Modelling and Analysis of Rail Grinding & Lubrication Strategies for Controlling Rolling Contact Fatigue (RCF) and Rail Wear

by

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ABSTRACT

Rails play a significant role in transport of goods and passengers. In Australia railway transport industry contributes 1.6% of GDP with goods and services worth $AUD 8 billion each year which includes $ AUD 0.5 billion per year in exports (Australasian Railway Authority Inc, 2002).

Rail track maintenance plays an important role in reliability and safety. The Office for Research and Experiments (ORE) of the Union International des Chemins de Fer (UIC) has noted that maintenance costs vary directly (60–65 per cent) with change in train speed and axle load. It was also found that the increase in these costs with increased speed and axle load was greater when the quality of the track was lower (ORR, 1999). Failures during operation are costly to rail players due to loss of service, property and loss of lives. Maintenance and servicing keep rail tracks in operating, reliable and safe condition. Therefore, technical and economical analysis is needed by rail players to reduce maintenance cost and improve reliability and safety of rail networks.

Over the past few years, there have been major advances in terms of increased speed, axle loads, longer trains, along with increased traffic density in corridors. This has led to increased risks in rail operation due to rolling contact fatigue (RCF) and rail wear. The infrastructure providers have less incentive to maintain a given infrastructure standard if its access charges are rigid and rolling stock standard is not achieved. It has been estimated that between 40 to 50 per cent of wagon maintenance costs and 25 per cent of locomotive maintenance costs are related to wheel maintenance (Railway Gazette International, 2003). The economic analysis of Malmbanan indicates that about 50% of the total cost for maintenance and renewal were related to traffic on rails and 50% not related to traffic, such as signaling, electricity and snow-clearance. The results from the analysis have made it possible for the mining company LKAB to start up the 30 Tonnes traffic with new wagons and locomotives on the Malmbanan line in year 2001 (Åhrén et al 2003). The rail infrastructure providers have challenges to maintain infrastructure due to government control on access charges and limited control on rail operations.

The aim of the research is to:

- Develop a maintenance cost model for optimal rail grinding for various operating conditions; and
- Develop integrated rail grinding and lubrication strategies for optimal maintenance decisions.

In this research real life data has been collected, new models have been developed and analysed for managerial decisions. Simulation approach is used to look into the impact on various costs such as rail grinding, operating risk, down time, inspection, replacement, and lubrication. The results of the models for costs and the effect of rail grinding and lubrication strategies are provided in this thesis.

In this research rail track degradation, rail failures and various factors that influence rail degradation are analysed. An integrated approach for modelling rail track degradation, rail wear, rail grinding and lubrication is developed. Simulation model and cost models for rail grinding are developed and analysed. It has been found through this research that rail grinding at 12 MGT interval is economic decision for enhancing rail life. It was also found that lubrication is most effective compared to stop/start and no lubrication strategies in steep curves.

Rail grinding strategies developed in this research have been considered by Swedish National Rail for analysing the effectiveness of their existing policies on grinding intervals. Optimal grinding and lubrication decisions have huge potential for savings in maintenance costs, improving reliability and safety and enhancing rail life.

Keywords: Rolling contact fatigue, wear, rail grinding, lubrication and rail degradation.

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STATEMENT OF ORIGINALITY

I declare that to the best of my knowledge the work presented in this thesis is original except as acknowledged in the text, and that the material has not been submitted, either in whole or in part, for another degree at this or any other university.

Signed:……P.V.Reddy……Venkatarami Reddy

Date:

LIST OF PUBLICATIONS

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5. Reddy, V., Chattopadhyay, G., Larsson, P. O., Technical vs. Economical decisions: A case study on preventive rail grinding, APIEM Dec 2004, Gold coast, Australia.

I, **Venkatarami Reddy**, a candidate for the degree of Master of Applied Science (BN 71) at Queensland University of Technology, have not been enrolled for another tertiary award during the term of my candidature without the knowledge and approval of the University's **Research Degree Committee**.

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NOMENCLATURE

a	Expected cost per derailment	[AUD]
A_c	Critical railhead area when rail replacement is recommended	[mm^2]
A_i	Cross sectional rail profile area i^{th} interval	[mm^2]
A_{GW_j}	Cross sectional area loss due to grinding in period j	[mm^2]
A_{TW_j}	Cross sectional area loss due to traffic wear in period j	[mm^2]
A_0	Cross sectional profile area of a new rail	[mm^2]
A_H	Hertzian contact area	[m^2]
A_{GW_q}	Cross sectional area loss due to grinding in period q	[mm^2]
A_{TW_q}	Cross sectional area losses due to traffic wear in period q	[mm^2]
A_0	Cross sectional profile area of a new rail	[mm^2]
A_{lub}	Area below lubricated wear rate for high rail (see figure-2)	[mm^2]
$A_{non\text{-}lub}$	Area above non-lubricated wear rate for high rail (see figure-2)	[mm^2]
C_r	Cost per rectification of rail breaks on emergency basis	[AUD]
C_{tot}	Total cost	[AUD/year]
c	Cost of each rail break repair on emergency basis	[AUD]
$\overline{c}$	Expected cost of each rail break repair on emergency basis	[AUD]
c_d	Down time cost	[AUD/year]
c_g	Grinding cost	[AUD/year]
c_i	Inspection cost	[AUD/year]
c_r	Risk cost	[AUD]
c_{re}	Replacement cost	[AUD/year]
c_{d_j}	Down time cost for lubrication strategy j	[AUD/year]
c_{g_j}	Grinding cost for lubrication strategy j	[AUD/year]
c_{i_j}	Inspection cost for lubrication strategy j	[AUD/year]
c_{r_j}	Risk cost for lubrication strategy j	[AUD]
c_{re_j}	Replacement cost for lubrication strategy j	[AUD/year]
c_{l_j}	Lubrication cost for lubrication strategy j	[AUD/year]
c_{tot_j}	Total cost for lubrication strategy j	[AUD/year]
d	Expected cost of down time due to traffic loss	[AUD/h]
D	Distance slipped	[m]

$\overline{E}$	Energy dissipation	[J/m]
$E\,[M_{i+1}, M_i]$	Expected number of failures over M_i *and* M_{i+1}	[-]
$E_j\,[M_{i+1}, M_i]$	Expected number of failures over M_i *and* M_{i+1} for j^{th} strategy	[-]
F_x ,F_y	Creep forces in x and y direction	[N]
$F_n(m)$ [$f_n(m)$]	Rail failure distribution [density] function	[-]
$F_j(m)$ [$f_j(m)$]	Rail failure distribution [density] function for j^{th} strategy	[-]
$f_2 = f(\mathrm{r_{lub}}) = f_2(\mathrm{R})$	is the function of curve radius for the lubricated curve	[mm^2]
$f_2(\mathrm{R}) = \phi(R) = 1$	, this is the traffic wear rate for Lubricated high rails	[MGT/mm^2]
$f_1 = \mathrm{f}(\mathrm{r_{non\text{-}lub}}) = f_1$ (R)	the function of curve radius for the non-lubricated curve	[mm^2]
f_1 (R) $= \phi(R) = 0$	, the traffic wear rate for non-lubricated high rail	[MGT/mm^2]
g	Cost of grinding per pass per meter	[AUD/pass/m]
$G(c)$	Distribution function of cost of each rail break repair	[-]
GD_j	Wear Depth due to rail grinding after period j	[mm]
GDq	Grinding Depth due to grinding after period q	[mm]
h	Vertical central wear on the railhead	[mm]
h_{DT}	Expected downtime due to each grinding pass	[h]
H	Material hardness	[Pa]
H	Weighted side- and height wear	[mm]
H_{limit}	Critical H when the rail must be replaced	[mm]
I	Cost in investment of rail for segment L	[AUD]
I_f	Inspection frequency in Millions of Gross Tonnes (MGT)	[-]
I	Index	[-]
i_c	Cost of each inspection	[AUD]
j	Index	[-]
j	Lubrication strategy	[-]
k	Cost of rectification of potential rail breaks based on NDT	[AUD]
K	Dimensionless coefficient	[-]
L	Length of rail segment under consideration	[m]
$L_{\%}$	Percent rail length under consideration	[-]
m	Millions of Gross Tonnes	[kg$\cdot$10^6]
m_j	MGT in period j	[-]
m_q	MGT in period q	[kg$\cdot$10^6]
M_i	Total accumulated MGT of the section studied up to decision I	[kg$\cdot$10^6]

M_j Total accumulated MGT for the section studied up to decision j [kg·10^6]

M_N Total accumulated MGT for rail life up to end of period N [kg·10^6]

M_Φ Spin moment [Nm]

n The number of failures [-]

n_{A_j} Number of accidents in period j [-]

n_{GP_i} Number of grinding passes for i^{th} grinding [-]

n_{NDT_j} Number of detected potential rail breaks using NDT [-]

n_{RB_j} Number of rail brakes in between two NDT inspections [-]

n_{A_q} Number of accidents in period q [-]

$n_{GP_{ij}}$ Number of grinding pass for i^{th} grinding in j^{th} strategy [-]

n_{NDT_q} Number of NDT detected potential rail breaks in period q [-]

n_{RB_q} Number of rail breaks in between two NDT inspections in period q [-]

N Normal load [N]

N Total number of periods up to safety limit for renewal [-]

$N(M_{i+1},M_i)$ Number of failures over M_i and M_{i+1} [-]

N_I Number of inspection over rail life [-]

N_j Total number of periods up to safety limit for renewal for strategy j [-]

$N_j(M_{i+1},M_i)$ Number of failures over M_i and M_{i+1} as per strategy j [-]

$P[.]$ Probability [-]

$P_i(A)$ Probability of undetected potential rail breaks leading to derailment [-]

$P_i(B)$ Probability of detecting potential rail breaks using NDT [-]

q Index [-]

r Discounting rate between preventive rail grindings [%]

r_i Discounting rate between inspections using NDT [%]

r_y Annual discounting factor [-]

R Track circular curve radii [m]

RC_w Estimated Rail Crown wear width [mm]

RG_w Estimated Rail Gauge wear width [mm]

R Track circular curve radii [m]

RC_w Estimated Rail Crown wear width [mm]

RG_w Estimated Rail Gauge wear width [mm]

s Flange wear [mm]

T	Tangential force	[N]
TD_j	Wear Depth due to traffic after period j	[mm]
TD_q	Traffic Depth due to wear after period q	[mm]
V_W	Wear volume	[m^3]
WOL_i	Worn out level of rail after i^{th} grinding	[%]
γ	Creepage	[m/m]
γ_x , γ_y	Creepage in x and y direction	[-]
Φ	Spin	[-]
Y_j	= Decision variable for lubrication strategy	[-]
	= 0 for no or continuous lubrication	[-]
	= 1 for stop/start lubrication	[-]
y	rail life in years	[-]
α	Miniprof degrees	[^{o}]
β, λ	Weibull parameters	[-]
$\Lambda(m)$	Failure intensity function associated with m	[-]
β_j, λ_j	Weibull parameters for failures in j^{th} strategy	[-]
$\Lambda_j(m)$	Failure intensity function associated with m in j^{th} strategy	[-]
ϕ	= Traffic wear rate	[MGT/mm^2]
T_{wear}	= Total wear rate between lubricated and non-lubricated curves	[MGT/mm^2]

Chapter 1

Introduction and Scope of work

1.1 Introduction

Australian rail industry generates 1.6% of Australia's gross domestic product (GDP) with significant economic benefits of $ AUD 8 billion each year, including 0.5 billion per year in exports (Australasian Railway Association Inc, 2002). The Office for Research and Experiments (ORE) of the Union International des Chemins de Fer (UIC) has noted that maintenance costs vary directly (60–65 per cent) with change in train speed and axle load. The research also found that the increase in these costs (with increased speed or axle load) was greater when the quality of the track was lower (ORR, 1999). The infrastructure providers are thus faced with challenges to minimise the railway track maintenance cost while ensuring high safety standards and providing reliable services to the track users.

With increased privatisation and competition, the relationship between the railway infrastructure providers and freight/passenger services has been transformed into economic and contractual relationships (O'Keeffe, 1995). Due to economic pressure there is a world-wide trend to increase axle loads, longer trains, traffic density and speed to reduce operating cost for increasing efficiency. American Railroads operating trains at axle loads of 33 to 35 tonnes. Axle loads around the world have increased in general from 25 tons to 32.5 tons in last ten years (Allen, 1999). This trend is also observed in Australia. This has led to increased risks in rail operation due to rolling contact fatigue (RCF), which occurs due to repetitive heavy axle load and rail wear due to wheel rail contact.

Rail players all over the world are conducting studies on rail grinding intervals based on various track, traffic and operating conditions. The uncertainty in this decision is mainly due to insufficient understanding of the different costs involved in maintenance of rail infrastructure up to an acceptable standard. It studies preventive grinding and lubrication strategies for developing models for optimal rail grinding and lubrication decisions to control rolling contact fatigue (RCF) and rail wear for improving reliability, safety and reducing operating costs.

This research identifies cost drivers and links decision process based on field and test curve data for stochastic modelling.

1.2 Aims and objectives of the study

Despite advances in maintenance, inspection and rail manufacturing technology, increased operating load and frequencies results in rail fatigue and traffic initiated wear. Recent review shows that rolling contact fatigue (RCF) such as squats (Figure 1.1 (a)) and head check (Figure 1.1 (b)) defects have been increasing due to introduction of longer and heavier trains with increased axle loads and speed (Railtrack Plc, 2001). European Union estimated that premature rail removal, renewal and maintenance costs due to these problems amount to 300 Million Euros ($US 319 Million) per year (Sawley and Reiff, 2000).

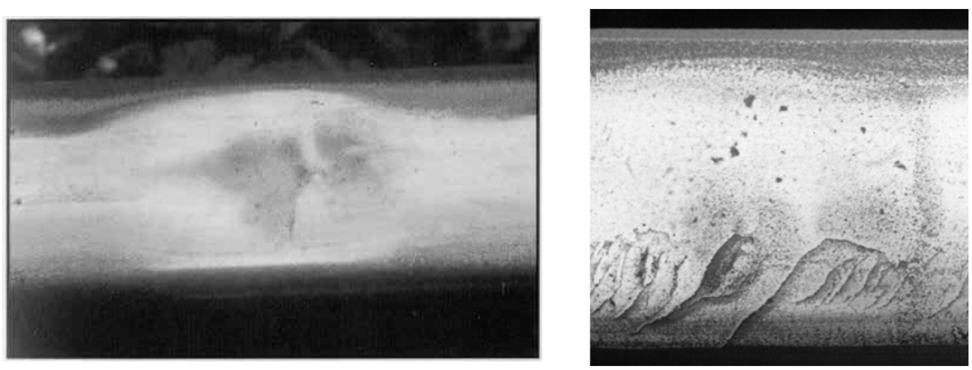

Figure 1.1: (a) Squats (b) Head Check

Recent research shows that rail grinding has an important role in reducing rail degradation, which can reduce rail brakes, early rail replacements and derailments (Kalousek and Magel, 1997).

The aim of this research is to analyse the effect of rail grinding and lubrication for the development of optimal maintenance decisions in controlling rolling contact fatigue (RCF) and rail wear.

The objectives of this study are:

- Development of a comprehensive understanding of characteristics of rail and track degradation under various conditions;
- Examination of existing track maintenance policies;

- Collection of data for RCF, traffic initiated wear, lubrication and rail grinding;
- Development of maintenance cost model for optimal preventive rail grinding interval under various operating conditions;
- Analyse models and compare results of various rail grinding strategies; and
- Develop integrated rail grinding and lubrication strategies for optimal maintenance decisions.

1.3 Research Methodology

This research started with reviewing railway track wear and fatigue related studies in Australia and overseas, for a comprehensive understanding of railway track degradation under various traffic, track and operating conditions. Data on maintenance cost, rail wear, rolling contact fatigue (RCF), lubrication and rail grinding for various million gross tonnes (MGT) of freight are collected from Queensland Rail (QR) and Swedish National Railways. These are analysed for development of the cost models for optimal rail grinding decisions.

1.4 Significance of the work

The mathematical models developed through research use rolling contact fatigue (RCF) and traffic wear data from QR and Swedish National Railways. Costs due to grinding, risks, inspection, down time, and replacements are considered in this study. Models to estimate annuity costs and cost per MGT are used as decision tools for developing effective maintenance strategies for a reliable and safe rail operation.

Squats and Spalling due to rolling contact fatigue (RCF) and Head Checks (HC) in curves and switches due to increased slippage towards the gauge corner and decreased area of wheel-rail contact have adverse effect on reliability and safety of rail track. These surface initiated cracks due to RCF, wear of railhead and wheel flanges are major challenges for railtrack owners (Hiensch et. al., 2001). Four people were killed and 34 injured on October 17th, 2000 when an Inter City Express train travelling at 115 miles per hour derailed on a curve near Hatfield on Britain's East Coast Main Line. The analysis of this accident showed that the cause was gauge corner cracking/head checking due to rolling contact fatigue leading to £ 580 Million bill for the cost of the re-railing and compensation for affected people and companies. The cost includes a £ 50 Million compensation package for the passengers who have suffered from the Hatfield train derailment which has closed many routes of the national rail network (International Railway Journal, 2001).

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Figure 1.2: Spalling (Railtrack Plc, 2001)

On March 17th, 2001, an Amtrak's train, California Zephyr, derailed near Nodaway, Iwoa while travelling from Chicago to Emerville, CA. The cause of derailment was defective rail and faulty replacement.

Maintenance in railway tracks is generally undertaken on an ad hoc basis around the world due to inefficient fund allocation. European railways have similar problems in maintenance planning and costing (Johnansson and Nilsson, 1998). Prediction of railway track degradation is therefore, vital for budgeting, planning and implementation of maintenance strategies (Zhang, Y., 2000).

Indian Railways with more than 100,000 km track carrying 11 Million passengers a day faces over 300 accidents per year. More than 33% of these accidents are caused by track defects and rail failures (India's Commission of Railway Safety Report, 1998-99). A significant percentage of these accidents can be prevented through effective maintenance strategies such as controlling rolling contact fatigue (RCF) and rail wear by appropriate rail grinding and lubrication strategies. This research will address these issues related to decision making in track maintenance.

In this research empirical approach has been used to fit the raw data for developing models in controlling rolling contact fatigue and wear.

1.5 The structure of the Thesis

The structure of this thesis is outlined below:

Chapter 1 provides background of the study, aims, objectives, research methodology and significance of this research work.

Chapter 2 provides a brief overview of the literature on railway track and maintenance models. It covers track characteristics and various operating and traffic conditions under which rails operate.

Chapter 3 provides analysis of failure mechanisms for rail track degradation. It addresses variables such as speed, Million Gross Tonnes (MGT), axle loads, wheel/rail interaction, wheel/rail wear, rolling contact fatigue, effect of rail grinding and lubrication. It also covers effect of curve radius, traffic density, rail material, track geometry, rail dynamics, inspection intervals and wear limits.

Chapter 4 deals with integrated framework for rail track degradation modelling in deciding optimal maintenance strategies. Real life data from North American Rails, Swedish National Rail and Queensland Rail in Australia are analysed. An integrated approach is developed for controlling fatigue initiated surface cracks and rail track maintenance. These models consider crack initiation/growth rate and wear due to traffic, lubrication and rail grinding.

Chapter 5 deals with modelling of preventive rail grinding for optimal intervals to control RCF and traffic wear. This chapter focuses on the rail breaks, rail degradation, grinding, inspection, down time, risks and rail replacement costs to develop economic models for optimal rail grinding decisions. Real life data are collected and analysed for developing these models. Illustrative numerical examples and simulation approaches are used for the analysis of the RCF and traffic wear based on various grinding intervals. This is finally applied for strategic decisions.

Chapter 6 deals with integrated rail grinding and lubrication strategies for optimal maintenance decisions. Lubrication cost data are collected from Queensland Rail (QR) and Swedish National Railways. Illustrative numerical examples are used for the analysis of annuity costs with lubrication, no lubrication and Stop/start lubrication strategies.

Chapter 7 provides a summary of the thesis with conclusions and limitations of current research and also provides scope for future research.

Chapter 2

Overview of Railway Tack Structure and Maintenance Models

2.1 Introduction

Most of the physical systems and their components degrade/fail over time. This affects the performance of the system and can lead to system failures. The deterioration process and its effects on the system failure are often uncertain. Failure during operation can be costly, e.g. loss of service, property and even life. Maintenance has the ability to rejuvenate an aging system in order to keep it operating with reliability and safety. Maintenance is the combination of all technical and administrative actions intended to retain an item in or restore it to a state in which it can perform its required function (Hastings, 2000).

Outline of this chapter is as follows: In section 2.2 overview of railway track structure is discussed. Track component characteristics are explained in section 2.3. In section 2.4 Maintenance is discussed. Section 2.5 presents maintenance of railway track. In section 2.6 existing maintenance models in industry are discussed. Summary and conclusions are discussed in section 2.7.

2.2 Railway track structure

A railway track structure is designed to provide safety and comfort to rail passengers and movement of goods at economic price. Tracks serve as a stable guide for trains with vertical and horizontal alignment (Esveld, 2001). Railtrack components are grouped into two main categories, the superstructure and substructure. The superstructure consists of the rails (Figure 2.1: A), sleepers (Figure 2.1: B) and a fastening system (Figure 2.1: C) to hold the components together.

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Figure 2.1: Railway Track Structure: Cross Section (Esveld, 2001)

The substructure consists of the ballast (Figure 2.1: D), sub-ballast (Figure 2.1: E) and the formation or subgrade (Figure 2.1: F). These two groups are separated by the sleeper-ballast interface. The other elements are rail joints or welds in continuous welded rail (CWR).

2.2.1 Rails

Rails are the longitudinal steel members that directly guide the train wheels evenly and continuously. The rail acts as an elastic spring under high frequency loading with sufficient vertical, lateral and rotational mass, stiffness and inertia that result in substantial energy absorption by the rail itself. The rails must possess sufficient stiffness in order that they can act as beams and transfer the concentrated wheel loads to the spaced sleeper supports without excessive deflection between supports (Ernest and John, 1994).

Rails are made from mild steel (up to 25% of carbon), which provides high fatigue toughness. Improved steel making processes are now being used to produce high quality steel and this has lead to a significant improvement in rail fatigue performance. Head hardened rails are used to increase wear resistance of the railhead, whilst retaining high fatigue toughness for rest of the rail. Surface hardening is done using quenching after hot rolling of a heat treatable grade steel. However, the head hardness is lost during the welding process at rail joints (Simson, 1999).

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Figure 2.2: Rail structure (dimensions for 60 Kg) (FOSTER Rail Products)

2.2.2 Sleeper (Tie)

Sleepers hold the rails to correct the gauge and transmit loads in the rails to the ballast. Sleepers or ties have several important functions (Esveld, 2001):

1. To receive the load from the rail and distribute it over the supporting ballast at an acceptable ballast pressure level;
2. To hold the fastening system to maintain the proper track gauge;
3. To restrain the lateral, longitudinal and vertical rail movement by anchorage of the superstructure in the ballast; and
4. To provide support to the rails to help develop proper rail/wheel contact.

