
  FtUp=ForctUpper(Notchtrac1)
 FtracNew(i)=RSW(FtracNew1(i).GE.FtLow,FtracNew1(i),FtLow)
 FtracNew(i)=RSW(FtracNew1(i).LE.FtUp,FtracNew1(i),FtUp)
Fte(i)=FtracNew(i)*1000
 Floco(i) =Fte(i)
 Armature(i)=Current(Notchtrac1,xd(i)*3.6)
 Power(i)=Floco(i)*xd(i)
 Pec(i)=Power(i)

 NotchtNow=Notchtrac
 Tracon=.NOT.Tracdn

else If(xd(1).GT.vref(1)+dv/2)then
 Dynon=.true.
 If(Dynon)Fte(i)=0.
Tracon=.NOT.Dynon
Tracdn=.NOT.Dynon

NotchtNew1=0
 NotchtNew=0
 Notchtrac1=0
 Notchtrac=0
 NotchtUp1=0
 NotchtUp=0
 NotchtLo=0
NotchtLo1=0
 NotchtNow=0

 NotchdUp=NotchdNow+1
  NotchdUp1=NotchdUp
  NotchdNew=RSW(NotchdUp1.LE.10.0,NotchdUp1,10.0)
   NotchdNew1=NotchdNew

  If (xd(1) .GT. 70/3.6)   then
  Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
  else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
  Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
```

```
   else If ((xd(1) .LE. 60/3.6).AND. (xd(1) .GT. 55/3.6))then
   Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
   else If ((xd(1) .LE. 55/3.6).AND.(xd(1) .GT. 45/3.6))then
   Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
   else If (xd(1) .LE. 45/3.6) then
   Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
  Endif

    Notchdyn1=Notchdyn
   FdynNew1(i)=DynBrake(Notchdyn1,xd(i)*3.6)

   FdLow=ForcdLow(Notchdyn1)
   FdUp=ForcdUpper(Notchdyn1)
  FdynNew(i)=RSW(FdynNew1(i).GE.FdLow,FdynNew1(i),FdLow)
  FdynNew(i)=RSW(FdynNew1(i).LE.FdUp,FdynNew1(i),FdUp)
  Fdb(i)=-sign(FdynNew(i),xd(i))*1000
  Floco(i)= Fdb(i)
  Armature(i)=0.d0
  Power(i)=Floco(i)*xd(i)
  Pec(i)=0.d0

  NotchdNow=Notchdyn
  Dyndn=.NOT.Dynon

else If(Dynon.AND.xd(1).LE.vref(1)+dv/2)then
  Dyndn=.true.
 If(Dyndn)Fte(i)=0.
Tracon=.NOT.Dyndn
Tracdn=.NOT.Dyndn

NotchtNew1=0
 NotchtNew=0
 Notchtrac1=0
 Notchtrac=0
 NotchtUp1=0
 NotchtUp=0
 NotchtLo=0
NotchtLo1=0
 NotchtNow=0

 NotchdLo=NotchdNow-1
 NotchdLo1=NotchdLo
 NotchdNew=RSW(NotchdLo1.GE.0.0,NotchdLo1,0.0)
 NotchdNew1=NotchdNew

If (xd(1) .GT. 70/3.6)  then
  Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
  else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
  Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
  else If ((xd(1) .LE. 60/3.6).AND. (xd(1) .GT. 55/3.6))then
  Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
  else If ((xd(1) .LE. 55/3.6).AND.(xd(1) .GT. 45/3.6))then
  Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
  else If (xd(1) .LE. 45/3.6) then
  Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
```

```
    Endif
        Notchdyn1=Notchdyn
    FdynNew1(i)=DynBrake(Notchdyn1,xd(i)*3.6)
    FdLow=ForcdLow(Notchdyn1)
    FdUp=ForcdUpper(Notchdyn1)
    FdynNew(i)=RSW(FdynNew1(i).GE.FdLow,FdynNew1(i),FdLow)
   FdynNew(i)=RSW(FdynNew1(i).LE.FdUp,FdynNew1(i),FdUp)
    Fdb(i)=-sign(FdynNew(i),xd(i))*1000
    Floco(i)= Fdb(i)
    Armature(i)=0.d0
    Power(i)=Floco(i)*xd(i)
    Pec(i)=0.d0
    NotchdNow=Notchdyn
   Dynon=.NOT.Dyndn