Various types of sleepers used in the railtrack system are:

1. Timber
2. Concrete
3. Steel

Timber sleepers are the most commonly used in the railway system. The reasons for choosing timber are its cost effectiveness, resilience, corrosion resistance, and workability, ease of handling, potential re-use and insulation. The life of timber sleepers can vary from 8 to 30 years depending on specie, quality and density of traffic, position in the track, climate and maintenance. Some species may even have a life of 50 years (McAlpine, 1991).

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Figure 2.3: Concrete sleepers and Fasteners (PANDROL)

Concrete sleepers are generally considered more economical than timber sleepers for heavy haul tracks. Concrete sleepers have much longer life than timber sleepers, with an anticipated life of 50 years (McAlpine, 1991). Prestressed concrete sleepers were first used in Australia in 1940 and are now widely spread used since the early 1980's (Muller, 1985). Tracks constructed with concrete sleepers also have higher buckling resistance, lower maintenance requirements and uniform specifications. However, due to heavy weight of more than 300 kg each, they need special laying machines for installation. They also need special considerations in specifying design loads to prevent cracking, and need rail pads to improve vibrations (McAlpine, 1991). Concrete sleepers are very sensitive to impact loads (Riessberger, 1984). Rail top irregularities need to be controlled to avoid impact loads.

Steel sleepers are used because of sleeper life advantages over timber sleepers (two to three times of that of timber sleepers) and resistance to insect attack (Brodie et al., 1977). They also provide greater lateral and longitudinal track resistance than timber sleepers (Birks et al., 1989). However, due to their special cross shape they require more tamping after initial installation. Special attention must also be paid to rail fastening selection and insulation. Although a steel sleeper has been used for many years, particularly in countries where termites are a problem, research is being undertaken in this area by British steel corporation (BSC) (Cope, 1993).

2.2.3 Fastening system

The fastener serves the purpose of clamping the rail to the sleeper. The clamping assists in transferring lateral loads from the rail to the rest of the track by limiting horizontal movement. The rail fastening must permanently and reliably transmit forces to the sleeper. Various types of fasteners used in railtrack system are (Zhang, 2000):

(a) Spikes
(b) Rail anchors
(c) Elastic fastening system

The selection of appropriate fasteners depends on railtrack structure (rail type and size, sleeper type and size, track curvature and superelevation), traffic conditions (axle loads, train speeds and annual tonnage), maintenance requirements and economic restraints (Zhang, 2000).

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Figure 2.4: (a) Spikes, (b) Rail Anchors and (c) Elastic Fastening System (PANDROL)

Elastic Rail Clips are extensively used in the railtrack system because these fasteners offer resistance to lateral and longitudinal load, maintaining gauge, arrest rail creep and prevent track buckling (Cope, 1993).

2.2.4 Ballast

Ballast is the selected crushed granular material placed as the top layer of the substructure in which the sleepers are embedded. The functions of ballast are:

- To resist vertical, uplift lateral and longitudinal forces applied to the sleepers to retain track in its required position;
- To provide some of the resiliency and energy absorption for the track;
- To provide large voids for storage of fouling material in the ballast, and movements of particles through the ballast;
- To facilitate maintenance surfacing and lining operations (to adjust track geometry) by the ability to rearrange ballast particles with tamping;
- To provide immediate drainage of water falling onto the track; and
- To reduce pressures from the sleeper bearing area to acceptable stress levels for the underlying material (Esveld, 2001).

2.2.5 Subballast

The layer between the ballast and the subgrade is the subballast (Figure 2.1: E). The functions of subballast are:

- To prevent upward migration of fine material emanating from the subgrade;
- To prevent interpenetration of the subgrade and the ballast; and
- To prevent subgrade attribution by the ballast, which in presence of water, leads to slurry formation and hence prevent this source of pumping. This is a particular problem if subgrade is hard (Ernest and John, 1994).

2.2.6 Subgrade

The subgrade is the platform upon which the track structure is constructed. It is also referred as formation (Zhang, 2000). Its main function is to provide a stable foundation for the subballast and ballast layers. The subgrade is an important substructure component which can have a significant influence on track performance and maintenance. It acts as superstructure support resiliency, and contributes substantially to the elastic deflection of the rail under wheel loading. Its stiffness magnitude is believed to influence ballast, rail and sleeper deterioration (Esveld, 2001).

2.3 Track component characteristics

The railtrack is composed of several components as outlined above. Each component has a specific function. The rail tracks experience vertical, horizontal, and longitudinal forces that can be static, dynamic, and thermodynamic (Zhang, 2000). These forces influence the functions of the basic components in the track which inturn affect degradation and the failure process. The failure of each component has an effect on the function of other components in the railtrack system. It is therefore, important to analyse the characteristics of the each component to be able to measure the defects and failures to prevent catastrophic failures.

2.3.1 Rail deterioration

Rails are designed to fit with the shape of the wheel to form a combination which will reduce contact stresses. This also reduces twisting effect of the wheel load on the rail by keeping the wheel/rail contact area away from the gauge corner shelling, head check fatigue damage and side wear. Further wheel loads produce bending moments and shear forces in the rail. They cause longitudinal compressive and tensile stresses which are mainly concentrated in the head and foot of the rail whilst the shear forces produce shear stresses which occur mainly in the web. It is important to provide adequate resistance against the bending moment which determines the areas of the head and foot of the rail (Cope, 1993). The rail head gets worn away by wheels on its surface and worsened by abrasive contact with the baseplate or sleeper on its underside. Corrosion leads to loss of rail section and the surface crack itself reduces the fatigue resistance of the rail. Traffic wear, rolling contact fatigue and plastic flow are growing problems for modern railways. Increased speed, higher axle loads, increased traffic and freight lead to the surface initiated cracks on the rail. These problems are addressed in detail in Chapter 3.

2.3.2 Sleeper Deterioration

Sleeper design depends on weight and speed of trains, curve design limits and the type of fastening system. The combination of hardness of the rail and springiness of the ballast under the sleeper, leads to distribution of the wheel loads between several sleepers, so that even if the wheel is directly over a sleeper, only about half of the wheel load is actually transmitted to that sleeper (Cope, 1993).

Timber Sleepers

Timber sleepers deteriorate in terms of splits, base plate/rail cut, break, termite attack and fungal decay. Most deterioration modes are mainly dependent on the timber species and quality, in-factory treatment and environmental factors such as climate conditions and locality (Zhang, 2000).

A survey of timber sleeper defects of Queensland Rail (ROA, 1990) revealed that fungal decay dominates sleeper deterioration, accounting for 53% of sleeper condemnations. Splitting and termite attack account for 23%, of which only 6% is caused by spike kill (2%) and rail cut (4%). Some sleepers (7%) also are rejected without apparent reason.

One of the critical aspects to determine the condition of track with respect to sleepers is the dispersion of defective sleepers in the railway track. A section of railway track with 50% defective sleepers may still be safe to operate if the failed sleeper lies between two sound ones (Wirth et al., 1998). The Association of American Railways (AAR) has conducted research into multiple sleeper failures (AAR Tie Working Group, 1985 reported in Goodall, 1998). The study has shown that the maintenance policy is a key factor in the occurrence of multiple sleeper failure. A further conclusion was that the number of clusters of defective sleepers of various sizes provides a more relevant basis for replacement decisions than just the percentage of failed sleepers in the section of track. Therefore, when comparing replacement strategies for the sleepers in the section of railway track, the clustering patterns of the defective sleepers should be taken into account (Adams, 1991).

Concrete Sleepers

Cracking is one of the possible failure modes of concrete sleepers. Although decay at bottom edges and soffit of sleepers has not been a general trend, it has been evident on Queensland Rail's Goonyella to Hay point heavy haul line (Powell, 1989). The edges of sleepers are rounded by abrasion, soffit material is worn off to various degrees, and the area surrounding the sleeper forms a slurry hole.

The attrition was considered to be a direct result of abrasion between the sleeper and ballast material which came about as a result of track pumping initiated by a localised track weakness (Zhang, 2000). Under indecisive conditions attrition of concrete sleepers could become a dominant deterioration model. Tests at the facility for accelerated service testing (FAST) shows that Heavy Axle-Load Loop indicated up to two millimetres of abrasion can be produced by 51 MGT traffic and harder rail pads caused more abrasion than softer (rubber based pads), (Reiff, 1993).

Steel Sleepers

Test results at FAST indicated that cracking of the fastener tabs has necessitated steel sleeper replacements (Dean and Kish, 1980). Possible reasons for cracking included residual stress from the original bending of tabs, plastic deformation of the tabs in service and fatigue bending stresses produced by combined vertical and lateral loads. It was suggested that the problem could be overcome by improvement in design of the fastener system. Smaller sleeper spacing can avoid excessive strains in sleepers. Sleepers spaced at 600 mm are able to tolerate axle loads up to 40 ton without strains exceeding the material's fatigue limit (Jeffs and Mayhew, 1990).

2.3.3 Ballast Deterioration

Ballast is used to support ties and keep the track in correct alignment while draining the precipitation. The condition of each of these elements declares the weight and type of equipment that can be used on the line, as well as the speeds allowed on the line (Cope, 1993). Ballast quality deteriorated with wheel load, total tonnage, the disturbance by maintenance and environmental factors. Ballast fouling and aggregate material deterioration are the major degradation modes (Zhang, 2000).

Ballast fouling is a process of ballast voids being filled with fines, either from ballast particle abrasion or form intrusion of foreign substances such as windblown dust, spillage from wagons and pumped fines from underlying subgrade (Selig et al., 1988). Ballast fouling restricts drainage and interferes with track maintenance. When ballast voids are completely filled with fines, the ballast will become deformable when wet and stiff when dry or frozen in cool weather (Watters et al., 1987). Both cases will prevent proper track surfacing. Research suggests that most of the fines are from the ballast itself as a result of abrasion, impact and physical and chemical weathering (Jeffs and Martin, 1994).

Track loading and particle size distribution have a significant influence on fouling. Particle shape and particle surface characteristics also influence fouling. Angular and rough surfaced particles produce more fines. However, this type of particle has good interparticle friction to maintain track bed stability (Watters et al., 1987).

Deterioration of ballast aggregate material occurs primarily through particle fracture and interparticle grinding or attrition, both of which correlate closely with material properties. There is no agreement on test procedures for evaluation of these properties. The variability and arbitrary nature of test limits reflect the uncertainties in understanding the behaviour of railway ballast (Jeffs and Tew, 1991).

2.3.4 Sub-grade Degradation

Track surface irregularity is closely related to sub-grade defects. It is difficult to predict contingent defects which are not the direct result of traffic such as clay holes, localised weakness, cut slope erosion due to blocked drainage, and short shoulder due to end of culvert failure (Selig and Waters, 1993). Traffic related failure modes are generally predictable. They include:

- massive shear failure or through track slide;
- progressive shear failure: shoulder slide and track squeeze; and
- attrition.

Material properties have the greatest effect on these failure modes (Stokely and McNutt, 1983). Massive shear failure is or through track slide is usually failure of a section of embankment although it can occur in a cut section. The signs of such failure include a change of alignment, loss of cross level and a bulged slope. Under normal loading conditions this form of failure should not occur because of increasing moisture content, especially at times of heavy rainfall and flooding (Selig and Water, 1993).

2.4 Maintenance

In case of failure/degradation, there are three options available: repair, overhaul and replacement. Selection among these alternatives depends on the cost and the resulting benefits from each option. Therefore, the optimal selection of such preventive or corrective actions and intervals are extremely important in the context of cost of operating those systems and associated risks.

2.4.1 Maintenance actions

Maintenance actions can be classified into two main categories they are (Blischke and Murthy, 2000):

- Preventive maintenance
- Corrective maintenance

2.4.2 Preventive maintenance

Preventive maintenance is a planned maintenance action to be carried out during operation of the system to reduce the system deterioration and/or risk of failure and if carried out properly it will retain the system in an operational and available condition. Reliability of a system is greatly affected by the implementation of an effective preventive maintenance program. Preventive actions can be divided into three sub categories.

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Figure 2.5: Failure rate with effect of (a) Replacement, (b) Minimal repair, (d) Overhauling (Coetzee, 1997)

- **Replacement**

  Planned replacement of component/system is carried out at constant intervals of time or based on other criteria (e.g. Number of revolution). The components or the parts could be replaced at predetermined age or usage. Replacement enables the system to be "as good as new" condition (Figure 2.5: a). This means the failure rate $r(t)$ of the system is restored to new condition (Jardine, 1973).

- **Minimal repair**

  A minimal repair makes insignificant improvement and the condition after maintenance is "as bad as old" (Figure 2.5: b). It does not change the total failure rate of the system since the aging of the other components is unchanged.

- **Overhauling**

An overhaul is a restorative maintenance action that is taken before the equipment or component has reached to a defined failed state (Jardine, 1973). An overhaul could not return the system to "as good as new" condition any more but can tune up the system by replacing the worn out components. Overhauling/major repair is also termed as imperfect repair. Imperfect repair of a component restores a substantial portion of wear and the hazard rate falls in between "as good as new" and "as bad as old" (Figure 2.5: c) (Coetzee, 1997), (Carter, 1986). It improves the reliability of the system/component up to a certain level based on the scope and availability of the upgrade.

- **Condition monitoring action**

Corrective maintenances like monitoring the condition of some equipment has an influence in maintenance decisions and helps in reducing the probability of failure based on the accuracy of diagnosis and appropriate action (Barlow and Hunter, 1960).

2.4.3 Corrective maintenance

Corrective maintenance is carried out followed by an occurrence of failure to return the system back to operation. This type of maintenance action does not need any planned schedule to perform the activity. These actions can be sub divided into two categories (Barlow and Hunter, 1960).

2.4.4 Replacement at failure

In case of non-repairable system/component, the failed system/component is replaced by a new one or a used but good one.

2.4.5 Repair actions

These types of maintenance actions are applicable to a system with repairable failed components. Repairable actions can again be sub-divided into:

a. Perfect repair or 'As good as new' repair: It is that type of maintenance action where the system would be brought back to "as good as new" condition. The failure rate and the reliability of a system experiencing perfect maintenance would be approximately the same as new system. Perfect repair is assumed to be suitable for a comparatively simple system with very few components.

b. Minimal repair: Under this repair policy when an item fails, it is repaired or restored minimally. It is also known as “as bad as old”. Minimal repair is used for large and complex systems. Repairing one or more components will not affect the total failure rate of the system since the aging of the other components will ensure that the system failure rate will remain unchanged.

c. Imperfect repair: When a system/component is repaired by replacing failed components and also other aged components, then the failure rate of the repaired system becomes less than that of failure before failure state but more than that of a new system. This type of repair is assumed to be in between perfect and minimal repair.

2.5 Maintenance of railway track

Maintenance is one of the major issues in a railway track system. Any flaw in the component or usage may lead to deterioration. This can lead to failures and huge loss to organisation. It is very important to detect the causes for these and to find effective solutions to overcome related problems (Simson, 1999).

Majority of Amtrak railway train accidents since 1993 have been found to be due train de-railing leading to injury and deaths. Some of these accidents were also caused by track buckling due to hot weather. This produced a “hump” along the track and stress occurred in the railtrack due to loads exceeding the permitted limit. Proper maintenance of railway tracks can prevent similar accidents. Exceeding the life spans and limits of rail track components can result in their failing to perform the intended function, thereby affecting the whole operation (Simson, 1999).

Various types of maintenance methods used are (Cope, 1993):

- 2.5.1 Rail grinding
- 2.5.2 Lubrication of rails
- 2.5.3 Rail transposition
- 2.5.4 Rail straightening
- 2.5.5 Rail replacement
- 2.5.6 Sleeper replacement
- 2.5.7 Ballast maintenance
- 2.5.8 Tamping
- 2.5.9 Subgrade stabilization

2.5.1 Rail grinding

Irregularities in rail geometry can give rise to very high dynamic loads. These defects partly occur during manufacture of the rails and are known as rolling defects and during operation in the form of corrugations.

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Figure 2.6: Rail Grinders (Queensland Rail)

The only remedy for such defects is grinding. A typical Rail Grinding train consists of a series of vehicles equipped with grindstones, which form a grinding effect on the rails surface, thus producing smooth surfaces and rail irregularities, and specific profiles (Cope, 1993). Rail profiling is done to keep larger contact bands at the wheel rails interface, reducing stress that causes shelling and corrugation. In addition, profiling can also provide steering effect through curves to reduce flange wear and noise from flanging and wheel screech. Large wheel rails are important for rail lubrication, to help reduce rail wear and screech (Simson, 1999).

Rail grinders are designed to grind away a thin layer of material from the rail surface before surface cracks can propagate (Kalousek and Magel, 1997). The accurate application of the rail grinding program enables transverse rail profiles to contribute to (Magel and Kalousek, 2002):

- Significant reductions in wheel-flange and high rail-gauge –face wear;
- Reductions in rolling contact fatigue;
- Improved vehicle stability;
- Reductions in the formation of corrugation; and
- Reductions in wheel/rail noise.

Rail grinding is a practical and economical technique for removing the surface defects and also for maintaining suitable rail profiles. Appropriate rail grinding interval depends on rail metallurgy, track curvature, axle loads and fasteners (Magel and Kalousek, 2002). Recent researches indicate that a multi-prolonged approach, including the use of premium, high hardness rail, wheel/rail lubrication and rail profile grinding is effective for extending rail life (Kalousek and Magel, 1997).

2.5.2 Lubrication of rails

Lubrication is used to reduce the friction and wear that occurs between the flange part of the wheel and the gauge side of the rail on curved tracks (Alp et al., 1996).

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Figure 2.7: Wayside Lubrication Units (PROTEC)

The lubrication performance is usually influenced by many factors including wheel and rail contours, rail geometry, dynamic characteristics of the truck, surface conditions of the wheel and rail, the viscosity and lubricity of the grease, operating temperatures of the wheel and rail, environmental factors such as temperature and precipitation. Transport mechanism can be influenced by the operating characteristics of the lubricators, train action, wheel slip, environmental contamination and human factors. Higher axle loads heavily influence rail and wheel wear and fatigue. This makes lubrication a crucial requirement for the cost-efficient operation of rail roads (Thelen and Lovette, 1996). There are various types of lubrication methods used:

- Wayside lubrication
- Locomotive flange lubrication

- Hi-rail based lubrication

The abrasive wear on the surface of the rails due to dynamic forces on the curve can be reduced by installing grease dispensers on either the rolling stock or the rails (Cope, 1993). Experiments have shown that proper lubrication can reduce rail/wheel wear rates about 10-15 times in 300-400 meters curve radius and 2-5 times in 600 meter curve radius which leads to a significant cost savings for both wheel and rail infrastructure owners (Jendel, 2002). Dry rail wears at a significantly higher rate than lubricated rail. Lubrication slows the initiation of surface and contact fatigue cracks but has adverse effect on crack propagation. When lubrication is interrupted then micro-cracks caused by ratchetting can start within five to eight MGT (Million Gross Tonnes) or a few weeks on some heavy-tonnage lines. When the lubricators are turned back on, the network of surface cracks propagate rapidly in the presence of lubricants and water (Kalousek and Magel, 1997).

2.5.3 Rail transposition

Transposition is carried on tight curves where wear on the high rail is the main cause of rail replacement. Rail from the high rail is changed to the low rail of the curve. Rail transposition requires rail grinding as the rail profile of transposed curves gives tight contacts, high contact stresses and poor lubrication. Transposed curves that are not profiled are likely to have higher wear rates, high wheel sequel and suffer gauge corner shelling (Simson, 1999).

2.5.4 Rail straightening

Welded rail joints can be straightened by stretching the joint. Rail straightening is commonly performed on previously mechanically jointed track that has been upgraded by rail welding. Even though the rail ends of mechanical joints are cropped before rail welding, a certain amount of rail misalignment can occur (Cope, 1993).

2.5.5 Rail replacement

Rail replacement is often done in conjunction with other major maintenance activities such as sleeper replacement. Figure 2.8 depicts Queensland Railways (QR) track laying gang in action.

Rail and the rail fasteners are replaced due to rail wear or fatigue defects or due to derailment damage that leaves notches or bends (Simson, 1999).

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Figure 2.8: Automated Re-Railing Machine (QR)

Occurrences of rail failures are important factors. Appropriate field data is required to predict the rail life and to plan the replacement actions. This research aims at extending rail life and reducing the maintenance costs.

2.5.6 Sleeper replacement

Sleeper replacement is a regular activity with timber sleepers. Sleeper's replacement is done either by mechanically or manually. The productivity of re-sleepering is greatly dependent on the density of defective sleepers to be replaced. If there is a long distance between defective sleepers, the productivity is low (Simson, 1999).

2.5.7 Ballast maintenance

Ballast rehabilitation or stone blowing is an automated operation that cleans the fines from the ballast with high-pressure air. Ballast rehabilitation or undercutting involves automated machinery that uses chains or mechanical arms to pull through the ballast bed for removing ballast fines (Wenty, 1996). Ballast undercutter scoop up the ballast and pass it over the strainer. The fines are removed and the rest of the ballast is returned to the track. At least 30% of the ballast bed is removed by a ballast rehabilitator/undercutter. As a result, extra ballast has to be added to maintain the depth of the ballast profile after undercutting (Simson, 1999).

2.5.8 Tamping

Tamping is the most effective way of correcting the rail-sleeper geometry faults. The tampers used by British Rail (BR) typically combine the functions of correcting top, cross level and line on the one machine and all corrections are carried out during the one pass of the machine. However, there are number of tamping methods and practices in use (Cope, 1993).

Chirsmer and Clark (1998), discusses the economics of continuous tamping over spot tamping and design lift tamping compared to conventional tamping. In conventional tamping, the track is lifted to return it to the design track profile and alignment. In design lift tamping the track is lifted to a mirror image to allow for the rapid settling of the track profile following tamping. This means the track has a much flatter profile after stabilising than it would with conventional tamping (Simson, 1999).

2.5.9 Subgrade stabilisation

Reactive soils or clay patches are a major problem in track maintenance, causing a whole range of defects. Lime slurry injection stabilises reactive soils by filling soil voids with lime slurry that hardens to cement. Lime slurry is injected into the sub-grade through a nozzle lowered through the ballast. Slurry injection will only affect the upper layers of the subgrade and several applications may be required to stabilise the subgrade (Simson, 1999).

2.6 Existing maintenance models in industry

A considerable number of different maintenance planning systems have been developed by American and European railways. Different approaches and methods have been used on these systems. But these systems face challenges due to increase of axle loads, high speed and growing traffic densities. To overcome these problems rail players have changed the intervals of inspection and maintenance.

2.6.1 New South Wales State Railway Authority's Wheel-Rail Management model

A wheel/rail management computer model has been developed for the State Rail Authority of New South Wales, Hunter Valley coal operations. The model can be used to determine cost effective procedure for wheel machining, rail grinding and lubrication (Soeleiman et al., 1991). This model focuses on wear related rail failure. This allows large amounts of condition data pertaining to alignment. Non-rail components are ignored and a more detailed examination of wear data is carried out.

2.6.2 Railways of Australia (ROA) Rail Selection Module

A technical and economic Rail Selection Module covering 31, 41, 47, 50, 53, 60 Kg/m, and 60 lbs /yd rail sections has been developed for the Railway of Australia (ROA), (Twiddle et al., 1991). The model utilises system specific operating conditions such as axle load, gauge, track stiffness, annual tonnage, curve radius, wheel/rail contact position, vehicle speed and superelevation. The model provides an output which indicates allowable head wear limits, rail life, rail costs, corrugation and defect warnings for various rail sections. It aids the design of new railway track and the selection of rails for replacement of worn and damaged rails.

2.6.3 Railways of Australia (ROA) Rail Grinding Model

Rail profile grinding can result in improved curving performance (wheel/rail interaction) and reduced propagation of surface cracks due to RCF. It is necessary to quantify the major cost factors influenced by the engineering phenomena associated with wheel rail interaction (Soeleiman and Rucinski, 1991).

The rail-grinding model can be used to determine an optimal grinding cycle, together with the cost sensitivity to variations (Soeleiman and Rucinski, 1991).

2.6.4 Railways of Australia (ROA) Wheel/Rail management model

This is a wheel and rail deterioration computer model (WRDM) for the railways of Australia (ROA), using a quasi-expert systems approach. It is a simple model that uses general track link data to determine what maintenance practices should be applied and what upgrading of track structure can minimise on going track maintenance costs (Soeleiman and Mutton 1993).

2.6.5 ECOTRACK

European Railway Research Institute (ERRI) has developed ECOTRACK. ECOTRACK plans track maintenance based on forecasts of track conditions for the next five years. It enables track maintenance to be optimised in terms of cost, time scale and maintenance crew resources or consumable resources. The most important use is a decision support tool. Savings of up to 5% ~ 10% on track maintenance are expected following evaluation trials (Leeuwen, 1997), (Korpanec, 1998).

ECOTRACK assesses homogeneous track sections as small as 200 meters at a time. It considers rail replacement, tamping, rail grinding and ballast rehabilitation, sleeper and fastener renewal maintenance activities. The system relies on user input to select the best maintenance activity and an expert system to select the timing of maintenance scheduling. ECOTRACK is designed as a modular system with an interface to use the existing database of the individual railway. ECOTRACK is dependent on the accuracy and extent of an existing track condition database. The database required to achieve the full potential of ECOTRACK is well beyond that is available with majority of railway systems (Leeuwen, 1997), (Korpanec, 1998).

Implementation of the ECOTRACK system has already been used by European railway, (SNCB) 5000-Km of track. The prototype of the system was tested on 10 European railways since 1995. The system is highly complicated and requires expert staff to run. ECOTRACK is the leading technology in the field of railway maintenance planning. It is flexible and can be modified to suit any railway operation having an existing detailed historical track condition database (Leeuwen, 1997), (Korpanec, 1998).

2.6.6 TOSMA

TOSMA is the new track maintenance system of Central Japanese Railways (JR). This is a highly specialised system that has been developed for a high speed rail operation. Specifically, Tokyo to Osaka, with 11 passenger trains an hour operating at speeds of up to 270 Km/hr (Ohtake and Sato, 1998). Such operating conditions clearly require more care than typical freight operations.

The key to the TOSMA is the data collection from JR Central's high speed track recording car that records track geometry every 10 days on the entire high speed system. Geometry data is for a 10 m versine is recorded at every track meter. Any irregularities showing rapid growth are identified immediately. The work priorities and volumes in track sections are calculated and interpolated into the feature for the whole line. TOSMA allows the planner to identify problem locations that may require sub-grade or formation work. It identifies any rapid deterioration problems before they become a hazard to traffic. It also allows the track engineer to program work volumes into the feature for tamping and ballast renewal operations (Ohtake and Sato, 1998).

2.7 Summary

Railtrack degradation depends on various components of the railway track structure. Failure characteristics of railtrack components are important for continuous safe and reliable operation. Existing railtrack maintenance models based on historical data does not include various factors such as traffic, speed, axle loads, curve radius, lubrication based on train operating and environmental conditions and their interrelations. These factors play an important role in the railtrack degradation and maintenance decisions. These issues are addressed in the subsequent chapters for developing cost models applicable to managerial decisions.

Chapter 3

Analysis of Railtrack Degradation and Failures

3.1 Introduction

A literature review on railway track structure and its functions, a brief introduction related to degradation of railtrack components and capability of existing maintenance models were discussed in Chapter 2. This chapter discusses factors influencing degradation and their effects on terms of rail defects; rail brakes; and derailments.

Degradation of railtrack is a complex process. It depends on rail material, traffic density, speed, curve radius, axle loads, Million Gross Tonnes (MGT), wheel-rail contact, wheel/rail wear, rolling contact fatigue (RCF), track geometry, rail/wheel replacements and maintenance such as preventive grinding, lubrication and other factors such as operating and weather conditions. The study of rail degradation is important for maintaining safety and reliability of rail infrastructure and economic operation.

The outline of this chapter is as follows: In section 3.2 railtrack degradation is discussed. Section 3.3 explains the effect of rail material. Section 3.4 presents effect of axle load. In section 3.5 effect of speed is explained. In section 3.6 effect of track geometry is discussed. Section 3.7 presents effect of rail grinding. Section 3.8 discusses effect of lubrication. Summary and conclusions are discussed in section 3.9.

3.2 Railtrack degradation

The profile of rail and curves make a large contribution to track degradation. Wear and plastic deformation are the main contributors to profile change. A growing problem for many railways is rolling contact fatigue (RCF). In Europe, there are more than 100 broken rails each year due to RCF. Rail maintenance cost within the European Union is estimated to 300 Million Euros per year (Olofsson and Nilsson, 2002).

Factors influencing the rail degradation are:

- Wear, which is due to wheel-rail contact, primarily in curves;
- Fatigue, which results in various defect types such as transverse defects and shells. When the rail reaches its fatigue limit, these defects occur more frequently;
- Plastic flow, which is often found in the form of corrugations in rails, together with mushrooming of the railhead; and wheel burns;
- Wheel material, wheel flange welding and wheel profile;
- Train speed, axle loads and MGT;
- Rail grinding, lubrication, track condition, sleeper, vertical and lateral wheel loads, wheel/rail interface; and
- Operating conditions and weather conditions.

Rail life is influenced by wear, contact fatigue damage, and internal defects (Zhang, 2000). Wear generally occurs at the gauge face in curves. Vertical head wear is caused by wheel contact and rail grinding.

3.2.1 Rail wear

Wear is a consequence of friction between wheel and rail. Wear of wheels and rails can be directly measured by the use of profilometers. Wear is influenced by material response to combined tangential and normal stresses and slippage. Wear coefficients are used in dynamic simulations of vehicle/track interaction (Ekberg et al., 2003).

The interaction of train/track dynamics and wear may result in periodic wear patterns on the wheel tread and the railhead. The ‘bouncing’ motion of the wheel on the rail causes some portions to wear more than others. If this continues over a long period then it can lead to formation of rail corrugations and wheel polygonalisation. These leads to increasing contact loads, and a significant increase in noise emissions called ‘roaring rail’ (Ekberg et al., 2003).

Wear is inevitable on railtrack. However, excessive gauge face wear and plastic flow on curves of heavy haul railway tracks is a problem for rail life (O’Rourke, 1987). This is evident on the metropolitan rail network of the public transport corporation, Victoria (Mutton, 1992). Kalousek (1987) also indicated that gauge face wear of high rails in curves is a dominating problem.

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Figure 3.1: Rail wear on rail head (Larsson, 2003)

The rail life is determined by head loss limit, which is a relative measure of the ratio of a worn rail head to the area of a new rail head (Zhang, 2000). In the wheel-rail contact both rolling and sliding occur. On straight track the wheel tread is in contact with the rail head. However, in curves the wheel flange may be in contact with the gauge corner of the rail, which results in a large sliding motion in the contact. The wheel load is transmitted to the rail through a tiny contact area causing high contact stresses. This results in repeated loading beyond the elastic limit causing plastic deformation (Nilsson, 2002). Plastic flow depends on the hardness of the rail and the severity of the traffic and the curves (Johnson, 1988) (Jones, 1997). Due to sliding in the contact area under poorly lubricated conditions wear occurs at wheel-rail contacts. In addition to the contact pressure and the size of the sliding component, lubrication, microstructure, hardness and temperature influences the wear rate (Garnham and Beynon 1992, Muster et al, 1996).

3.2.2 Rolling Contact Fatigue (RCF)

Plastic deformation of material causes damage of the surface layer, and eventually can cause the formation of cracks. A crack grows under the influence of mechanical loading and trapped fluid. There is close interaction between wear and fatigue. Small initiated cracks may be worn off if the wear rate is sufficiently high. However, wear will also alter the contact geometry, which may promote a faster initiation of new cracks. Poor contact geometry leads to high stress below the surface. The result may be the formation of sub-surface RCF. If material defects are present, local stress concentrations will be high, and cracks may develop deep inside the material. If such a crack is not detected and appropriate measures adopted, it may result in a catastrophic failure of wheel or rail (Ekberg et al., 2003).

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Figure 3.2: Rolling contact fatigue, (Larsson, 2003)

Surface fatigue has been related to the occurrence of surface plasticity, where as multiaxial fatigue is responsible for sub-surface fatigue (Ekberg et al., 2003). Preventive grinding programs are designed to grind away a thin layer of material from the rail surface before surface cracks can propagate deep into the rail head. The depth at which surface cracks appear determines the amount of material that has to be removed (Kalousek and Magel, 1997). For softer rail steel any damaged material is worn off before the critical deformation is reached (Pointer and Frank, 1999). A hard rail will not wear as much, but after a certain time it will suffer from contact fatigue damage. Lubrication reduces wear and shifts the failure mode from wear to crack formation. Cannon and Pradier (1996) identified different types of surface initiated cracks appearing in the rail heads caused by rolling contact fatigue (RCF) (Figure 3.3), head checks (Figure 3.4) and squats. Head checks (HC) are traffic-induced angled cracks which form near the (rail) gauge corner usually on the high rail of the curves and crossing rails due to repeated plastic deformation and consecutive accumulated damage. If HC joins up it results in pieces of the gauge corner breaking up to a depth of several millimetres. In rare cases, the cracks propagate in a transverse direction, eventually producing a complete fracture of the rail (Railtrack Plc, 2001).

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Figure 3.3: Head Checking (Railtrack Plc, 2001)

This figure is not available online. Please consult the hardcopy thesis available from the QUT library.

Figure 3.4: Longitudinal section of head check (Railtrack Plc, 2001)

It is often presumed that plastic deformations occur initially and the material then returns to an elastic response due to material hardening and the formation of residual stresses in the wheel, called elastic shakedown.

This assumption is justified, under extreme conditions (in sharp curves) where repeated plastic deformation of the material develops cracks after a short time. Grassie and Kalousek (1997) suggest that cracks initiated by ratchetting (head checks) grow perpendicular to the direction of the resultant traction force (Figure

3.4). In sharp curves due to high wheel set angles of attack and dominating lateral traction forces cracks develop parallel to the direction of travel. For mixed longitudinal and lateral traction, the cracks can grow at any angle with respect to the direction of travel. Thus, cracks indicate how well vehicle is being steered through curves.

3.2.3 Rail Corrugations

Rail corrugation is a periodic rail defect (Zarembski, 1984). It gives rise to rail dynamic force causing noise, discomfort to passengers, damage wheels, accelerate wear, damage sleepers and fastening elements.

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Figure 3.5: Corrugation developed on rail (Larsson, 2003)

Rail corrugations (Figure 3.5) (Suda et al., 2002) can lead to worn rails, worn pads, loose fasteners, deteriorated sleepers and pulverized ballast. However, the formation of corrugation is very complex (Liu et al., 2003).

Corrugations are classified into short wavelength or long wavelength. There is no clear classification of wavelengths. Short wavelengths may be either 25-50 mm (Mair et al., 1980) or 25-80 mm (Grassie and Kalousek, 1993). Long wavelengths can be either 200-300 mm (Grassie and Kalousek, 1993) or 200-1500 mm (Clark, 1985). There is a gap between long and short wavelengths. Daniels (1993) narrowed the gap by defining an intermediate range of wavelengths, in which 100 mm and less is defined as short wavelengths, 150-225 mm as intermediate wavelengths, and 250-300 mm as long wavelengths (Zhang, 2000).

Corrugations with the same range of wavelength may not have the same formation mechanism or consequences of damage to the rail, because of variations in traffic and track conditions. Grassie and Kalousek (1993) classified it into six groups:

1. heavy haul corrugation (200-300 mm),
2. light rail corrugation (500-1500 mm),
3. booted sleepers type corrugation (45-60 mm),
4. contact fatigue corrugation (150-450 mm),
5. rutting corrugation (50 mm (trams), (150-450 mm), and
6. roaring rail corrugation (25-80 mm).

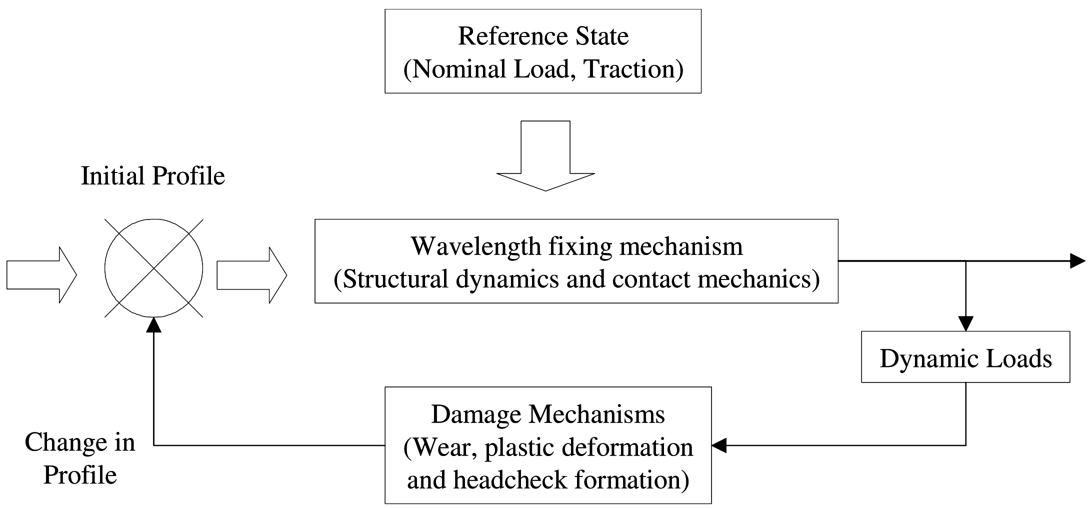

Figure 3.6: Feed-back loop of structural dynamics and contact mechanics

Figure 3.6 shows feed-back loop of structural dynamics and contact mechanics (wavelength-fixing mechanism) and damage mechanism. The rail is initially uncorrugated, but the profile has components of roughness at all wavelengths and inevitably some irregularities are larger than others (Grassie and Kalousek, 1993). The initial roughness in combination with other factors such as traction, creep and the friction characteristics at the wheel-rail contact excites dynamic loads which cause damage of some type, thereby modifying the initial profile. If sufficient trains pass over the site at a similar speed then wavelength at which the dynamic load varies is similar from one train to another and corresponds to the specific wavelength-fixing mechanism. The same irregularities stimulate each train and the damage caused by one train tends to aggravate vibration of sub-sequent trains, leading to further problems at a specific wavelength. The dynamic loads may be normal to or in the plane of the wheel-rail contact with damage mechanisms are plastic flow and wear (Grassie and Kalousek, 1993). Wavelength results from the dynamic interaction of wheel-set and track. Both the structural dynamics and material behaviour aspects are integrated to a feedback loop (Grassie and Kalousek, 1993). Mair et al., (1978) found that "soft" rail materials are more prone to corrugations. Clark, (1985) contradicts their findings. Kalousek and Johnson (1992) found that the conformity of rail-wheel contact promotes rail corrugation. Bhaskar et al., (1997) contradicts their findings. Due to the lack of satisfactory theory, the phenomenon is still a problem to most railway systems. The rail grinding removes rail corrugation but fails to prevent it.

In heavy haul lines corrugations are often associated with wagons carrying heavy axle loads (15 tonnes and over). Light rail corrugations are present near the welds. Corrugations from booted sleepers are found to occur on systems where concrete sleepers use resilient "boots" to reduce ground borne vibration from track. Low rails in sharp curves with a radius of less than 400 m are most vulnerable. Corrugation due to contact fatigue occurs in well-lubricated curves. Rutting corrugations are commonly found on the inside rail of sharp curves on metro tracks with monomotor bogies. "Roaring rails" is a problem due to corrugation associated with high-speed mainline tracks with relatively light axle loads (less than 20 tonnes). It occurs on tangent track and in mild curves.

Daniels (1993) found that corrugations are the results of multiple wave-producing mechanisms, which agrees with Grassie and Kalousek (1993). However, his findings were based on a survey of 18 North American transit agencies, field measurements and laboratory tests supports two corrugation theories:

1. unsprung mass moving on the track stiffness, and
2. wheel "stick-slip".

Corrugation characteristics for intermediate and long wavelengths are similar for same track types irrespective of type of service, vehicle parameters, train speed and curve radius. This supports the prediction of the Unsprung Mass Riding on the Track Stiffness theory which suggests the primary resonant response is driven by the track stiffness. For short wavelengths, his findings supported Wheel Stick Slip theory based on curving increased wheel flange lubrication.

Although there are no general rules on corrugation development, Clark (1985) listed four rules:

- Dampness in atmosphere
- Rigid foundations
- Small variety of vehicles and
- Speed within narrow band

Despite extensive efforts in corrugation characterisation, few studies have been conducted in relation to specified track condition and traffic parameters (Bramwell and McElory, 1978).

3.3 Rail material and its effect.

Rail strength has been increasing to withstand heavy axle loads. “Premium” rails around 1300-1400 N mm^{-2} tensile strength are now being used in large quantities in North America and European railways. These high strengths are achieved by making the spacing between the pearlite lamellae finer by controlling the growth of pearlite. Alloying elements such as chromium and nickel are added to improve material properties. Alternatively, the rail is cooled quickly to reduce the time available for diffusion. British steel’s rolling mill at Workington was the first European rail maker to introduce a heat treatment process in 1985 to achieve enhanced rail life. Hardness is increased to reduce wear rate. Figure 3.7 shows hardness properties and resistant to wear (Yates, 1996).

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Figure 3.7: The wear rate (mg m^{-1}) vs hardness (HV) of rail steel (Yates, 1996)

3.4 Effect of Axle Loads

As the railroad industry moves to increase the average wheel load (39 ton axle load), concern is raised for the impact on wheel and rail. Clayton (1996) shows a linear relation between wear rate and load. Research on heavier axle loads have been carried out in North America, by the Association of American Railroads (ARR) and Office of Research and Experiments (ORE) – part of International Union of Railway (UIC). In late 1980s, the AAR conducted extensive investigation on effects of 39-ton axle loads. Tests were conducted at AAR's Transportation Test Centre (TTC), with the Facility for Accelerated Service Testing (FAST).

In an early report Reiff (1990) indicated that track maintenance costs could increase over 60% with a 20% rise in axle load for Heavy Tonnage Loop (HTL) with sharp curves and frequently-encountered turnouts. Further examination indicated that the magnitude was not so severe for nominal rails.

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Figure 3.8: Linear Wear Rate vs. Contact Pressure Curves (Clayton, 1995)

BHP-Billiton Iron has increased on an average 16% axle load per year to 37 tonnes/ axle in the past 15 years. A 330-car train is now being run daily; to improve productivity. Nine trains a day transport about 70 million net tonnes per year. Heavy axle loads result in a shortened track component life, increased track structure degradation rate, and increased risk of derailments. To reduce risks remote condition monitoring is being explored.

3.5 Effect of speed

Along with the increase of the axle loads rail players have been increasing the train speeds. This has had a significant impact on rail wear rate. The fast trains in France TGV (300 kilometre per hour with 515 kilometres per hour in test run), Japanese shinkansen (or bullet trains, 262 kilometres per hour with 443 kilometres per hour in test run) and the German Intercity City Express (ICE), 280 kilometres per hour with 408 kilometres per hour in test run are examples of current speeds of high speed trains. Australia Transwa, Western Australia's country passenger rail (International Railway Journal, 2003), "Tilt trains" are faster than current trains (but slow by world standards). However, these trains use the existing tracks. Question arose whether fast trains are safe and economical in saving travel time or not. In 1998, an Inter City Express, travelling at about 200 kilometres per hour, derailed near Eschede in Germany, killing 102 people and injuring hundreds more. After the investigation it was found that accident was due to broken wheel tyre on the axle of the car. The tyre was caught in the flange guide of a switch, which broke off and derailed the first car

120 meters later, the derailed axle hit another switch, which caused all the cars to fall off the track. Four people were killed and 34 injured on October 17th 2000 when an Inter City Express train travelling at about 180 kilometres per hour (115 miles per hour) derailed on a curve near Hatfield on Britain's East Coast Main Line.

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Figure 3.9: Train Accident near Hatfield (UK) (IRJ, 2001)

The cause of the crash was identified as a broken rail weakened by internal cracking. The cause was gauge corner cracking or head checking, due to rolling contact fatigue (International Railway Journal, 2001). As a result of the crash Britain's private track company Railtrack, had to absorb a £580 Million bill for re-railing and compensations including £50 Million for the passengers who suffered from derailment which has closed many routes on the national rail network (International Railway Journal, 2001).

After the Hatfield accident extensive investigation was carried out all over Britain's rail network. The number of broken rails on the network increased sharply from 656 in 1995-96, to 949 in 1999-2000. With the new technology it was possible to achieve greater speeds but only at increased risk if maintenance is not addressed properly.

3.6 Effect of track geometry

Maintenance of accurate track geometry is vital for reducing railtrack degradation and failures. Wheels roll over on railtrack contacting at various places from tread to flange. Rails suffer from contact at the same spot while the wheel contact may vary considerably due to wear and maintenance (Grohmann and Schoech, 2002). Wheelsets induce the vertical and tangential forces at wheel-rail interface which vary with the frequency of creepage (in sharp curves). The variation of tangential forces and average creepage produces a dissipation of energy that causes rail wear (Diana et al. 2001). Rails show maximum wear where maximum deviations from the geometry occur. Track conditions are key factors in wheel/rail interaction and maintenance of track standards (Wenty, 1996).

3.7 Effect of rail grinding

Rail grinding is used to remove corrugation and surface crack and reduce internal defects and improve the rail profile to give better vehicle steering control (Sawley and Reiff, 1999). Rail grinding has been demonstrated to have improved rail life in rail curves compared to other strategies (Judge, 2000). It is important to remove just enough metal to prevent the initiation of rolling contact fatigue defects. High rail should be ground to a profile which is similar to wheel wear to ensure that there is relatively little wheel/ rail contact in the area around the gauge corner and shoulder of the rail (Grassie et al., 2002). Inappropriate grinding can reduce rail life by removing excessive metal and by producing profiles that cause high wheel/rail stresses (Sawley and Reiff, 1999). Combined with a proper lubrication program, a carefully planned grinding program can extend rail life from 50% to 300% (Judge, 2002).