    Endif


    if (Fdb(1).LT.(Fgrad(1)+Frr(1)-1.0))then
    Dynon=.true.
    If(Dynon)Fte(i)=0.
    Tracon=.NOT.Dynon
    Tracdn=.NOT.Dynon

   NotchtNew1=0
     NotchtNew=0
     Notchtrac1=0
     Notchtrac=0
     NotchtUp1=0
     NotchtUp=0
     NotchtLo=0
   NotchtLo1=0
     NotchtNow=0

     NotchdUp=NotchdNow+1
      NotchdUp1=NotchdUp
       NotchdNew=RSW(NotchdUp1.LE.10.0,NotchdUp1,10.0)
        NotchdNew1=NotchdNew

      If (xd(1) .GT. 70/3.6)   then
      Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
      else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
      Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
      else If ((xd(1) .LE. 60/3.6).AND. (xd(1) .GT. 55/3.6))then
      Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
      else If ((xd(1) .LE. 55/3.6).AND.(xd(1) .GT. 45/3.6))then
      Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
      else If (xd(1) .LE. 45/3.6) then
      Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
     Endif

       Notchdyn1=Notchdyn
     FdynNew1(i)=DynBrake(Notchdyn1,xd(i)*3.6)

     FdLow=ForcdLow(Notchdyn1)
```

```
FdUp=ForcdUpper(Notchdyn1)
FdynNew(i)=RSW(FdynNew1(i).GE.FdLow,FdynNew1(i),FdLow)
FdynNew(i)=RSW(FdynNew1(i).LE.FdUp,FdynNew1(i),FdUp)
Fdb(i)=-sign(FdynNew(i),xd(i))*1000
Floco(i)= Fdb(i)
Armature(i)=0.d0
Power(i)=Floco(i)*xd(i)
Pec(i)=0.d0

NotchdNow=Notchdyn
Dyndn=.NOT.Dynon

else if (Fdb(1).GT.(Fgrad(1)+Frr(1)+1.0) then
Dyndn=.true.
If(Dyndn)Fte(i)=0.
Tracon=.NOT.Dyndn
Tracdn=.NOT.Dyndn

NotchtNew1=0
NotchtNew=0
Notchtrac1=0
Notchtrac=0
NotchtUp1=0
NotchtUp=0
NotchtLo=0
NotchtLo1=0
NotchtNow=0

NotchdLo=NotchdNow-1
NotchdLo1=NotchdLo
NotchdNew=RSW(NotchdLo1.GE.0.0,NotchdLo1,0.0)
NotchdNew1=NotchdNew

If (xd(1) .GT. 70/3.6)  then
Notchdyn=RSW(Notchdnew1 .le. 2.0,Notchdnew1,2.0)
else If ((xd(1) .LE. 70/3.6).AND. (xd(1) .GT. 60/3.6))then
Notchdyn=RSW(Notchdnew1 .le. 3.0,Notchdnew1,3.0)
else If ((xd(1) .LE. 60/3.6).AND. (xd(1) .GT. 55/3.6))then
Notchdyn=RSW(Notchdnew1 .le. 4.0,Notchdnew1,4.0)
else If ((xd(1) .LE. 55/3.6).AND.(xd(1) .GT. 45/3.6))then
Notchdyn=RSW(Notchdnew1 .le. 5.0,Notchdnew1,5.0)
else If (xd(1) .LE. 45/3.6) then
Notchdyn=RSW(Notchdnew1 .le.10.0,Notchdnew1,10.0)
Endif
Notchdyn1=Notchdyn
FdynNew1(i)=DynBrake(Notchdyn1,xd(i)*3.6)
FdLow=ForcdLow(Notchdyn1)
FdUp=ForcdUpper(Notchdyn1)
FdynNew(i)=RSW(FdynNew1(i).GE.FdLow,FdynNew1(i),FdLow)
FdynNew(i)=RSW(FdynNew1(i).LE.FdUp,FdynNew1(i),FdUp)
Fdb(i)=-sign(FdynNew(i),xd(i))*1000
Floco(i)= Fdb(i)
Armature(i)=0.d0
Power(i)=Floco(i)*xd(i)
Pec(i)=0.d0
```

```
    NotchdNow=Notchdyn
Dynon=.NOT.Dyndn

Endif

End!........of Procedural
```

11.4 Program Control Macros

Sub trac_data()!..................Track Data Representation
'
' trac_data Macro