3.8 Effect of Lubrication

Wheel/ rail wear increase with the level of friction at the interface. The wear is reduced by lubrication of the side of rail or the gauge face primarily on curves (Sawley and Reiff, 1999). However, large lateral forces still occur as the train goes around the curve causing degradation in the track structure (DeGaspari, 2001). Larsson (2000) found in field measurements that rail head wear on the main line in the north of Sweden indicate that wear rates on the flange can have an average 0.82 mm/month during the winter when no lubrication was used. Table 1 shows the results of a study performed at FAST which looked at the improvements in the rail wear caused by lubrication (Elkins et al., 1984).

In the European rail research project ICON (Integrated study of rolling CONtact fatigue), (Nilsson, 2002), showed that the railhead wear rate is low during some parts of the year and high during other parts.

Table 3.1: Rail wear rate for different lubrication levels (Elkins et al., 1984)

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There is a need to reduce the waste of lubricants and stop/start lubrication based of the weather conditions to improve efficiency of rail lubrication. Recent study shows that enormous amount of lubricant is used to reduce wear, RCF and fuel consumption. Excessive lubrication can cause a number of problems ranging from operating conditions to environmental impacts (Sims et al., 1996). It has been recently shown that lubrication differences between the high and low rail in a curve can cause low rail rollover (Kramer, 1994). Another problem with lubrication is the inability to have controlled and regular rail wear. Wear can cause surface and shallow subsurface fatigue defects to be worn away (Reiff, 1984). Top of the rail contamination can also cause problems in operation. Because the lubricant usually can be spread easily, it has a tendency to migrate to the top of the rail even if applied at the gauge face. The combination of stop/start lubrication with preventive grinding has a potential for an efficient and economical use of lubrication and grinding strategies and is discussed in Chapter 6.

3.9 Summary

An analysis of railtrack degradation and failures along with various factors are discussed in this Chapter. Rolling contact fatigue and rail wear are major issues to rail players. Increased traffic density, axle loads, improper lubrication and increased speed are contributors to those problems. Correct track geometry, profiling of wheel/rail, improved material properties; appropriate inspection, rail grinding and lubrication can reduce problems due to rolling contact fatigue (RCF) and wear. An integrated approach to modelling railtrack degradation for managerial decisions is discussed in Chapter 4. Cost models are developed and analysed in subsequent chapters.

Chapter 4

An Integrated Approach to Modelling Railtrack Degradation for Deciding Optimal Maintenance Strategies

4.1 Introduction

An analysis of railtrack degradation and failures and the various factors that influence rail degradation were discussed in Chapter 3. A system approach is used in this Chapter to develop maintenance models for controlling fatigue initiated surface cracks. Railtrack Degradation modelling is complicated due to the large number of variables and their interactions. Predicting degradation is extremely important for safety and reliability of rail infrastructure. Researchers in modelling rail degradation have looked into total Million Gross Tonnes (MGT), lubrication, rail and wheel grinding and other factors in isolation which has limited the effectiveness of prediction models. There is a need for integrated studies to improve the accuracy of predictive models (Clayton, 1996).

The Swedish iron-ore mining group LKAB and rail infrastructure players, Banverket (in Sweden) and Jernbaneverket (in Norway), conducted a joint study in 1995 to assess the economic, technical and environmental consequences of a 30 tonne axle load instead of a 25 tonne load on the existing tracks in Malmbanan. They found that about 50% of the total cost for maintenance and renewal was due to traffic and balance was due to other elements such as signalling, electricity, snow-clearance etc. Based on the analysis, a 30 tonne axle load with new wagons and locomotives was introduced to the Malmbanan line in 2001. Subsequent technical findings revealed that rolling contact fatigue (RCF) due to the increased axle load resulted in squats, shelling and Head Checks (HC) in curves and switches. This was due to increased slip towards the gauge corner and decreased area of wheel-rail contact. These surface initiated cracks due to RCF, wear of railhead and wheel flanges are currently major challenges of heavy haul lines around the world (Hiensch et al., 2001).

The Swedish National Rail Administration (Banverket called BV) started a rail grinding program on the 130 km ore line between Kiruna and Riksgränsen in 1997. Åhrén et al. (2003) evaluated this programme and found that 12000 ± 1900 m rail (with 1.55 Million AUD) needs to be budgeted for replacement each year. The yearly cost of rail grinding of this track was estimated to be around 4 Million SEK ($0.65 Million AUD), resulting in a total yearly maintenance budget of 2.19 Million AUD (Åhrén et al. 2003). This Chapter presents an integrated approach to modelling rail track degradation for deciding efficient technical and economic preventive maintenance strategies.

The out line of this Chapter is as follows: In section 4.2 overview of the wear models are discussed. Section 4.3 explains the study of factors behind degradation. Section 4.4 explains the framework for integrated model. Section 4.5 presents field wear measurements. Proposed model is explained in section 4.6. Section 4.7 discusses summary and conclusion

4.2. Overview of the wear models

Existing theories have limitations in accurately predicting rolling contact fatigue (RCF) and initiation of crack leading to rail breaks. The stages of fatigue crack as outlined by (Milker, 1997) are as follows:

- Stage 1 (shear stress driven initiation at the surface)
- Stage 2 (transient crack growth behaviour)
- Stage 3 (subsequent tensile and/or shear driven crack growth)

Ringsberg (2001) has explained this with illustrations.

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Figure 4.1: Three phases of (rolling contact) fatigue crack.

There are different approaches to analyse fatigue crack initiation such as, the defect-tolerant approach and the total-life approach. The total-life approach estimates the resistance to fatigue crack initiation based on nominally defect-free materials/

components (Ringsberg, 2001). The strain-life approach together with the elastic-plastic FE model is used to predict:

- The position for greatest fatigue damage
- The orientation of crack planes
- The fatigue life to crack initiation due to both low-cycle fatigue and ratchetting.

Cannon and Pradier (1996) analysed various surface initiated cracks in railheads. Head checks (HC) occur near the (rail) gauge corners of the curves and crossings due to repeated plastic deformation and consecutive accumulated damage at the surface of railhead due to rolling contact fatigue (RCF). These accumulated head checks can cause gauge corner break up to a depth of several millimetres. In rare cases, the cracks propagate in a transverse direction with a complete fracture of the rail, known as rail break. Comparison of the predicted direction of the resultant traction force and the orientation of observed head checks in the track are useful to analyse dynamic train/track interaction.

Bogdanski and Brown (2002) studied 3-dimensional squat behaviour. They developed a model for semi-elliptical shallow-angle rolling contact fatigue (RCF) initiated cracks.

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Fatigue crack growth rate [mm/cycle]

Crack front position

Figure 4.2: Influence of fluid on fatigue growth.

They combined numerically obtained (FEM) linear elastic fracture mechanics (LEFM) crack from loading histories with mixed-mode fatigue crack growth and found that the length of the crack is important in deciding whether a crack will probably branch upwards to spall, or downwards to initiate a transverse defect. The result in Figure 4.2 shows that small squat cracks extending down the rail in the longitudinal direction in a co-planar mode without residual stress. With residual stress spalling is evident in dry conditions. However, for a large squat, with or without friction a transverse crack forms across rail and extends down the rail in the direction of travel of the wheels. There is often a step-like function in describing the wear rate dependence on parameters in the contact between wheel and rail. The concept of mild and severe wear is introduced by Jendel (1999). The jump from mild to severe wear is generally governed by a combination of sliding velocity, contact pressure and temperature in the contact region. In mild wear the wear process is slow and similar to oxidation wear and generally observed at the wheel tread and rail crown. Severe wear is much faster. This is similar to adhesive wear and is found at the wheel flange and gauge face. It is often dominated by curve and dry conditions. Important factors affecting the wear mechanisms and rate are shown in Table 4.1.

Table 4.1: Wear factors, (Jendel, 1999)

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Wear model using energy dissipation per running distance can be expressed as wear index, and is given by

$$\overline{E} = F_x\gamma_x + F_y\gamma_y + M_\phi\phi \tag{4.1}$$

Where $F_x\gamma_x$ = Product of creep forces and creepages in x direction, $F_y\gamma_y$ = Product of creep forces and creepages in y direction, ϕ = Spin and M_ϕ = Spin moment. The energy dissipation $\overline{E}$ is defined as the product of the creep forces and creepages, spin moment and spin, and is proportional to the amount of wear. Relations between the energy dissipation and material worn off are used for prediction of absolute wear. Step-like behaviour of the wear rate can be modelled by assigning different constants for different levels of energy dissipation.

The energy approach is adopted in the rail/wheel analysis to study the relationship between wear rate and contact conditions. This is done to comply with a wear model from the non-linear curving (Elkins and Gostling, 1997). Bolton and Clayton (1984) found that wear rate is a linear function of tangential force (T) times slide/roll ratio (γ) divided by Hertzian contact area (A_H) for a narrow range of materials. McEwan and Harvey (1988) applied this to a full-scale laboratory test. $T\gamma/A_H$ parameter (Wear parameter) calculated from the curving model was used to predict wear performance as a function of suspension characteristics and wheel-rail profiles. Martland and Auzmendi (1990) modified wear parameter to fit railroad practice. It is extremely difficult to accurately describe it using existing models because of the stochastic process involved in rail wear. Therefore, there is a need for an integrated approach where a wear model, combined with updated track field measurement, is able to predict rail degradation wear more accurately.

The complexity of the problem indicates that empirical models combined with continuously updated field test data might be a realistic way of predicting and controlling the wear at different parts of the track. This would be useful to railway players in planning cost effective maintenance of rail infrastructure.

Archard's wear equation (1953) for sliding adhesive wear is given by:

$$\frac{V_w}{D} = K \bullet \frac{N}{H} \tag{4.2}$$

Where V_W = Wear volume

D = Sliding distance

N = Normal load

H = Material hardness

K = Wear coefficient of Archard's equation

The wear is proportional to the normal load and inversely proportional to the hardness of the softer material. The coefficient of friction is not explicitly included. In the wheel/rail case the coefficient of friction and the degree of lubrication greatly influence the size of creep forces in contact and wear. The energy dissipation model assumes that wear is proportional to the work done by forces in sliding contact. Fries and Davila (1985) eliminated the spin component. The wear coefficient (*K*) of Archard's equation comes from laboratory measurements or by extensive calibrations based on geometrical comparisons between simulated and measured wheel profiles. Jendel (2002) expressed the wear coefficient with sliding velocity on the horizontal axis and contact pressure on the vertical axis.

Magel and Kalousek (2002) investigated the relationships of contact mechanics to wheel/rail performance. They considered factors such as contact stress, creepage, conicity, conformity and curving and introduced a technique for optimal wheel and rail profiles. Experiments at North American railroads and field-testing measurements suggest that life on the high rail of curves can be extended by lubrication and two-point conformal contact in most heavy-haul environments. Since, the difference between the conformal one- and two-point contacts is only about 0.5 mm, accurate rail profiling is important for achieving extended rail life. In real life, the wheel and rail profiles change due to wear when trains pass over a section of rail.

Berghuvud (2001) studied ore lines in Sweden (Malmbanan) operating old types of three-piece bogie wagon (25 tonne axle loads) at 50 km/h carrying 52 ore wagons. Train/track simulations were performed at a test site in Boden with a train speed of 40 km/h, axle load of 25 tonnes (loaded), and 5 tonnes (unloaded), curve radius of 595 m, cant of 0 mm, track gauge of 1435 mm, rail inclination of 1:30 (Standard in Sweden) and lateral acceleration of 0.2 m/s^2. Åhren et al. (2003) analysed Berghuvud

(2001) study in order to investigate the wear rate sensitivity as a function of the wheel/rail profiles. Seven different wheel profiles were used to compare the influence of wear rate as a function of wheel profile status. Changes in wheel profile had only a small influence on contact forces, contact dimensions and positions on the high rail for the trailing wheel set. Energy dissipation was used as an indicator for the amount of expected relative change of wear for different profiles. Energy dissipation for different wheel/rail profiles is given in Table 4.2.

Table 4.2: Energy dissipation for wheel-rail profiles at Boden site (Åhren et al., 2003)

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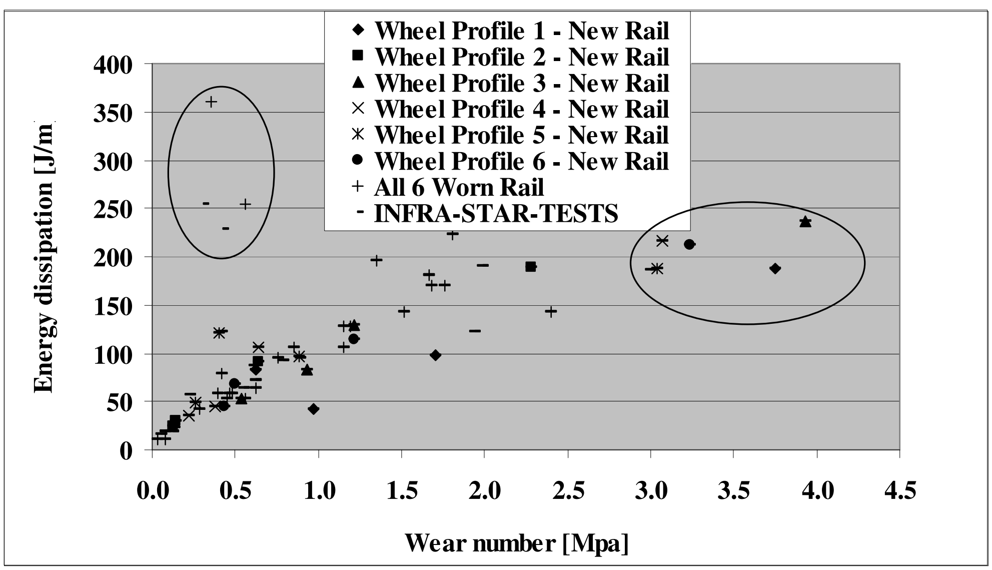

Figure 4.3: Energy dissipation for wheel/rail contact

The curving performance for a 595 radii meter curve at 40-km/h speed was analysed. Energy dissipation for the wheel/rail contact as a function of simulated wear number based on sixty-four different combinations of train/track interactions is shown in Figure 4.3. The upper left circle in Figure 4.3 is a two point contact situation with a low wear number high-energy dissipation area due to high sliding. The right hand circle in Figure 4.3 is data from the leading wheel set, high rail contact, in the three-piece bogie. The leading wheel set in a bogie hits the curvature first and contributes more to the steering of the car, compared to the second wheel set in the bogie. Finally the linear relationship represents wheel/rail contact for the high-rail, low-rail, worn wheels, new wheels, worn rails and new rails (Larsson and Chattopadhyay, 2003).

4.3. Integrated study of factors behind degradation

Research on lubrication technologies is addressed by rail players in most of the countries. However, bogie types and metallurgies, and wheel/rail contact mechanics are often overlooked or not studied properly. The geometry of the wheel/rail contact influences wear, fatigue, corrugation, stability and derailment. Magel and Kalousek (2002) studied performance of rail profiles based on analysing large number of new and worn wheels.

Kalousek and Magel (1997) discuss optimal "wear rate" to prevent RCF initiated failures. The rate of wear is larger if softer rail is used and any damage or cracks are worn away before the critical deformation is reached (Pointer and Frank, 1999). A hard rail suffers from contact fatigues. Lubrication reduces wear and shifts the failure mode from wear to crack formation.

4.4. Frame work for integrated modelling

The integrated model using information from traffic, vehicles, track, maintenance and expertise is shown in Figure 4.4.

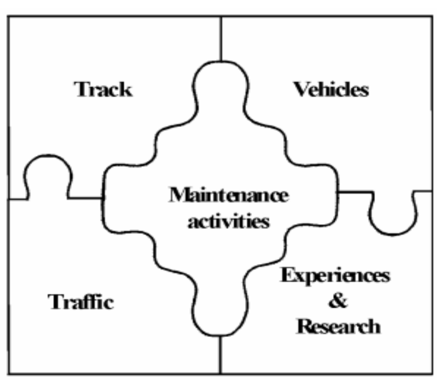

Figure 4.4: Maintenance prediction puzzle

Larsson and Gunnarsson (2003) propose an interactive model using technical and cost aspects of track maintenance. Banverket (Swedish Rail Administration) along with Damill AB and Luleå Railway Research Centre developed a prediction puzzle shown in Figure 4.4. The limitations of existing models are the assumptions of one type of traffic, vehicle and track. Thereby, the simulation has not considered any effect of changes in preventive maintenance. However, as the input of data from filed observations is updated prediction of cost would be based on new data. The effect of different maintenance activities can be simulated using the field data together with models for rail degradation. The factors that need to be considered for cost analysis are shown in Table 4.3. Each unit of energy expended through creepage in the wheel/rail contact removes a given quantity of the material. This is in line with Archard's (1953) Equation 4.2.

McEwan and Harvey (1988) proposed that material removed per unit area per distance rolled is equal to constant times the energy expended per unit area per distance rolled. There is often a step-like function describing the wear rate dependence on parameters in the contact between wheel and rail.

Table 4.3: Factors need to be analysed for cost model

Track	Vehicles	Experiences and Research	Traffic
Curve radius Cant Track gauge	Train speed Type of bogie (steering performance)	Leftover fatigue in previous grinding cycle	Number of axle passes Type of cars
Rail inclination Rail weight	Wheel condition and profile	Weather condition	Axle load (loaded, un loaded)
Rail profile		Other published results	

McEwan and Harvey (1988) suggest the creepage conditions lead to severe wear where the whole of the contact area is in full slip. Thus, the severe case is given by:

$$W = k\frac{T\gamma}{A} + K \tag{4.3}$$

Where:

W = wear rate, wt loss/unit area/unit distance rolled [$kg/m^2/m$]

k = Constant

T = Tangential creep force [N]

γ = Creepage [-]

A = Constant area [m^2]

K = Constant

The constant, k, may be expected to be dependent on the properties of the steel in question and, to some extent, on the steel with which it is paired in the wear system. The constant, K, is determined by extrapolation. Alternatively the cross sectional area loss per number of axels passage can be used. Material removed per unit length per load cycle is equal to a constant multiplied by the energy expended per unit area per load cycle.

W_A = Cross-sectional wear rate, area loss/unit area/unit distance rolled [$m^2/m^2/m$]

$$\rho = \frac{m}{V} = \frac{m}{lb\Delta r} \tag{4.4}$$

$$W_A = \frac{b\Delta r}{n_p l} = \frac{m}{\rho l}\frac{1}{n_p l} = \frac{m}{\rho l^2 n_p}; \qquad \Delta r << b \tag{4.5}$$

$$W_A = C_1 \frac{T\gamma}{A} + C_2 \qquad [m^2/cycle] \tag{4.6}$$

Where:

C_1 = Constant	[m^4/N/cycle]
T = Tangential creep force	[N]
γ = Creepage, sliding distance per meter	[m/m]
A = Contact area	[m^2]
C_2 = Constant	[m^2/cycle]
n_p = Number of axle passes	[-]
l = the unit length of tested area	[m]
Δr = The change in radius	[m]
b = the width of the contact band on the rail head	[m]
m = Mass	[kg]
V = Wear volume	[m^3]
ρ = Mass density	[kg/m^3]

$$W = \frac{m}{bl}/n_p = \frac{m}{l^2 n_p b} = \frac{\rho b l \Delta r}{bl}\frac{1}{n_p l} = \frac{\rho \Delta r}{n_p l} \tag{4.7}$$

$$W_A = \frac{b\Delta r}{n_p l} = \frac{m}{\rho l}\frac{1}{n_p l} = \frac{m}{l^2 \rho n_p} = \frac{m}{l^2 n_p}\frac{1}{\rho} \tag{4.8}$$

$$W_A = W\frac{b}{\rho} = \frac{m}{l^2 n_p}\frac{1}{b}\frac{b}{\rho} = \frac{m}{l^2 n_p}\frac{1}{\rho} \tag{4.9}$$

4.5. Field wear measurements

Rail wear measurements on curves provide data for a typical traffic situation. Cross section area loss [mm^2] as a function of the number of axles as is shown in Figure 4.5 and Figure 4.6.

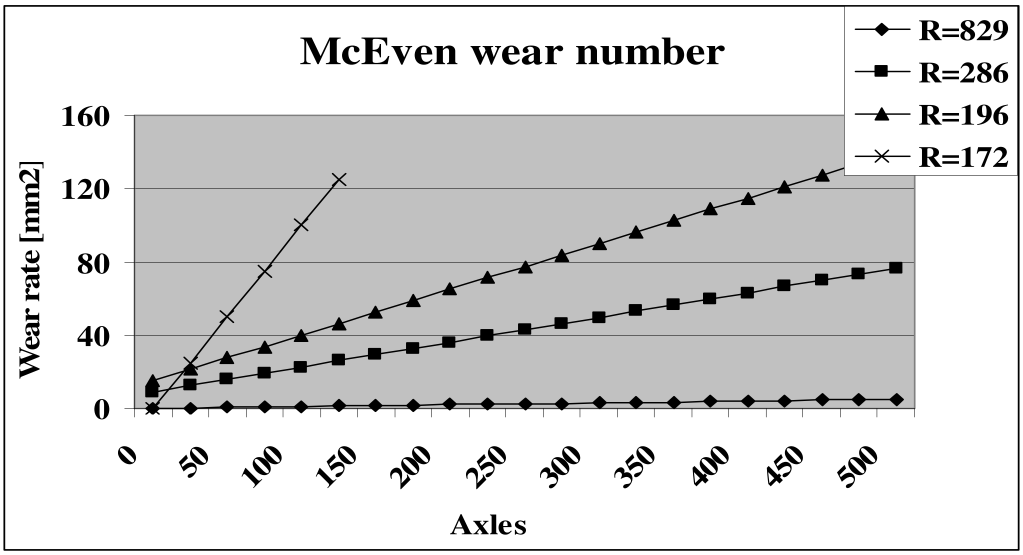

Figure 4.5: Wear rate [mm^2] as function of axle's passages

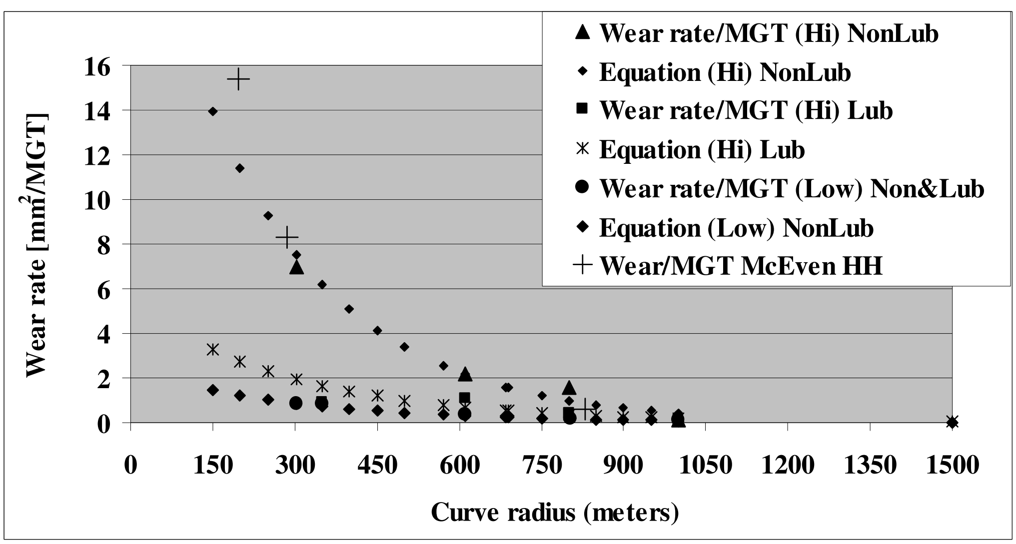

Figure 4.6: Wear rate [mm^2/MGT] as function of curve radius

The area loss on both the high rail and the low rail can be monitored using on board or hand operated profile measurement devices. The railhead area loss as function of grinding, traffic and lubrication for a specific track section can be obtained by (McEwen and Harvey, 1988):

1. Experience from a number of curves with different curvature along the same route.
2. Measurement and monitoring the railhead for initiation of RCF, grinding to remove the cracks and traffic wear rate as function of number of (loaded/unloaded) axle's passage per time period and MGT per time period.
3. Calculation of the wear number $T\gamma/A$ using train/track computer simulation program for the same curves; wheels and rail profiles.
4. Taking into account, longitudinal, lateral and spin creepages and relative creep forces and moments, friction of the coefficient and angle of attack. Plotting the simulated results as a function of track curvature. Identifying sections and curves with high and critical wear numbers and plotting in the same diagram, the measured wear rate [mm^2/number of axels and/or MGT] as function of simulated wear number for each identified curve.
5. Plotting of measured wear rate [mm^2/number of axels and/or MGT] and the measured grinding removal of railhead [mm^2/number of axels and/or MGT] as function of curve radii, curve fitting a general traffic wear-function based on simulations and measurements and also fitting the needed grinding removal to control RCF as function of radii. For estimating traffic wear and grinding "wear".
6. Setting up a wear and RCF map as function of track curvature for the line, based on filed measurement combined with simulated curving performance of the car and its wheel/rail contact for predicting the life of the rails on the investigated track sections.

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Figure 4.7: Railhead area loss [mm2/MGT] (Larsson, 2003)

"Wear rate/MGT (Hi) NonLub" is High Rail wear rate non-lubricated. "Equation (Hi) NonLub" is fitted equation to the High Rail wear rate non-lubricated. "Wear rate/MGT (Hi) Lub" is High Rail wear rate lubricated. "Equation (Hi) Lub" is fitted equation to High Rail wear rate lubricated. "Wear rate/MGT (Low) Non & Lub" is Low Rail wear rate for non-lubricated and lubricated. "Equation (Low) NonLub" is fitted equation Low Rail wear rate for non-lubricated and lubricated. "Wear/MGT McEven HH" is data from test performed by (McEwan and Harvey, 1988). "Equation (Max) and (Min) Grinding" is curve fitted values from Table 4.1. "35.678, 42.259, 45.532 and 46.216-Grind" is field measurements of Queensland Rail Cole line in Goonyella region. "Goonyella (Wear)" is traffic wear from the in Goonyella region (Larsson, 2003).

Figure 4.7 shows railhead area loss [mm^2/MGT] as function of curve radius and shows the tendencies in railhead area loss due to traffic and grinding. Data is collected from different traffic such as commuter traffic in south of Stockholm, heavy Cole line traffic in Queensland Australia and heavy haul line in North America.

4.6. Proposed model

An overview of the proposed model is shown in Figure 4.8. Technical input data is from train/track simulations and filed test observations. Data for grinding wear due to

RCF, wear due to traffic, RCF safety recommendations and safety wear limits are collected for development of modelling and simulation results. Statistical data of grinding performance, RCF, traffic wear, rail breaks, non destructive testing (NDT), derailments can be used in the integrated model. Economic data is available from maintenance databases. Data for estimation of risk costs can be taken from safety reporting, non-destructive testing reports of rail breaks and derailments.

Area loss/MGT due to traffic and grinding as a function of track length and track curvature is generated. Then the expected area loss/MGT is estimated based on simulated and measured data. This is repeated until the safety limit for rail replacement is reached.

Costs related to the actual grinding programs are grinding cost, down time (loss of traffic, production) costs, replacement costs of worn-out rails. Depending on how grinding is performed i.e. profile targeting, crown and/or gauge depth removal, different grinding costs to be considered.

The total cost of maintaining the segment of rail can then be set equal to rail grinding cost + rectification and associated cost with rail breaks + cost of derailment + down time cost due to rail grinding (loss of traffic) + replacement cost of worn-out unreliable rails + inspection costs considered. Estimation of risk is built in to this model.

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Figure 4.8: Proposed integrated model, (Larsson and Chattopadhyay, 2003)

4.7. Summary

This Chapter has proposed an integrated model for accurately predicting rail degradation by combining train/track simulations and fracture mechanics. Results from this integrated approach can be used to predict wear and RCF on a specific track and estimate cost per MGT. Emphasis is given on combining both theoretical research considerations and practical validation. The mathematical modelling and simulation results are presented in subsequent chapters.

Chapter 5

Mathematical Modelling for Optimal Rail Grinding in Maintenance of Rails

5.1 Introduction

An integrated approach to modelling railtrack degradation for deciding optimal maintenance strategies and the existing wear models are discussed in Chapter 4. This chapter analyses railtrack degradation and develops mathematical models for optimal rail grinding intervals.

Maintenance of rail has impact on reliability and safety of railroads. Rail breaks and derailments can cost the rail player's in terms of loss of revenue, property or even loss of life. Estimation of these costs and analysis of risks are important in deciding effective maintenance strategies. It requires identification of factors, measurement of these factors and development of mathematical models to predict those risks associated with degradation.

Outline of this chapter as follows: In section 5.2 System approach in modelling is discussed. In section 5.3 Modelling rail breaks are explained. In section 5.4 Rail degradation model is developed. Section 5.5 deals with Economic model for optimal grinding decisions. Numerical Examples are provided in section 5.6. Simulation results are analysed and interpreted in section 5.7. Analysis of annuity cost/meter for each MGT is discussed in section 5.8. In the concluding section results are summarised and contributions are discussed.

5.2 Systems approach to modelling

Rail degradation can be modelled using a systems approach as shown in Figure 5.1.

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Figure 5.1: Systems Approach to Solving Problems, (Murthy et al, 1990)

System approach to rail degradation modelling can provide a framework to study related problems in an integrated and unified manner for solving this real life complex problem.

5.3 Modelling rail breaks

Chattopadhyay et al. (2002) developed models for optimal maintenance of high volume infrastructure components. Kalousek and Magel (1997) propose magic wear rate in maintenance of railway tracks. They applied contact mechanics to rail profile design and rail grinding. Ringsberg (2001) developed models on life prediction in rolling contact fatigue crack initiation. Jendel (2002) developed prediction models for wheel profile wear and compared with field measurements.

In the integrated approach failures are modelled as a point process. Point process is a continuous time characterised by events that occur randomly along the time continuum when an item is put into operation or it fails.

5.3.1 Assumptions

In this economic model, the following assumptions are made:

- Drivers follow recommended speed consistently.
- Wheels are maintained at a regular interval to retain condition and the profile within considerable level.
- Length of trains is assumed as same.
- Trains carrying goods such as iron ore are filled to the capacity of the wagons and the MGT per train is assumed to be consistent.
- All the drivers are experienced and they are consistent in train handling as per instructions.
- Curves are fitted with lubricators and all lubricators are working satisfactorily.
- Rail grinding reduces fatigue stress and restores life (in terms of total service life, MGT) compared to infrastructure without rail grinding for removing RCF such as head checks.
- Rail Grinder operators are all of the same skill level and remove material necessary for grinding degradation due to RCF (i.e., mistakes in grinding is very low).
- Rail breaks/ derailments are influenced by rolling contact fatigue.
- Most of these assumptions are realistic for a track with a small variation of traffic type and have been in service for some years.
- Influence of variation of temperature and wet, dry and snow seasons are not considered.

The model proposed here is based on a total cost of rail maintenance. Cost data collected from infrastructure players are inspection cost, grinding cost, down time cost due to rail grinding (loss of traffic), replacement of worn-out rails, rectification and associated cost with rail breaks and derailment.

5.3.2 Counting processes

A point process $\{N(t), t \geq 0\}$ is a counting process where *N(t)* represents the total number of failures that have occurred up to time *t*. It must satisfy:

1. $N(t) \geq 0$
2. N (s, t] is integer valued random variable counting the number of failures that occur in the time interval (s, t]. It includes both the number of failures occurring in (s, t] and the times when they occur.
3. If s < t, then $N(s) \leq N(t)$
4. For s < t, $\{N(t) - N(s)\}$ equals the number of events that have occurred in the interval (s, t].

Λ(m) is an intensity function where *m* represents Millions of Gross Tonnes (MGT) and *Λ(m)* is increasing function of *m* indicating that the number of failures in a statistical sense increases with MGT. $F_n(m)$ denote the cumulative rail failure distribution modelled as Weibull distribution (Crowder et al., 1995) given by:

$$F_n(m) = 1 - \exp(-(\lambda m)^{\beta}) \tag{5.1}$$

$$S(m) = 1 - F_n(m) \tag{5.2}$$

where *S(m)* is survivor function.

Then the density function is expressed as:

$$f_n(m) = \frac{dF(m)}{dt} = -\frac{ds(m)}{dt} \tag{5.3}$$

Then intensity function, *Λ(m)* is given by:

$$\Lambda(m) = \frac{f_n(m)}{1 - F_n(m)} \tag{5.4}$$

$$\Lambda(m) = \frac{f_n(m)}{1 - F_n(m)} = \frac{\lambda\beta(\lambda m)^{\beta-1}\exp(-(\lambda m)^{\beta})}{1 - (1 - \exp(-(\lambda m)^{\beta})} = \lambda\beta(\lambda m)^{\beta-1} \tag{5.5}$$

$$\Lambda(m) = \lambda\beta(\lambda m)^{\beta-1} \tag{5.6}$$

with the parameters β > 1 (shape parameter) and λ > 0 (scale parameter (characteristic life)). This is an increasing function of *m*. Note that this corresponds to the failure rate of two-parameter Weibull distribution.

As a result, $N(M_{i+1}, M_i)$ the number of failures over M_{i+1} and M_i are function of MGT and random variable. With condition on $N(M_{i+1}, M_i) = n$, the probability is given by:

$$P\{N(M_{i+1}; M_i) = n\} = \{\int_{M_i}^{M_{i+1}} \Lambda(m)dm\}^n e^{-\int_{M_i}^{M_{i+1}} \Lambda(m)dm} / n! \tag{5.7}$$

This type of characterisation is considered appropriate because rail track is made operational through repair or replacement of the failed segment and no action is taken with regards to the remaining length. Since the length of failed segment replaced at each failure is very small relative to the whole track, the rectification action can be viewed as having negligible impact on the failure rate of the track as a whole (Barlow and Hunter, 1960). Then the expected number of failures over M_{i+1} and M_i is given by:

$$E[N(M_{i+1}, M_i)] = \lambda^{\beta}((M_{i+1})^{\beta} - (M_i)^{\beta}) \tag{5.8}$$

where the total accumulated MGT, M_i, is given by:

$$M_i = \sum_{i=0}^{i} m_i \tag{5.9}$$

where m_i is MGT in period i.

5.4 Modelling rail degradation

MINIPROF (Greenwood Engineering) is a standard system used for the determination of rail profiles in the field. The sensing element consisted of a magnetic wheel 12 mm in diameter attached to two joint extensions. When the magnetic wheel is moved manually over the rail surface, two angles are measured and stored in a computer. The profile is then transformed to Cartesian co-ordinates. Marks on the edge of the rail are used to ensure that the measurements were performed at the same location each time. The accuracy of the MINIPROF system is of the order ± 0.015 mm for similar profiles.

Figure 5.2: Rail profile measurement using MINIPROF rail profile system

From profile measurement data a stochastic rail model is developed using effect of traffic wear and grinding wear. The area after i^{th} period modelled as:

$$A_i = A_0 - \sum_{j=o}^{i}\left((RC_w + RG_w)TD_j + (RC_w + RG_w)GD_j\right) \qquad [\mathrm{TD}_0, \mathrm{GD}_0 = \mathrm{i}] \qquad (5.10)$$

where A_0 is the cross sectional profile area of a new rail, RC_w is Rail Crown wear width, RG_w is Rail Gauge wear width, *TD* is the wear Depth from Traffic, *GD* is the Grinding Depth due to grinding. It can be expressed as:

$$A_i = A_0 - \sum_{j=0}^{i} A_{TW_j} + A_{GW_j} \qquad [A_i \geq A_c] \qquad (5.11)$$

where A_{TW_j} is the area loss due to traffic wear i.e.

$$A_{TW_J} = (RC_w + RG_W)TD_j \qquad (5.12)$$

and A_{GW_j} is the area loss due to grinding wear in period *j*.

$$A_{GW_i} = (RC_W + RG_W)GD_j \qquad (5.13)$$

A_c is the critical railhead for rail replacement based on safety recommendation. A_i is the cross sectional rail profile area at i^{th} interval.

The % worn out level of rail after i^{th} period is given by:

$$WOL_i = 100 * \frac{A_0 - A_i}{A_0 - A_c} \qquad (5.14)$$

5.4.1 Numerical example

The Swedish National Rail Administration (Banverket) used the MINIPROF Rail profile system to measure the profiles just before and after rail grindings (Åhrén et al. 2003). Transverse profiles are measured for outer and inner rails at 60 positions on Malmbanan line in Sweden. The rate of metal removal by rail grinding is about 0.2 mm across the railhead for every 23 MGT.

The Swedish National Rail Administration (Banverket) considers two measurements for railhead wear (Regulations BVF 524.1, 1998). The vertical wear on the railhead *h* and the flange wear *s*, 14 mm down from the top of a new rail profile (Figure 5.3) is explained in Equation 5.15.

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Figure 5.3: Central vertical wear *h* and side wear *s*, (Åhrén et al, 2003)

$$H_{BV} = h_{BV} + \frac{S_{BV}}{2} \qquad (5.15)$$

The mean wear per year and amount of material removal per year due to grinding is presented in Table 5.1. [* Example of bigger railheads]

Table 5.1: Measurements of grinding (radii < 800 [m])(Åhrén et al, 2003)

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Total Wear

Figure 5.4: Measurement of rail wear, (Åhrén et al. 2003)

Using the relation between measured *s* and *h* one can achieve A_c, the critical railhead area. The Malmbanan line shows the annual *h*/*s* from traffic wear 0.16/0.24 mm and that from grinding wear 0.48/0.42 mm per year for 23 MGT intervals at curve radii *R*<800 meters. The relation between *s* and *h* to *H* is as follows:

For traffic: $$H_{Traffic} = h_{TBV} + \frac{0.24}{0.16*2} * h_{TBV} = 1.75 h_{TBV} \qquad (5.16)$$

For grinding: $$H_{Grinding} = h_{GBV} + \frac{0.42}{0.48*2} * h_{GBV} = \frac{23}{16} h \approx 1.44 h_{GBV} \qquad (5.17)$$

Total: $$H_{Total} = h_{(TBV+GBV)} + \frac{0.66}{0.64*2} * h_{(TBV+GBV)} \approx 1.52 h_{(TBV+GBV)} \qquad (5.18)$$

The safety wear limit H_{limit} is set to 11 mm for the 50-kg/m BV50-rail profiles in Malmbanan line. A_c can be calculated as function of h_{BV} given by:

$$A_c = h * RC_W + s * RG_W \qquad (5.19)$$

where RC_w is the estimated Rail Crown wear width and RG_w is the estimated Rail Gauge wear width. Results are shown in Table 5.2. [* Example of bigger railheads, UIC 60 profile]

Table 5.2: Safety limit for Malmbanan (Åhrén et al. 2003)

s
Traffic

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The critical area that corresponds to the safety limit of 11 mm (BV50) is 440 mm^2 and for UIC 60 it is estimated to be 560 mm^2. For a theoretical 80 kg/m rail, 1000 mm^2 wear area is used (Åhrén et al. 2003).

5.5 Economic model for optimal grinding decisions

A huge share of the operational budget is spent on maintenance and replacement of rails and wheels. Although many factors contribute to degradation but the influence of wheel/rail contact conditions, the magnitude of friction coefficient and the rail wheel condition are extremely important. Advancements in materials technology and heat treatment have reduced problems related to traffic wear. However, rolling contact fatigue (RCF), corrugation, welds and track geometry are still a great challenge to railway players all over the world.

Sawley and Reiff (2000) has analysed the rail failures over 30 years – 1969 to 1999 and found that the number of broken rails on railtrack (named as British Rail before the year 1994) was on an average 767 per year with a standard deviation of 128. In 1998/99 they had 952 breaks and in 1999/00 they had 918 breaks. The number of defective rails removed per year has been increased from around 1,250 in 1969 to around 8,700 in 1999. The possible reasons for the increase in broken rails through 1990s include:

- Falling levels of rail renewals over the last 30 years
- Increased reliance on manual ultrasonic rail inspection.
- A worsening of track quality and a possible increase in wheel irregularities and higher dynamic forces.
- Increased traffic which has not been followed up by increased inspections, and revised minimum action criteria for defect removal.
- Acceleration of rolling contact fatigue as a result of the introduction of bogies with higher wheelset yaw stiffness.

Kalousek and Magel (2002) identified the favourable “wear rate”, as shown in Table 5.3. The vertical crack rate is estimated to be 0.05 to 0.15 mm/ 10 MGT. The preventive rail grinding is used to control the vertical crack propagation rate with removal of railhead material.

Table 5.3: The ideal grinding for heavy-haul (Kalousek, 2002)

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It is important to develop effective maintenance strategies combining technology and safety methods for optimal rail grinding in controlling RCF and wear. Some of the associated costs are:

- Restricted track access while grinding.
- Rail grinding cost per meter
- Replacement of worn-out rails.
- Derailment and damage of track, train, property, life, and down time.
- Repairing rail breaks in terms of material, labour, and equipment and down time.
- Inspecting rail tracks in terms of material, labour, equipment and down time.

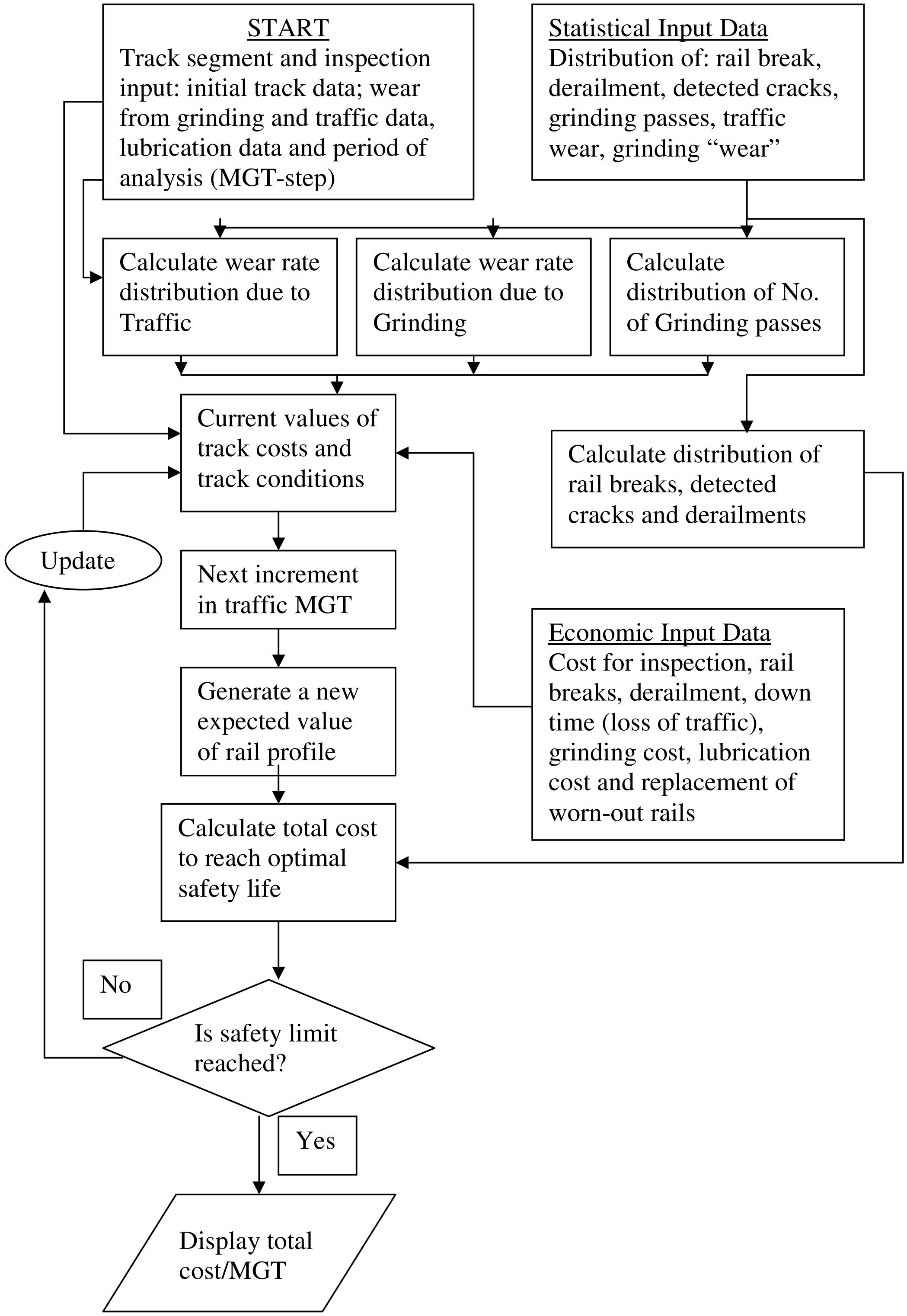

Figure 5.5: Flow chart of the track monitored base model.

The grinding at Malmbanan has been an increasing problem. In 2001 a new ore carrier was introduced with 30 tonne axel loads. This rise in axle load from 25 tonnes resulted RCF damages. BV carried out rail profile measurements before and after grinding activities for analysis of its effectiveness in controlling rolling contact fatigue (RCF) (Åhrén et al. 2003). The grinding campaign is analysed in Table 5.4. Rail track length is used based on actual dimensions in Swedish ore line.