```
    ChDir "C:\Complete Program"
    Workbooks.Open FileName:="C:\Complete Program\Track.xls"
    ActiveWindow.ScrollRow = 1
    Range("A2:C1000").Select
End Sub
```

Sub driver()!.....................Locomotive Commands for train handling
'
' driver Macro

```
    Workbooks.Open FileName:="C:\Complete Program\Command.xls"
    ActiveWindow.ScrollRow = 1
    Range("A2:E2000").Select
End Sub
```

Sub Brake_data()!...............Brake Data Representation
'
' Brake_data Macro

```
    Workbooks.Open FileName:="C:\Complete Program\Brake_data.xls"
    Range("B2:M4").Select
End Sub
```

Sub consist()!......................Definition of train consist simulated
'
' consist Macro

```
Workbooks.Open FileName:="C:\Complete Program\Consist.xls"
    Range("A2:J205").Select
End Sub
```

Sub coupler_data()!................Coupler characteristics for rolling stock
'
' coupler_data Macro

```
    Workbooks.Open FileName:="C:\Complete Program\couplers.xls"
    Range("A2:H4").Select
    ActiveWindow.SmallScroll ToRight:=1
End Sub
```

```vba
Sub ref_details()!..................User Details
'
' ref_details Macro

ChDir "C:\Complete Program"
    Workbooks.Open FileName:="C:\Complete Program\reference_details.xls"
    Range("C17").Select
    ActiveWorkbook.Save
End Sub


Sub exit_run()!.......................Exiting Simulation Window
'
' exit_run Macro

Range("C36").Select
    ActiveWindow.ScrollRow = 1
    ActiveWorkbook.Save
  . ActiveWindow.Close
End Sub


Sub loco_data()!.....................Locomotive characteristics data
'
' loco_data Macro

Workbooks.Open FileName:="C:\Complete Program\More_Locodata.xls"
End Sub


Sub output()!.........................Conversion of output to Excel format
'
' output Macro
ChDir "C:\myacsl"
    Workbooks.OpenText FileName:="C:\myacsl\result2.dat", Origin:=xlWindows, _
    StartRow:=1, DataType:=xlFixedWidth, FieldInfo:=Array(Array(0, 1), Array(15

  _
    , 1), Array(30, 1), Array(45, 1), Array(60, 1), Array(75, 1), Array(90, 1))
    Columns("A:A").ColumnWidth = 12.71
    Columns("B:B").ColumnWidth = 18
    Columns("C:C").ColumnWidth = 11.57
    Columns("C:C").ColumnWidth = 13.14
    Columns("D:D").ColumnWidth = 10
    Columns("D:D").ColumnWidth = 11.86
    Columns("D:D").ColumnWidth = 13.43
    Columns("E:E").ColumnWidth = 12.71
    Range("A1:J65000").Select
    Selection.Cut
    ChDir "C:\Complete Program"
    Workbooks.Open FileName:="C:\Complete Program\Output.xls"
    Range("A2:J65001").Select
    ActiveSheet.Paste
End Sub
```

Sub run()!.......................Running the ACSL program automatically
'

' run Macro

    ActiveWindow.ScrollRow = 1
    Range("K1").Select
    Selection.Hyperlinks(1).Follow NewWindow:=False, AddHistory:=True
End Sub

Sub wagon_data()!.......................Wagon Data
'

' wagon_data Macro

ChDir "C:\Complete Program"
    Workbooks.Open FileName:="C:\Complete Program\Wagon_Detail.xls"
    ActiveWindow.ScrollColumn = 1
    Range("A2:V3").Select

End Sub

Sub Notes1()!.......................Notes on locomotive 1
'

' Notes1 Macro

Workbooks.Open FileName:="C:\Complete Program\Notes1.xls"
    Range("B2:B50").Select
End Sub

Sub Notes2()!.......................Notes on locomotive 2
'

' Notes2 Macro

Workbooks.Open FileName:="C:\Complete Program\Notes2.xls"
    Range("B2:B50").Select
End Sub

Sub Notes3()!.......................Notes on locomotive 3
'

' Notes3 Macro

Workbooks.Open FileName:="C:\Complete Program\Notes3.xls"
    Range("B2:B50").Select
End Sub

Sub Loco_type1()!.......................Defines class of locomotive
'

' Loco_type1 Macro

Range("F3").Select
    Application.Run "More_Locodata.xls!Loco_type1"

End Sub

Sub Loco1()................Editing of locomotive characteristics
'
' Loco1 Macro
```
Range("F3").Select
    ActiveSheet.Shapes("Option Button 37").Select
    Selection.OnAction = "Motor_data1"
    ActiveSheet.Shapes("Option Button 38").Select
    Selection.OnAction = "Tractive_effort1"
    ActiveSheet.Shapes("Option Button 39").Select
    Selection.OnAction = "Dynamic_Brake1"
End Sub
```

Sub Motor_data1()...............Armature Current Data for loco1
'
' Motor_data1 Macro
```
Workbooks.Open FileName:="C:\Complete Program\11E_Current.xls"
    ActiveWindow.ScrollRow = 1
    Range("A2:O91").Select
End Sub
```

Sub Tractive_effort1().............Tractive Effort Data for loco1
'
' Tractive_effort1 Macro
```
    Workbooks.Open FileName:="C:\Complete Program\11Etract.xls"
    Range("A2:O103").Select
End Sub
```

Sub Dynamic_Brake1()!................Dynamic Brake Data for loco1
'
' Dynamic_Brake1 Macro
```
Workbooks.Open FileName:="C:\Complete Program\11Edyn.xls"
    Range("A2:K94").Select
End Sub
```

Sub Tables()!...........................Converting tables to format recognised in
ACSL
'
' Tables Macro
```
Workbooks.Open FileName:="C:\Complete Program\Tables.xls"
    Workbooks.Open FileName:="C:\Complete Program\11Etract_try.xls"
    ActiveWindow.WindowState = xlMaximized
    ActiveWindow.ScrollRow = 1
    Range("B3:P93").Select
    Selection.Cut
```