Table 5.4: Track path divided into sections, (Larsson et al., 2003)

Sections

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In spite of aggressive grinding programs along with frequent onboard non-destructive measurements rail breaks happen. Other factors such as weld joints; rail geometry and corrugation contribute to the risk. The cost of these unplanned replacements is treated as risk cost. For an infrastructure player it is essential to measure and manage these risks by implementing cost effective traffic and maintenance management strategies (Larsson et al 2003). Questions commonly asked are:

- How much is the current risk of derailment on a specific track section?
- Will the current risk change with changed maintenance strategies in the future? and
- What is the cost/benefit ratio of various strategies in terms of maintenance costs and risk costs?

The total cost of maintaining any segment of rail is modelled as the sum of costs for; rail grinding, down time due to rail grinding (loss of traffic), rectification and associated costs of rail breaks, derailment, inspection and replacement of worn-out rails.

Results from the analysis show that different sections have different technical life for high rail and low rail. This analysis did not consider changes in technology of steel making for rail material. Using the statistical data on derailments, rail breaks and rectifications initiated by routine inspections the expected costs are estimated. Finally the total costs for different traffic situation and grinding strategies are analysed using an annuity method.

5.5.1 Modelling preventive rail grinding cost

Let G be the cost of grinding per pass per meter and n_i be the number of grinding pass for i^{th} grinding, *L* be the length of rail segments (0-300, 300-450, 450-600, 600-800 meters of curve radius sections) under consideration, *N* be the total number of periods up to safety limit for renewal, and *r* be the discounting rate per period. It is assumed that payments are made to subcontractors after each of the (*N-1*) grinding.

Then total grinding cost in present value =

$$\sum_{i=1}^{N-1}\frac{G_i}{(1+r)^i} \tag{5.20}$$

The total present value of grinding cost is spread over in equal amounts to each year of those N periods. Then is the annuity cost is (G) for each period and total annual grinding cost can be given by:

$$G\sum_{i=1}^{Y}\frac{1}{(1+r_y)^i} \tag{5.21}$$

where y is expected life in years and r_y is yearly discounting factor. Discounting factor for grinding interval, r, is given by (r_y*i/12) where i is months interval between grindings.

Results of 5.20 and 5.21 equation are same.

$$G\sum_{i=1}^{Y}\frac{1}{(1+r_y)^i} = \sum_{i=1}^{N-1}\frac{G_i}{(1+r)^i} \tag{5.22}$$

Then Annuity cost can be derived from equation 5.22:

$$\text{Annuity cost G} = \frac{\sum_{i=1}^{N-1}\frac{G_i}{(1+r)^i}}{\sum_{i=1}^{Y}\frac{1}{(1+r_y)^i}} \tag{5.23}$$

Equation 5.21 can also expressed as:

$$\text{Total cost} = \frac{G}{(1+r_y)^1}+\frac{G}{(1+r_y)^2}+\frac{G}{(1+r_y)^3}+\dots\dots\dots\dots+\frac{G}{(1+r_y)^Y} \tag{5.24}$$

After simplification,

Annuity cost G = $\left\{ \sum_{i=1}^{N-1} \frac{G_i}{(1+r)^i} \right\} * \frac{r_y}{\left[1 - \left(\frac{1}{(1+r_Y)^Y} \right) \right]}$ (5.25)

Therefore the annuity cost for rail grinding is given by:

$$c_g = \{ \sum_{i=1}^{N-1} (G * n_i * L) / (1+r)^i \} * r_y / (1 - (1/(1+r_y)^Y)) \quad (5.26)$$

5.5.2 Modelling down time cost due to rail grinding (loss of traffic)

Let h_{DT} be the expected downtime due to each grinding pass, n_{GP_i} be the number of grinding pass for ith grinding and *d* be the expected cost of down time per hour. Then down time cost due to rail grinding leading to loss of traffic is given by:

$$c_d = \{ \sum_{i=1}^{N-1} n_{GP_i} * h_{DT} * d / (1+r)^i \} * r_y / (1 - (1/(1+r_y)^y)) \quad (5.27)$$

Congestion cost, delay costs are not considered in this research.

5.5.3 Modelling inspection cost

Let I_f be the inspection per MGT and i_c be the cost of one inspection. Then annual spread over inspection cost over the rail life is given by:

$$c_i = \{ \sum_{j=1}^{N_I} (i_c / (1 + r_i)^j \} * r_y / (1 - (1 / (1 + r_y)^y)) \quad (5.28)$$

where

$$N_I = Integer[\frac{M_N}{I_f}] \quad (5.29)$$

and r_i is discounting rate associated with interval of Non Destructive Testing (NDT).

5.5.4 Modelling risk cost of rail breaks and derailment

Let cost per rectification of rail breaks on emergency basis, C_r be modelled through *G(c)*, and is given by

$$G(c) = P[C_r \leq c] \quad (5.30)$$

For an example, if *G(c)* follows exponential distribution (Crowder et al, 1995), then it is given by

$$G(c) = 1 - e^{-\rho c} \quad (5.31)$$

where $\bar{c}$ denote the expected cost of each rail break repair on emergency basis and is given by:

$$\bar{c} = [1/\rho] \tag{5.32}$$

Let k be the expected cost of repairing potential rail breaks based on NDT in a planned way and a be the expected cost per derailment. Then k and a could be modelled in similar manner.

The risk cost associated with rail break and derailment is based on the probability of NDT detecting potential rail breaks, rail breaks not detected by NDT, derailments and associated costs.

Let $P_i(B)$ be the probability of detecting potential rail break in NDT, $P_i(A)$ be the probability of undetected potential rail breaks leading to derailments, n_{NDT_j} be the number of NDT detected potential rail breaks, n_{RB_j} be the number of rail brakes in between two NDT inspections and n_{A_j} be number of accidents in period. Then the risk cost is given by:

$$c_r = \{\sum_{i=0}^{N} E[N(M_{i+1}, M_i)] * [P_i(B) * k + (1 - P_i(B)) * (P_i(A) * a + (1 - P_i(A)) * \bar{c}] / (1+r)^i\} * (1 - (1/(1+r_y))) * (1+r_y) / (1 - (1/(1+r_y)^y)) \tag{5.33}$$

where $P_i(B)$ and $P_i(A)$ could be estimated based on n_{NDT_j} the number of NDT detected potential rail breaks, n_{RB_j} the number of rail brakes in between two NDT inspections and n_{A_j} be number of accidents in between two NDT inspections over j periods.

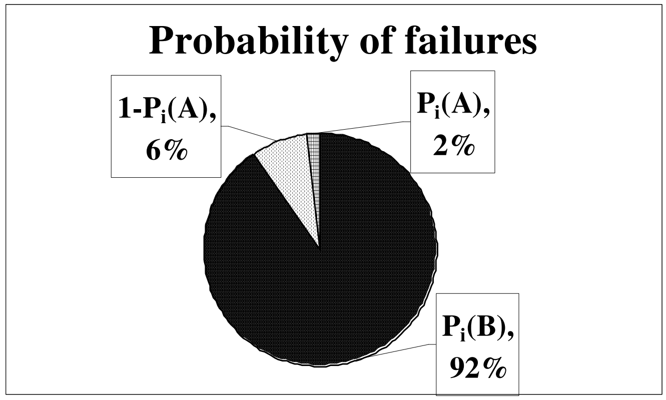

Figure 5.6: Probabilities of failures

5.5.5 Modelling Replacement Costs of Worn-Out Unreliable Rails

Let c_{re} be the expected cost of replacement for segment L and consists of labour, material, and equipment, consumable and down time cost for rail replacement. Let I be the cost of current investment in new rail. In this model the cost of replacement is assumed to be occurring at the beginning of each year and is simplifies as the annual spread over of investment of new rail. Then c_{re} is given by:

$$c_{re} = I * (1 - (1/(1 + r))) / (1 - (1/(1 + r_y)^y)) \tag{5.34}$$

5.5.6 Modelling Total Cost of Rail Maintenance

Costs associated with rail maintenance are estimated separately for low rail, high rail and curve radius and added up to obtain total cost of maintenance. Therefore, the total cost of maintaining a segment of rail is equal to the sum of cost for; Preventive rail grinding cost (c_g), Down time cost due to rail grinding (loss of traffic) (c_d), Inspection costs (NDT) (c_i), Risk cost of rectification based on NDT, rail breaks and derailment (c_r) and Replacement cost of worn-out unreliable rails (c_{re}). It is the given by:

$$C_{tot} = c_g + c_d + c_i + c_r + c_{re} \tag{5.35}$$

5.6 Cost and life data

Data is collected from field observations and in these calculations Weibull distribution is used with the parameters β= 3.6 and $2350 < 1/\lambda < 1250$ (Besuner et al., 1978), to estimate the rail breaks and derailments. In this case the grinding speed is set to 10 km/h with 3 passes (Table 5.1) to a total cost of 2 AUD/ meter/pass. Rest of the costs is given in Table 5.5. Discounting factor is used assuming 10% per year.

Table 5.5: Estimated costs and area safety limits

Cost of grinding per pass per meter	2.00	[AUD/pass/m]
Cost of replacement of one rail for segment L due to worn out regulation	152	[AUD/m]
Expected costs of repairing rail brakes	1700	[AUD/brake]
Expected cost per derailment (accident)	3000000	[AUD/accident]
Expected cost of down time per hour	3136	[AUD/h]
Inspection cost	0.0043	[AUD/m/MGT]
New rail cross sectional area	2960	[mm^2]
Critical area for replacement decision (BV50)	2520 – 585	[mm^2]
Critical area loss for replacement decision (UIC60)	2400 – 745	[mm^2]
Critical area loss for replacement decision theoretical 80 kg/m profile	1960 – 1000	[mm^2]

5.6.1 Analysis of results

Data is used in simulation model developed and analysed using Mat lab and Microsoft Excel and results are shown in sections 5.6.2 to 5.8.

5.6.2 Grinding cost

Grinding cost is estimated using the grinding cost/meter/pass data ($AUD 2.00/meter/pass) and the average number of passes per section (minimum 2 and maximum 5 passes per section). Grinding cost estimation method is shown in Figure 5.7.

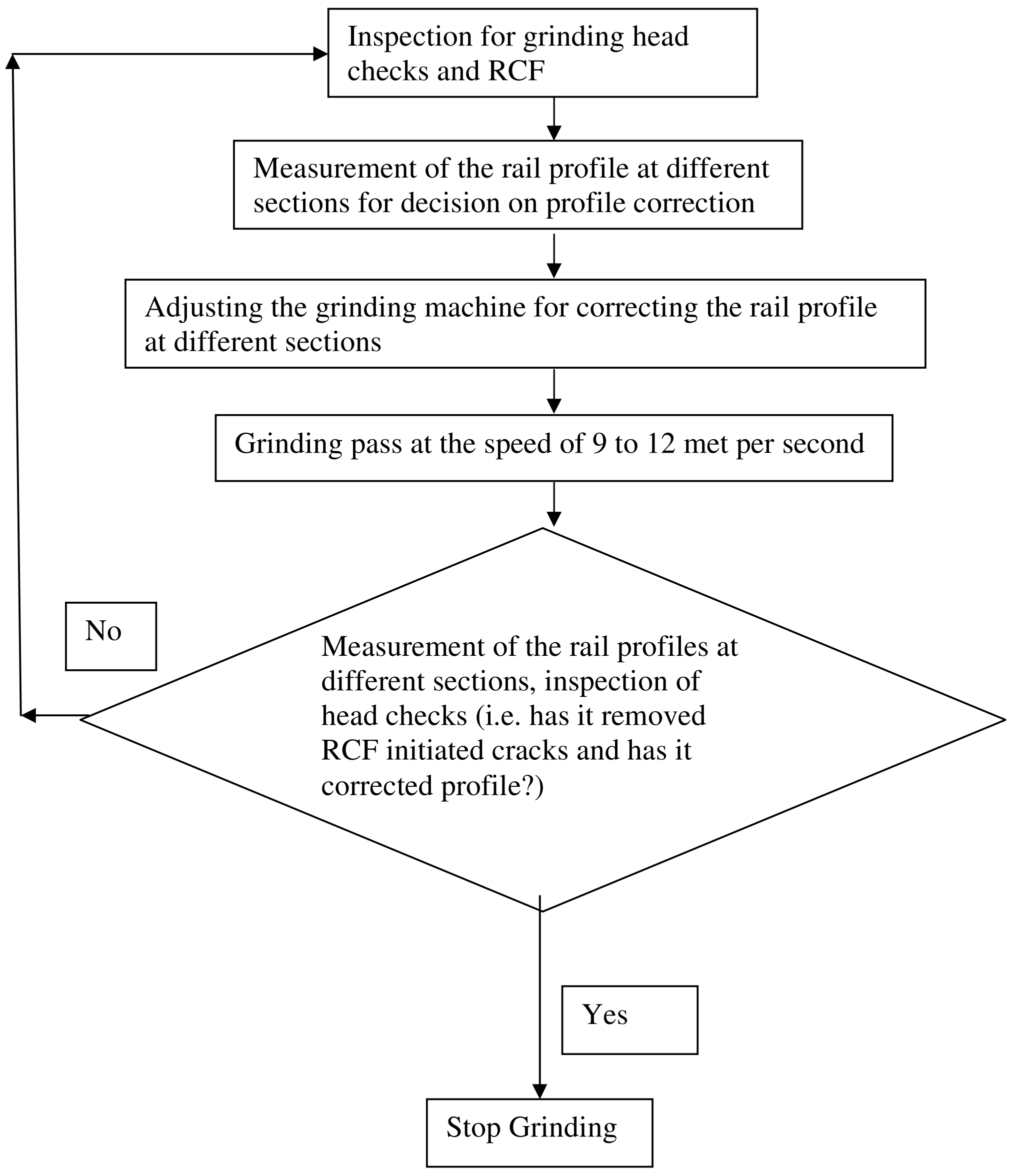

Figure 5.7: Grinding cost estimation method

5.6.3 Grinding cost/meter

Analysis of grinding cost/meter for 23, 12, 18 and 9 MGT is compared for curve radius from 0 to 800 meters. Results are given in Table 5.6.

Table 5.6: Grinding cost/meter for curve radius from 0 to 800 meters

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Grinding cost/meter ($AUD)**			
1318	0-300	10	20	18	36
1384	300-450	16	12	22	40
36524	450-600	16	16	26	30
33235	600-800	6	8	32	22

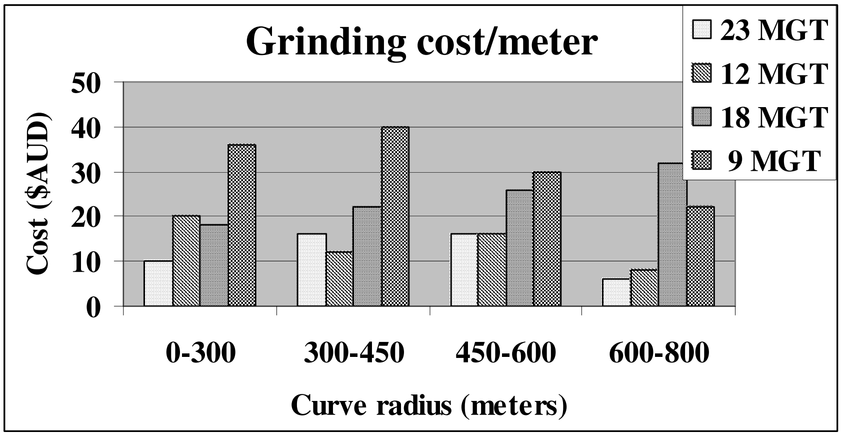

Figure 5.8: Grinding cost/meter for curve radius from 0 to 800 meters

Figure 5.8 shows the analysis of grinding cost/meter for 23, 12, 18, and 9 MGT of curve radius from 0 to 800 meters. It is observed that cost is higher for lower grinding intervals. The costs for lower curve radius 0-300 meters are in general more compared to higher curve (300-450 or more) sections of rail segment. This indicates more rolling contact fatigue (RCF) in steeper curves.

5.6.4 Grinding cost/MGT/meter

Analysis of grinding cost/MGT/meter for 23, 12, 18 and 9 MGT is compared for curve radius from 0 to 800 meters. Results are given in Table 5.7.

Table 5.7: Grinding cost/MGT/meter for curve radius from 0 to 800 meters

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Grinding cost/MGT/meter ($AUD)**			
1318	0-300	0.43	1.67	1	4
1384	300-450	0.7	1	1.22	4.44
36524	450-600	0.7	1.33	1.44	3.33
33235	600-800	0.26	0.67	1.78	2.44

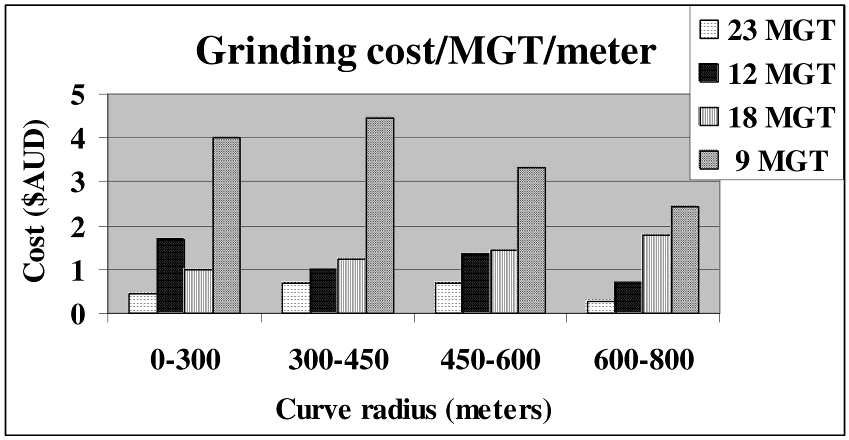

Figure 5.9: Grinding cost/MGT/meter for curve radius from 0 to 800 meters

Figure 5.9 shows the analysis of grinding cost/MGT/meter for 23, 12, 18, and 9 MGT of curve radius from 0 to 800 meters. It is observed that cost/MGT/meter trend is similar to per meter costs.

5.6.5 Risk cost/meter

Analysis of risk cost/meter for 23, 12, 18 and 9 MGT is compared for curve radius from 0 to 800 meters. Results are given in Table 5.8.

Table 5.8: Risk cost/meter for curve radius from 0 to 800 meters

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Risk cost/meter ($AUD)**			
1318	0-300	0.00004	0.0000076	0.00002	0.0000013
1384	300-450	0.00003	0.0000080	0.00001	0.0000012
36524	450-600	0.00000	0.0000003	0.00000	0.0000000
33235	600-800	0.00000	0.0000003	0.00000	0.0000000

5.6.6 Risk cost/MGT/meter

Analysis of risk cost/MGT/meter for 23, 12, 18 and 9 MGT is compared for curve radius from 0 to 800 meters. Results are given in Table 5.9.

Table 5.9: Risk cost/MGT/meter for curve radius from 0 to 800 meters

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Risk cost/MGT/meter ($AUD)**			
1318	0-300	0.000002	0.000001	0.000001	0.000000
1384	300-450	0.000002	0.000001	0.000001	0.000000
36524	450-600	0.000000	0.000000	0.000000	0.000000
33235	600-800	0.000000	0.000000	0.000000	0.000000

From the above Tables 5.8 and 5.9 it is observed that risk cost is negligible in these sections. This is due to the fact that rail operators work in a conservative manner related to rail replacements and rail repairs. It may be also due to the fact that many of the failure and accident data are not reported to avoid public criticism.

5.6.7 Down time cost/meter

Analysis of down time cost/meter for 23, 12, 18 and 9 MGT is compared for curve radius from 0 to 800 meters. Results are given in Table 5.10.

Table 5.10: Down time cost/meter for curve radius from 0 to 800 meters

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Down time cost/meter ($AUD)**			
1318	0-300	1.57	3.14	2.82	5.64
1384	300-450	2.51	1.88	3.45	6.27
36524	450-600	2.51	2.51	4.08	4.7
33235	600-800	0.94	1.25	5.02	3.45

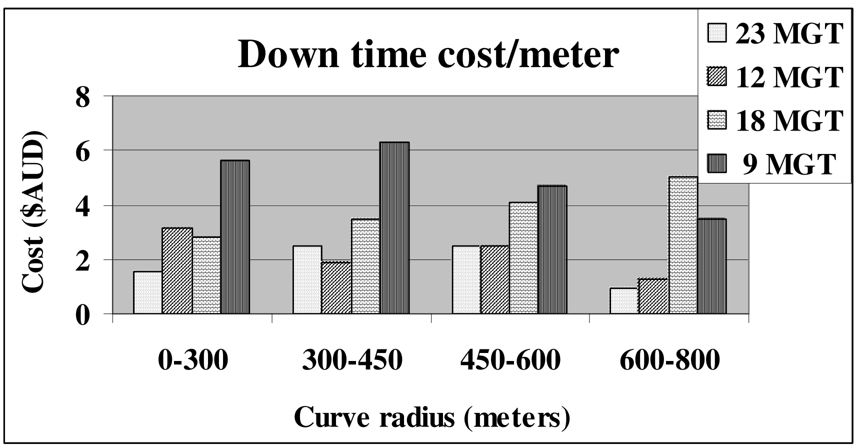

Figure 5.10: Down time cost/meter for curve radius from 0 to 800 meters

Figure 5.10 shows the analysis of down time cost/meter for 23, 12, 18, and 9 MGT of curve radius from 0 to 800 meters. It is observed that cost is higher for 9 MGT compared to 23, 12 and 18 MGT. This is due to increased number of set ups for lower MGT intervals. Costs are higher for steeper curves compared to other sections of rail segment. This may be due to increase in grinding passes due to more rolling contact fatigue (RCF) in steeper curves.

5.6.8 Down time cost/MGT/meter

Analysis of down time cost/MGT/meter for 23, 12, 18 and 9 MGT is compared for curve radius from 0 to 800 meters. Results are given in Table 5.11.

Table 5.11: Down time cost/MGT/meter for curve radius from 0 to 800 meters

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Down time cost/MGT/meter ($AUD)**			
1318	0-300	1.57	3.14	2.82	5.64
1384	300-450	2.51	1.88	3.45	6.27
36524	450-600	2.51	2.51	4.08	4.7
33235	600-800	0.94	1.25	5.02	3.45

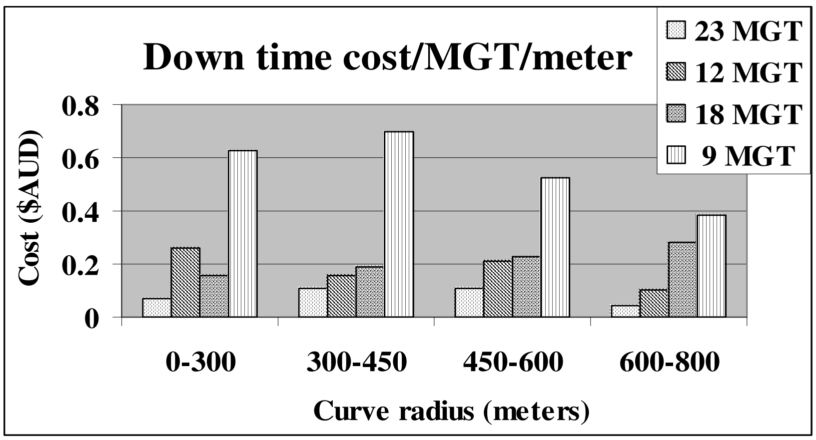

Figure 5.11: Down time cost/MGT/meter for curve radius from 0 to 800 meters

Figure 5.11 shows the analysis of down time cost/MGT/meter for 23, 12, 18, and 9 MGT of curve radius from 0 to 800 meters. It is observed that cost/MGT/meter trends are similar to per meter costs.

5.7 Annuity cost/meter

Annuity cost/meter for 23, 12, 18 and 9 MGT is estimated. Results are compared for each MGT and for different curves. Annuity costs/meter for grinding, risk, down time, inspection and replacement are estimated using mathematical model.

5.7.1 Annuity cost/meter for grinding

Analysis of annuity cost/meter for grinding 23, 12, 18 and 9 MGT is compared for curve radius from 0 to 800 meters. Results are shown in Table 5.12.

Table 5.12: Annuity cost/meter for grinding of curve radius (0 to 800 m)

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Annuity cost/meter for grinding ($AUD)**			
1318	0-300	5.42	6.82	11.41	14.00
1384	300-450	5.95	6.08	11.00	12.00
36524	450-600	6.00	7.12	11.00	10.00
33235	600-800	5.88	6.86	12.00	11.00

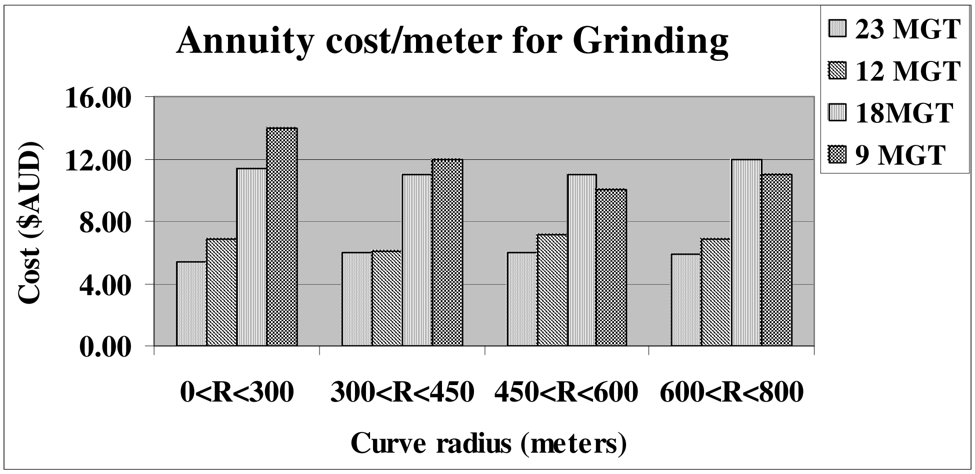

Figure 5.12: Annuity cost/meter for grinding of curve radius (0 to 800 m)

Figure 5.12 shows the analysis of annuity cost/meter for grinding 23, 12, 18, and 9 MGT of curve radius 0 to 800 meters. It is observed that annuity cost/meter for grinding is higher for 9 and 18 MGT. This is due to excessive grinding in these intervals. The 18 and 9 MGT intervals are based on 3 monthly and 6 weekly traffic volume at QR per MGT cost could be comparable.

5.7.2 Annuity cost/meter for risk

Analysis of annuity cost/meter for risk 23, 12, 18 and 9 MGT are compared for curve radius from 0 to 800 meters. Results are shown in Table 5.13.

Table 5.13: Annuity cost/meter for risk of curve radius from 0 to 800 meters

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Annuity cost/meter for risk ($AUD)**			
1318	0-300	0.0016	0.0002	0.0011	0.0000
1384	300-450	0.0018	0.0004	0.0002	0.0000
36524	450-600	0.0001	0.0000	0.0000	0.0000
33235	600-800	0.0001	0.0000	0.0000	0.0000

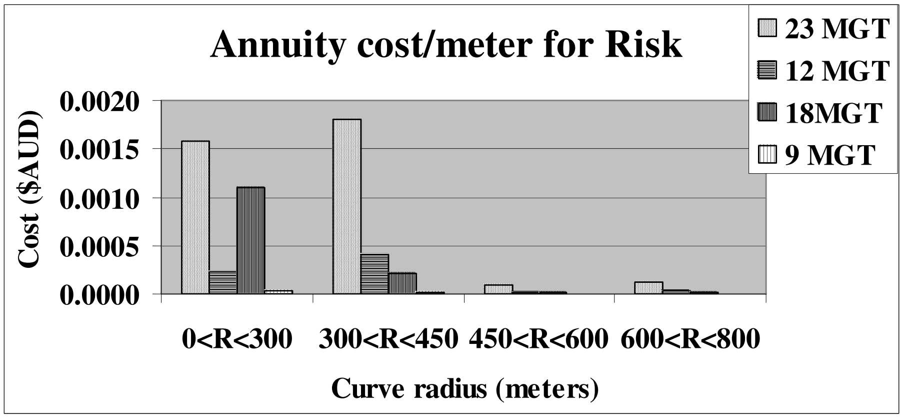

Figure 5.13: Annuity cost/meter for risk of curve radius from 0 to 800 meters

Figure 5.13 shows the analysis of annuity cost/meter for risk 23, 12, 18 and 9 MGT of curve radius from 0 to 800 meters. It is observed that annuity cost/meter for risk trend is similar to cost/MGT/meter of grinding. The data on risk cost based on very small number of derailment incidents and there is enough scope for estimating actual risk cost based on real life derailment data.

5.7.3 Annuity cost/meter for down time

Analysis of annuity cost/meter for down time 23, 12, 18 and 9 MGT is compared for curve radius from 0 to 800 meters. Results are shown in Table 5.14.

Table 5.14: Annuity cost/meter for down time of curve radius (0 to 800 meters)

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Annuity cost/meter for down time ($AUD)**			
1318	0-300	0.85	1.07	1.79	2.14
1384	300-450	0.93	0.95	1.56	1.85
36524	450-600	0.94	1.12	1.77	1.57
33235	600-800	0.92	1.08	1.83	1.74

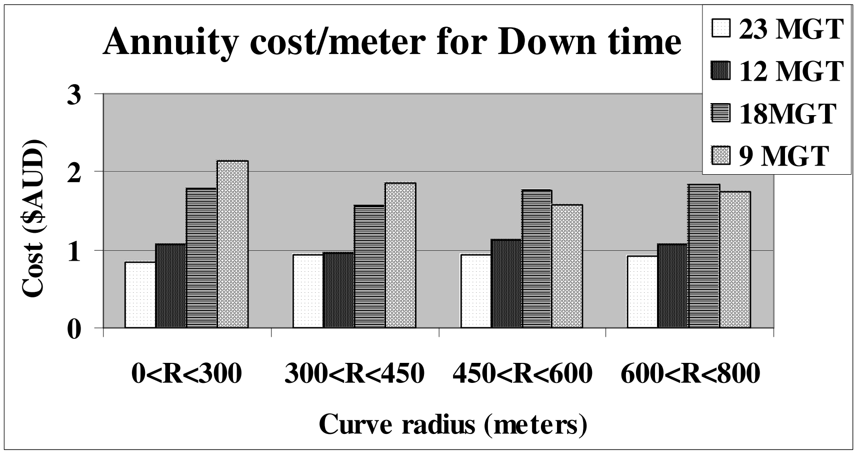

Figure 5.14: Annuity cost/meter for down time of curve radius (0 to 800 m)

Figure 5.14 shows the analysis of annuity cost/meter for down time 23, 12, 18 and 9 MGT of curve radius from 0 to 800 meters. It is observed that annuity cost/meter for down time trend is similar to annuity cost/meter of grinding.

5.7.4 Annuity cost/meter for inspection

Analysis of annuity cost/meter for inspection 23, 12, 18 and 9 MGT is compared for curve radius from 0 to 800 meters. Results are shown in Table 5.15.

Table 5.15: Annuity cost/meter for inspection of curve radius (0 to 800 m)

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Annuity cost/meter for inspection ($AUD)**			
1318	0-300	0.044	0.023	0.035	0.017
1384	300-450	0.044	0.023	0.033	0.017
36524	450-600	0.044	0.023	0.030	0.016
33235	600-800	0.044	0.023	0.031	0.018

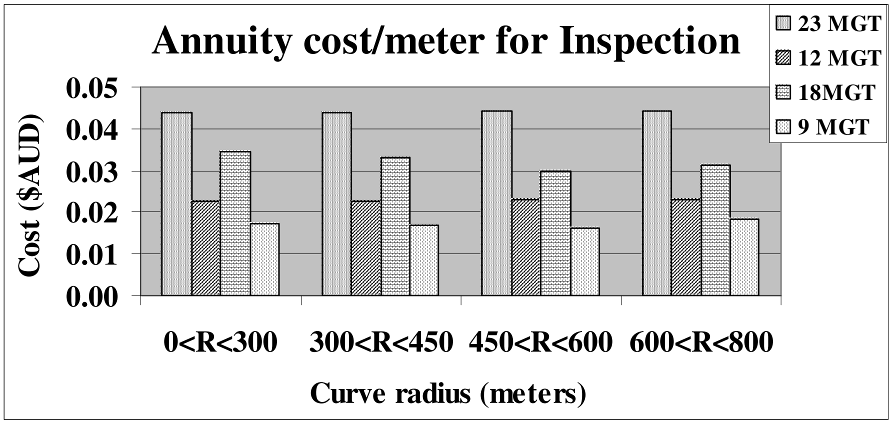

Figure 5.15: Annuity cost/meter for inspection of curve radius (0 to 800 m)

Figure 5.15 shows the analysis of annuity cost/meter for inspection 23, 12, 18 and 23 MGT for curve radius 0 meters to tangent track. It is observed that the cost for inspection is slightly higher for 23 MGT and 18 MGT compared to 9 and 12 MGT. This is due to increased life and number of inspections.

5.7.5 Annuity cost/meter for replacement

Analysis of annuity cost/meter for replacement 23, 12, 18 and 9 MGT is compared for curve radius from 0 to 800 meters. Results are shown in Table 5.16.

Table 5.16: Annuity cost/meter for replacement of curve radius (0 to 800 m)

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Annuity cost/meter for replacement ($AUD)**			
1318	0-300	17.65	15.00	16.00	20.62
1384	300-450	15.17	13.10	24.00	25.00
36524	450-600	16.06	11.63	32.00	28.00
33235	600-800	15.00	11.49	21.00	28.00

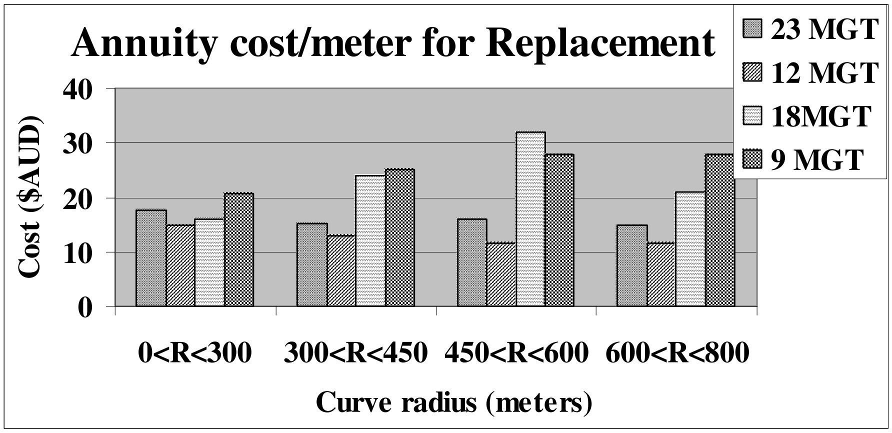

Figure 5.16: Annuity cost/meter for replacement of curve radius (0 to 800 m)

Figure 5.16 shows the analysis of annuity cost/meter for replacement 23, 12, 18 and 9 MGT of curve radius from 0 to 800 meters. It is observed that cost for replacement is higher for 9 and 18 MGT compared to 23 and 12 MGT. This may be due to more replacements and excessive grinding in higher MGT intervals.

5.7.6 Total annuity cost/meter

Analysis of total annuity cost/meter for 23, 12, 18 and 9 MGT is compared for curve radius 0 to 800 meters. Results are shown in Table 5.17.

Table 5.17: Total annuity cost/meter for curve radius from 0 to 800 meters

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Total annuity cost/meter ($AUD)**			
1318	0-300	23.96	22.91	29.24	36.78
1384	300-450	22.09	20.15	36.59	38.87
36524	450-600	23.04	19.89	44.80	39.59
33235	600-800	21.84	19.45	37.86	40.76

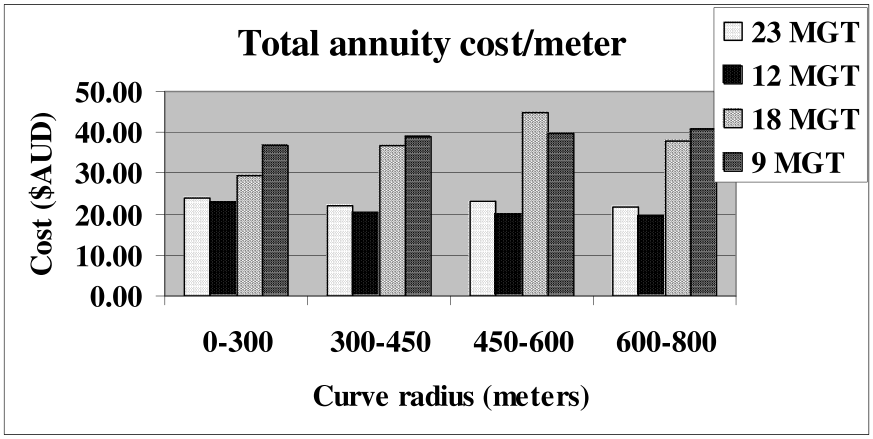

Figure 5.17: Total annuity cost/m for replacement of curve radius (0 to 800 m)

Figure 5.17 shows the analysis of total annuity cost/meter for 23, 12, 18 and 9 MGT of curve radius from 0 to 800 meters. From the analysis it is observed that cost is higher for 18 and 9 MGT intervals. This may be mainly due to more rail replacements due to excessive grinding for lower MGT intervals. The 18 and 9 MGT intervals are based on 3 monthly and 6 weekly traffic volume at QR per MGT costs are comparable. It is also observed that cost is more in steeper curves.

5.8 Annuity cost/meter assessment for each MGT

5.8.1 Annuity cost/meter for 23 MGT

Analysis of annuity cost/meter of grinding, risk, down time, inspection and replacement for 23 MGT of curve radius from 0 to 800 meters is compared. Results are shown in Table 5.18.

Table 5.18: Annuity cost/meter for 23 MGT of curve radius (0 to 800 meters)

Radius (meters)	0-300	300-450	450-600	600-800
Length (meters)	1318	1384	36524	33235
Maintenance costs	**Annuity cost/meter ($AUD)**			
Grinding	5.42	5.95	6.00	5.88
Risk	0.00	0.00	0.00	0.00
Down time	0.85	0.93	0.94	0.92
Inspection	0.04	0.04	0.04	0.04
Replacement	17.65	15.17	16.06	15.00

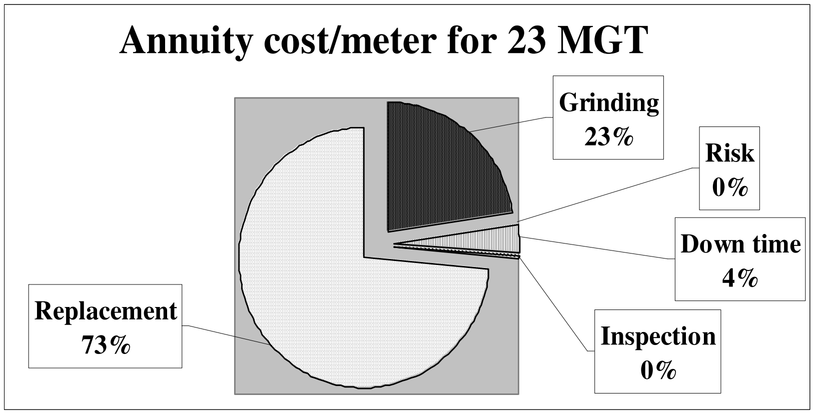

Figure 5.18: Annuity cost/meter for 23 MGT of curve radius (0 to 800 m)

Figure 5.18 shows the analysis of annuity cost/meter for 23 MGT of curve radius from 0 to 800 meters. It is observed that replacement and grinding costs are higher compared to other costs.

5.8.2 Annuity cost/meter for 12 MGT

Analysis of annuity cost/meter of grinding, risk, down time, inspection and replacement for 12 MGT of curve radius from 0 to 800 meters is compared. Results are shown in Table 5.19.

Table 5.19: Annuity cost/meter for 12 MGT of curve radius (0 to 800 m)

Radius (meters)	0-300	300-450	450-600	600-800
Length (meters)	1318	1384	36524	33235
Maintenance costs	**Annuity cost/meter ($AUD)**			
Grinding	6.82	6.08	7.12	6.86
Risk	0.00	0.00	0.00	0.00
Down time	1.07	0.95	1.12	1.08
Inspection	0.02	0.02	0.02	0.02
Replacement	15.00	13.10	11.63	11.49

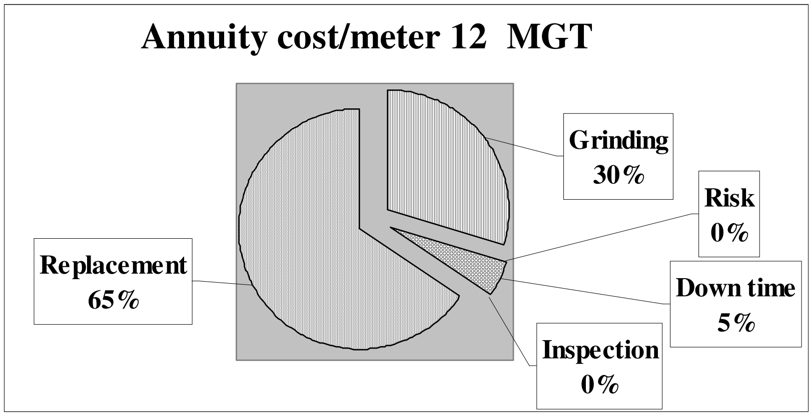

Figure 5.19: Annuity cost/meter for 12 MGT of curve radius (0 to 800 m)

Figure 5.19 shows the analysis of annuity cost/meter for 12 MGT of curve radius from 0 to 800 meters. It is observed that the cost is higher for replacement and grinding.

5.8.3 Annuity cost/meter for 18 MGT

Analysis of annuity cost/meter of grinding, risk, down time, inspection and replacement for 18 MGT of curve radius from 0 to 800 meters is compared. Results are shown in Table 5.20.

Table 5.20: Annuity cost/meter for 18 MGT of curve radius (0 to 800 m)

Radius (meters)	0-300	300-450	450-600	600-800
Length (meters)	1318	1384	36524	33235
Maintenance costs	**Annuity cost/meter ($AUD)**			
Grinding	11.41	11.00	11.00	12.00
Risk	0.00	0.00	0.00	0.00
Down time	1.79	1.56	1.77	1.83
Inspection	0.03	0.03	0.03	0.03
Replacement	16.00	24.00	32.00	24.00

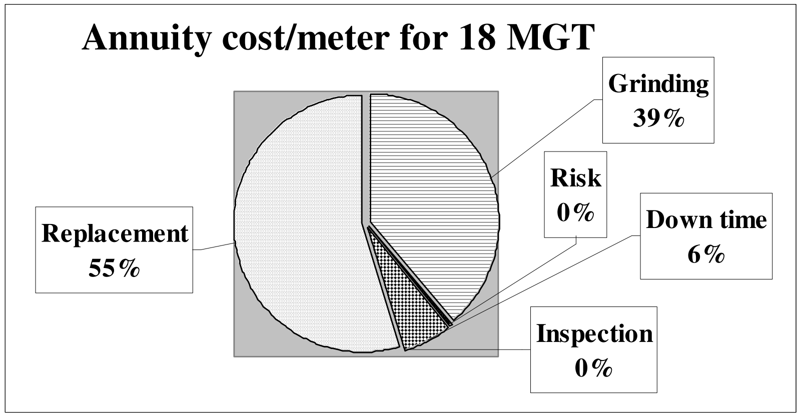

Figure 5.20: Annuity cost/meter for 18 MGT of curve radius (0 to 800 m)

Figure 5.20 shows the analysis of annuity cost/meter for 18 MGT of curve radius from 0 to 800 meters. It is observed that the cost for replacement and grinding are higher compared to other costs.

5.8.4 Annuity cost/meter for 9 MGT

Analysis of annuity cost/meter of grinding, risk, down time, inspection and replacement for 9 MGT of curve radius from 0 to 800 meters is compared. Results are shown in Table 5.21.

Table 5.21: Annuity cost/meter for 9 MGT of curve radius (0 to 800 m)

Radius (meters)	0-300	300-450	450-600	600-800
Length (meters)	1318	1384	36524	33235
Maintenance costs	**Annuity cost/meter ($AUD)**			
Grinding	14.00	12.00	10.00	11.00
Risk	0.00	0.00	0.00	0.00
Down time	2.14	1.85	1.57	1.74
Inspection	0.02	0.02	0.02	0.02
Replacement	20.62	25.00	28.00	28.00

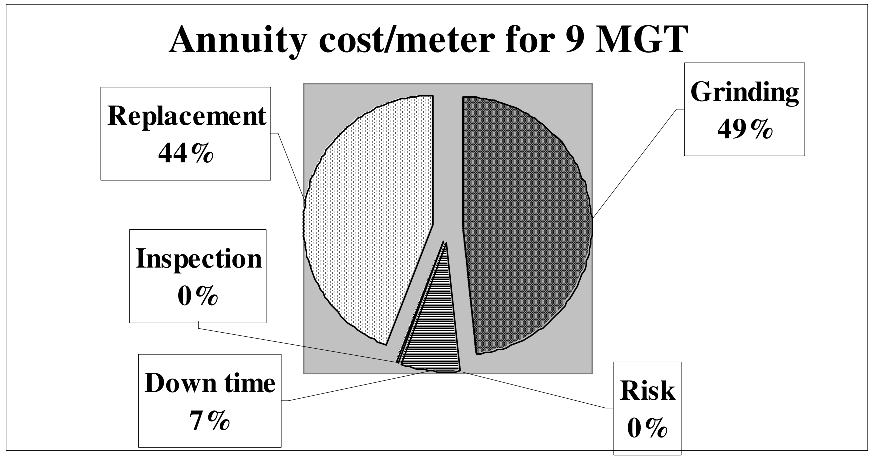

Figure 5.21: Annuity cost/meter for 9 MGT of curve radius (0 to 800 m)

Figure 5.21 shows the analysis of annuity cost/meter for 9 MGT of curve radius from 0 to 800 meter. It is observed that grinding cost is higher compared to other costs.