```
ActiveWindow.Close
Range("A10").Select
ActiveSheet.Paste
Workbooks.Open FileName:="C:\Complete Program\11Edyn_try.xls"
ActiveWindow.ScrollRow = 1
Range("B3:L93").Select
Selection.Cut
ActiveWindow.Close
ActiveWindow.SmallScroll Down:=103
Range("A114").Select
ActiveSheet.Paste
Workbooks.Open FileName:="C:\Complete Program\11E_current2.xls"
Range("B3:P103").Select
Selection.Cut
ActiveWindow.Close
ActiveWindow.SmallScroll Down:=106
Range("A215").Select
ActiveSheet.Paste
Workbooks.Open FileName:="C:\Complete Program\7Etract_try.xls"
Range("B3:P93").Select
Selection.Cut
ActiveWindow.Close
ActiveWindow.SmallScroll Down:=108
Range("A326").Select
ActiveSheet.Paste
Workbooks.Open FileName:="C:\Complete Program\7Edyn_try.xls"
ActiveWindow.ScrollColumn = 1
ActiveWindow.ScrollRow = 1
Range("B3:L93").Select
Selection.Cut
ActiveWindow.Close
ActiveWindow.SmallScroll Down:=106
Range("A430").Select
ActiveSheet.Paste
Workbooks.Open FileName:="C:\Complete Program\7E_current2.xls"
ActiveWindow.ScrollRow = 1
ActiveWindow.ScrollColumn = 1
Range("B3:P103").Select
Selection.Cut
ActiveWindow.Close
ActiveWindow.SmallScroll Down:=98
Range("A531").Select
ActiveSheet.Paste
ActiveWorkbook.SaveAs FileName:="C:\Complete Program\Tables.inc", _
    FileFormat:=xlCSV, CreateBackup:=False
ActiveWindow.Close
End Sub
```

```
Sub Motor_data2()!...............Armature Current Data for loco2
'

' Motor_data2 Macro

Workbooks.Open FileName:="C:\Complete Program\7E_current.xls"
    Range("A2:O102").Select
End Sub


Sub Dynamic_Brake2()!..............Dynamic Brake Data for loco2
'

' Dynamic_Brake2 Macro
' Macro recorded 00/03/28 by Lumka Majola
'

' Keyboard Shortcut: Ctrl+w
'

    Workbooks.Open FileName:="C:\Complete Program\7Edyn.xls"
    Range("A2:K94").Select
End Sub


Sub Tractive_effort2()!..................Tractive Effort Data for Loco2
'

' Tractive_effort2 Macro

    Workbooks.Open FileName:="C:\Complete Program\7Etract.xls"
    Range("A2:O104").Select
End Sub


Sub sim_parameters()!.................Simulation parameters
'

' sim_parameters Macro

Workbooks.Open FileName:="C:\Complete Program\sim_par.xls"
    Range("A2:E2").Select
End Sub
```