5.9 Summary

This chapter is on application of system approach to develop cost models for rail grinding decisions. Field data from Sweden have been used for practical validation. Results from this investigation have been used in maintenance and replacement decisions of rails. The annuity cost/meter for grinding, risk, down time, inspection, replacement and lubrication are analysed. Results for 23, 12, 18 and 9 MGT of curve radius from 0 to 300, 300-450, 450-600 and 600-800 meters are modelled. Analysis shows that rail players can save with 12 MGT intervals compared to 23 MGT intervals. There is enormous scope to extend these models for optimal maintenance decisions considering wheel profiling, lubrication (track and/or on board) and variation of weather conditions. Some of these are considered in next chapter.

Chapter 6

Integrated model for optimal rail grinding decisions based on lubrication and grinding and weather conditions

6.1 Introduction

The friction at contact area results wear of wheel and rail. To minimise wear, lubrication at wheel flange and rails especially on sharp curves has been accepted as an effective solution. Railroads generally use three methods for lubrication. They are:

- Way side lubrication system
- On board lubrication system
- Hi-rail lubrication system

In way-side lubrication system, grease is applied at track when the lubricator is activated either mechanically or electronically by passing wheels. In on-board lubrication, the lubricator is mounted on the locomotive and the lubricant is applied using a spray system to the locomotive wheel flanges. Hi-rail lubrication system uses a specially designed mobile truck for the grease application. The lubricant is applied from the nozzle as a thin bead along the rail gage face. By using one or more of the above systems, railroads can achieve significant savings in fuel and cost of wheel/track maintenance. However, there are some harmful effects of using excessive lubricant. These are wastage, loss of locomotive traction due to presence of lubricant on the top of rail and environmental concerns of underground water contamination (Pandey et. al., 2000).

The out line of this chapter is as follows: Section 6.2 presents role of lubrication and its impact over rail life. Section 6.3 discusses its effect on rail wear and rolling contact fatigue. Integrated model combining rail grinding and lubrication is developed in section 6.4. Section 6.5 provides numerical examples and simulation results. Summary and conclusion is provided in section 6.6.

6.2 Role of Lubrication

In Sweden Curves less than 600 m are routinely lubricated by stationary wayside equipment. However, the Swedish National Rail Administration found in their study that only 25% of the installed lubricating equipments were working satisfactorily (Larsson, 2000). An experimental test program of wheel/rail adhesion and wear was undertaken by Kumar et al. (1996) to analyse the effects of axle load, adhesion coefficient, angle of attack, class of wheels and mode of operation. The influencing parameters identified are:

- Rail curvature or angle of attack
- Adhesion coefficient
- Axle loads

Thelen and Lovette (1996) discussed the effect of lubrication at the gauge corner. It is influenced by a number of parameters such as frequency of trains, lubrication passes and the amount of lubricant in each pass. Sims et al. (1996) studied the influence of coefficient of friction on wear. Nilsson (2002) discusses important factors influencing rail wear such as friction coefficient (based on humidity, temperature, surface texture), type of lubrication equipment (on board or wayside), grease contamination from dust, leaves, worn away metal particles, water, rail and wheel profile rectification. Other factors are track irregularities (vertical, lateral, cant, gauge), curve radius, magnitude of creep in wheel/rail contact, traction braking and acceleration.

Grease consumption for rail lubrication varies between 0.7 kg/km to 2.5 kg/km per year for different countries based on traffic condition (Larsson, 2000). The variation depends on the number and type of trains, track curvature and application equipment. The Russian railway system consumes an estimated 95,000-100,000 metric tonnes of lubricants annually. The annual lubricant consumption in Russia (2nd largest in the world with 87 000 km of main track and 77.7 % of freight lines) is 30% higher than many other rail systems (Habali, 1999). Studies on lubrication effectiveness shows that 30% of fuel savings were achieved in running 100 ton capacity cars at a constant speed of 40 miles per hour in a fully lubricated FAST (Facility for Accelerated Service Testing) loop with respect to unlubricated conditions. Gangloff (1999) analysed lubricants used in railroad applications and found that most of those are petroleum-based greases and special graphite lubricants. He also predicted that by 2008 the railroad lubricant demand in U.S. would be in the order of 110,000 metric tonnes per year out of which a significant portion of the grease would be wasted due to wayside lubrication. It has potential for ground water contamination. There is a need for optimal application of type and quantity lubrication depending on need and changed environmental protection regulations.

Goyan et al. (1997) discussed environmental regulations related to rail lubrication. Biodegradable grease with low toxicity provides excellent extreme pressure, low wear rate properties, low temperature pumpability, suitable dropping points, and the ability to be transported a reasonably long distance (at least 1.5 km down the track). Kramer (1994), found that grease based projects lubrication, used on main lines is prone to waste and rail players have already started for developing solid lubrication.

The development and use of effective lubrication practices, both wayside and vehicle mounted, has decreased wear in curves. However, there is encouraging scope for research to improve effectiveness and reliability of lubricators and lubricants (Allen, 1999). The study in Hunter Valley, New South Wales Australia had following findings (Marich et al., 2001):

1. Curves with radii greater than 500 m do not have any significant gain out of lubrication.
2. Positioning of rail mounted lubricators near sharp curves, with radii up to 300 to 400 m, leads to excessive wastage of lubrication if activated by the loaded traffic and has the potential for running surface contamination, loss of traction, wheel burns/skids and rail gauge corner defects.
3. Efficient lubrication can be achieved by using the standard lubricant in concrete sleepered track, containing tight curves, even up to 6/8 km away from the lubricators. This can be achieved by:
    - Positioning lubricators at the end of curves, which are activated by empty rather than loaded traffic
    - Positioning lubricators at the end of curves with radii of 600 to 1000 meters: Common practice of positioning lubricators near the tighter curves has an adverse effect of reducing lubricant available for subsequent curves, since the lubricant is squeezed out and wasted by the higher wheel/rail flange contact pressures, leading to increased lubricant wastage and contamination of the rail running surface, and

- Positioning lubricators within curves of 1000 to 2000 meters; in single track operation. This has the advantage of the lubricator acting in a bidirectional mode and therefore covering a much longer track section.

4. Application of steering, which tends to reduce the flanging forces and therefore provides more stable environment for spreading and retaining the lubricant, even in sharper curves.
5. Setting up of the lubricators based on the condition of the wheels and the track in a way so that lubricant is not wasted.

This study led to a reduction in the number of trackside lubricators in the concrete sleepered track. These were then applied and assessed in timber-sleepered track, with tight curves containing rails that had not been maintained at regular intervals. This also led to a reduction in the number of active lubricators, which in turn resulted in improved traction characteristics and reduced cost of maintaining ineffective lubricators (Marich et al., 2001).

6.3 Lubrication effect over rail wear rate

In ICON project, KTH (Royal Institute of Stockholm) studied traffic wear rate of Stockholm commuter trains. Results shown in Figure 6.1 indicate that lubrication has a significant influence over the rail wear rate. The rail wear rate decreases with increase in curve radius for both high and low rails. The wear rate ratio between non-lubricated and lubricated sites also decreases with increase in curve radius.

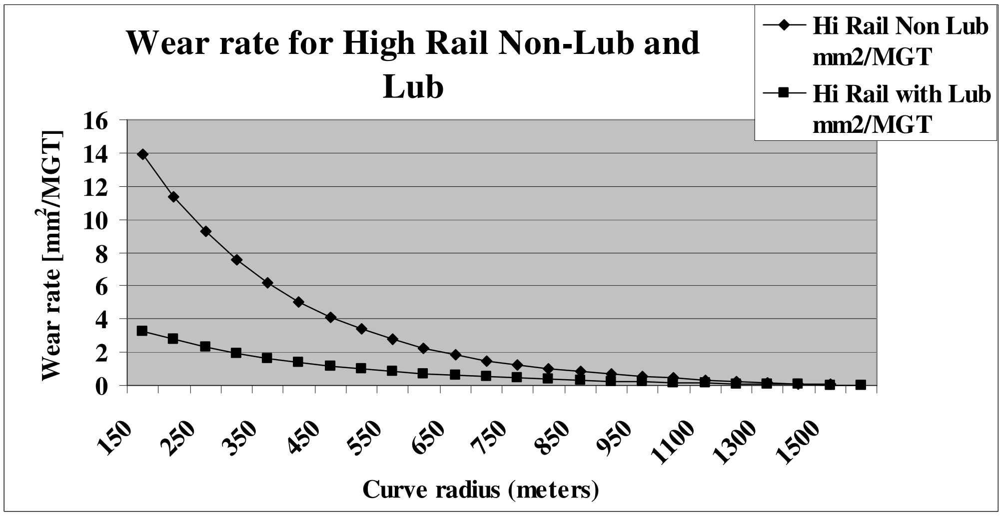

Figure 6.1: Traffic Wear rate for High Rail Non-Lubricated and Lubricated

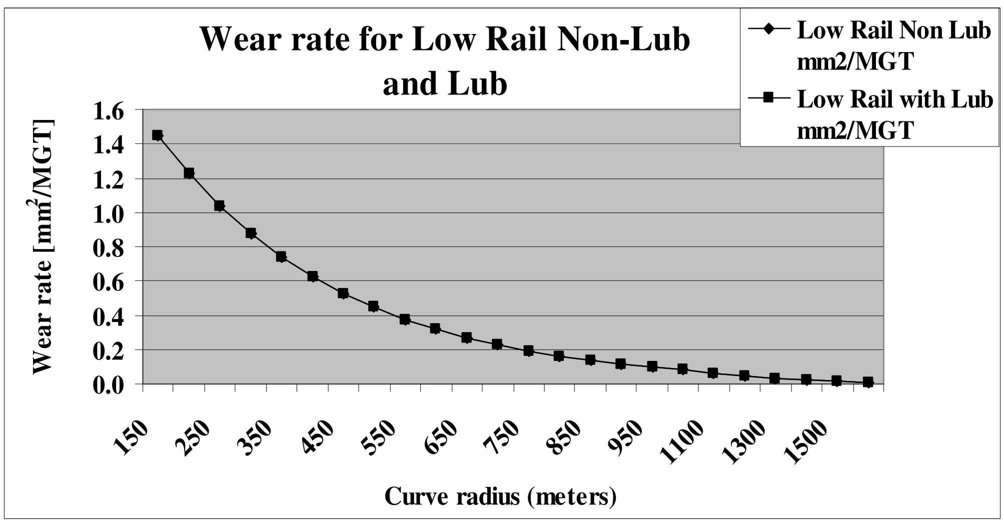

Figure 6.2: Traffic wear rate for lubricated and non-lubricated low rails

Figure 6.2 shows that the effect is same for both lubricated and non-lubricated low rail. The reason for this might be due to the contact environment at the low rail does not change. Another possible reason may be that the vehicle performance at the low rail is obtained due to lubrication of the high rail (Nilsson, 2002).

The area A_{lub} below the lubricated wear rate for high rail (Figure 6.3) is considered as a safe region where the rail life can be extended for a few more years. The lubricated wear rate curve may not be the optimal solution to reduce the traffic wear rate. The area $A_{non\text{-}lub}$ above the non-lubricated wear rate for high rail is considered as a worn off area, where rail must be replaced to avoid risk of rail break and derailment problems. Depending on how the rail is operated (type of traffic, lubricator efficiency, climate conditions etc.) the traffic wear rate [mm^2]/MGT can be in-between the two curves. A way to measure, indicate and compare (performance indicator) if a track is operated close to the upper curve, $f_1(R)$, (non-lubricated high wear scenario) or close to the lower curve, $f_2(R)$, (effectively lubricated) is to compare the actual operating point with respect to these two curves.

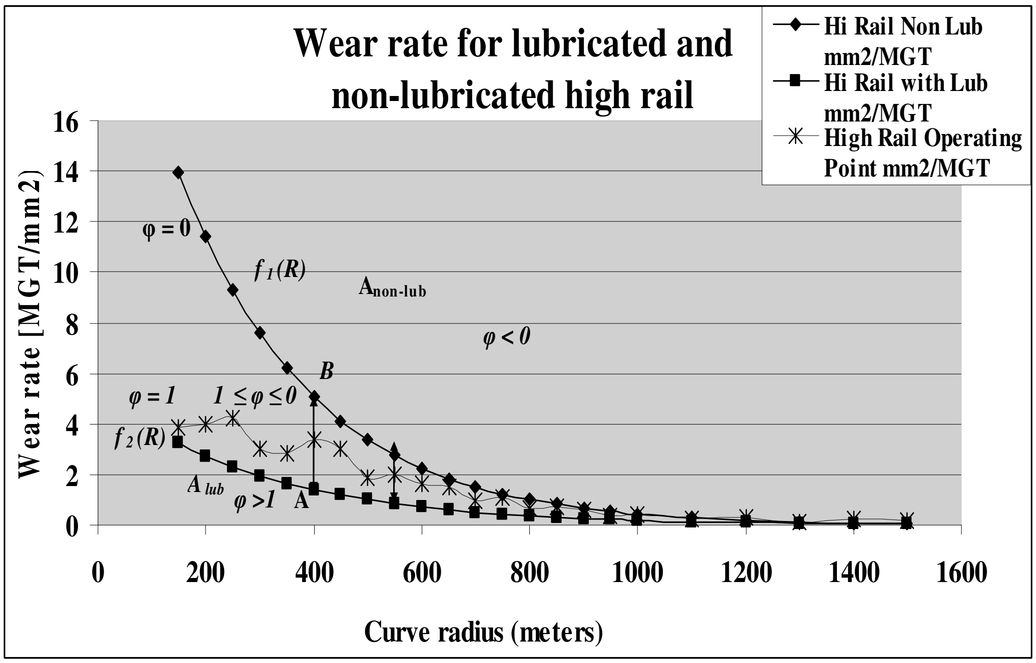

Figure 6.3: Traffic wear rate for lubricated, non-lubricated & operating point

Therefore $\left(f_1(R) \geq f_2(R)\right)$

Let $\alpha(R)$ and $\left(1-\alpha(R)\right)$ be the rail wear rate for curve radius 500 m between points A and B. Total wear rate between A and B is given by

$$T_{wear} = \alpha(R) + (1-\alpha(R)) \tag{6.1}$$

Operating point from non-lubricated curve of rail wear

$$\alpha(R) = \frac{\left(f_1(R) - f_2(R)\right)}{f_1(R)} \tag{6.2}$$

Operating point from lubricated curve of rail wear

$$\left(1-\alpha(R)\right) = 1 - \frac{\left(f_1(R) - f_2(R)\right)}{f_1(R)} \tag{6.3}$$

Figure 6.3 shows that the operating points for radii 300, 500 and 800 m is at 3.00 mm^2, 1.85mm^2, and 0.65 mm^2 respectively. To find the optimal operating point, it is important to look into maintenance costs such as grinding cost, lubrication cost, risk cost, down time cost, Inspection cost and replacement cost.

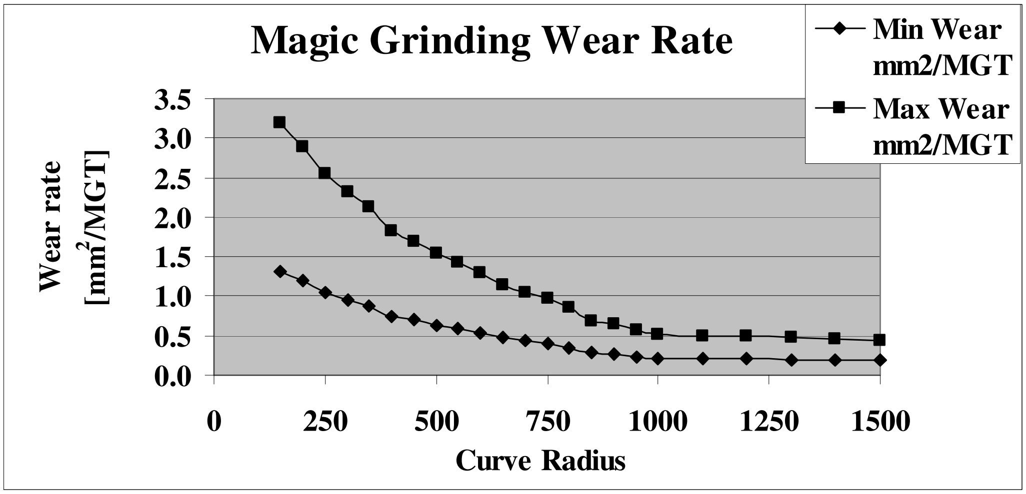

Figure 6.4: Magic grinding wear rate for high and low rails

Figure 6.4 shows that the preventive grinding programs to grind away a thin layer of material (0.0001 – 0.0002 µm from gauge corner of the rail and 0.00005-0.00015 µm from the crown) before surface cracks propagate. Kalousek and Magel (1997) analyzed grinding interval for heavy-haul and found that it should be around 5 - 8 MGT on curves 0 – 600 m, 10 – 15 MGT on curves 600 – 700 m and 18 – 25 MGT on curves of 700 – tangent. In curves with high-hardness, high-cleanliness premium rail steel with intermediate gauge-corner relief, the grinding interval can be extended to 12 – 15 MGT in sharp curves and 24 – 30 MGT in mild curves. In light grinding at regular intervals the rail is methodically worn to remove the fatigued layer. With control of grinding process, the head of a 60 Kg rail section can yield 700 – 1000 MGT of rail life on sharp curves; 1400 – 2000 MGT on mild curves; and well above 2000 MGT on tangent track.

A combination of start/stop lubrication based on weather condition and preventive rail grinding is being considered by some rail players. This strategy changes with the hardness of the materials, the average contact stresses, wheel set- steering performance, the co-efficient of friction, and the effectiveness of the lubrication. In

ICON project Nilsson (2002) indicated that the combination of the lubrication method, lubricants, vehicles and track parameters can lead to nearly similar wheel-rail contact situations.

The influence of track-side lubrication is significant on rail wear. Field study in KTH Sweden shows that the wear rate is approximately one-fifth at the lubricated sites compared to the wear rate for the corresponding non-lubricated sites (Jendel, 2002). By comparing the wear rate it is observed that the effect of lubrication is significant. The wear rate for lubricated curve at 200 m distance is approximately twice compared to the wear rate at 50 m distance from the lubrication device. Decision on lubricant type and lubrication system depend on a range of factors including local topography, climate, average train length and frequency, number and radius of curves, rolling stock types, axle loads, and application method.

6.4 Integrated rail grinding and lubrication model

Rail wear rate and rolling contact fatigue are influenced by wheel-rail contact and weather conditions. Water, snow or ice, alters the friction coefficient of wheel and rail. Reduced friction reduces the maximum tangential stresses before slip. It influences the overall force balance between the vehicle and the track and hence changes the location of the contacts. Other elements such as organic debris from trees and fields, and non-organic debris in contact with water/moisture, worn metallic debris from rails and silicon debris from the concrete sleepers/ballast can influence contact conditions. Air temperature and exposure to sun are other factors influencing evaporation from and water condensation to the rail surface (Nilsson, 2002).

The cost model developed in Chapter 5 is extended here to include lubrication strategies. As already explained earlier $\Lambda_j(m)$ is an intensity function for rail defects where m represents Millions of Gross Tonnes (MGT) and j indicates lubrication strategy. Number of failures in a statistical sense increases with MGT and is influenced by different lubrication strategies. Cumulative rail failure distribution $F_j(m)$ modelled as Weibull distribution is given by:

$$F_j(m) = 1 - \exp(-(\lambda_j m)^{\beta_j}) \qquad (6.4)$$

j = l means lubricated

= s means start/ stop lubrication

= nl means no lubrication

In case of l (i.e. lubricated) strategy rails are expected to have maximum life. Here, s means start/stop lubrication strategy where lubrication is operated based on seasons and requirements. In the cold countries like Europe and North America lubrication is stopped during the winter and starts operating during dry seasons.

$\Lambda_j(m)$ is given by (Similar inline with Equation 5.6, 5.7 and 5.8):

$$\Lambda_j(m) = \frac{f_j(m)}{1-F_j(m)} = \frac{\lambda_j \beta_j (\lambda_j m)^{\beta_j - 1} \exp(-(\lambda_j m)^{\beta_j})}{1-(1-\exp(-(\lambda_j m)^{\beta_j})} = \lambda_j \beta_j (\lambda_j m)^{\beta_j - 1} \qquad (6.5)$$

with the parameters $\beta_j > 1$ and $\lambda_j > 0$.

with condition on $N(M_{i+1}, M_i) = n$, the probability is given by:

$$P\{N(M_{i+1}; M_i) = n\} = \{\int_{M_i}^{M_{i+1}} \Lambda_j(m)dm\}^n e^{-\int_{M_i}^{M_{i+1}} \Lambda_j(m)dm} / n! \qquad (6.6)$$

The expected number of failures over period i and (i+1) is given by:

$$E_j[N(M_{i+1}, M_i)] = \lambda_j^{\beta_j}((M_{i+1})^{\beta_j} - (M_i)^{\beta_j}) \qquad (6.7)$$

6.4.1 Modelling preventive rail grinding cost

When g be the cost of grinding per pass per meter and $n_{GP_{ij}}$ is the number of grinding pass for i^{th} grinding, under j^{th} strategy, then for L, the length of rail segment under consideration, N_j the total number of periods up to safety limit for renewal can be estimated. The combination of lubrication and preventive grinding reduces traffic wear and RCF. Preventive rail grinding cost varies with lubrication strategy. Then the rail grinding cost/year is given by:

$$c_{g_j} = \{\sum_{i=1}^{N_j - 1}(g * n_{GP_{ij}} * L)/(1+r)^i\} * r_y /(1-(1/(1+r_y)^{y_j})) \qquad (6.8)$$

6.4.2 Modelling loss of traffic due to rail grinding

For h_{DT}, the expected downtime due to each grinding pass, n_{GP_i}, the number of grinding pass for i^{th} grinding and d, the expected cost of down time per hour can be estimated. Down time cost varies with lubrication strategy. Rail companies loss the traffic due to continuos lubrication and stop/start lubrication strategy. Down time cost due to rail grinding and lubrication strategy leading the loss of traffic can be modelled as:

$$c_{d_j} = \{\sum_{i=1}^{N_j - 1} n_{GP_{i_j}} * h_{DT} * d / (1+r)^i\} * r_y / (1 - (1/(1+r_y)^{y_j})) \tag{6.9}$$

6.4.3 Modelling cost of rail breaks and derailment

Risk cost associated with rail breaks and derailment depends on track/wheel condition based on preventive grinding and lubrication strategy. It is observed that grinding and lubrication can balance the wear and rolling contact fatigue to enhance rail life. Risk is reduced due to lubrication compared to non-lubricated curves of lower radius. The risk cost can be modelled as:

$$c_{r\,j} = \{\sum_{i=0}^{N_j} E_j[N(M_{i+1}, M_i)] * [P_i(B) * k + (1 - P_i(B)) * (P_i(A) * a + (1 - P_i(A)) * \bar{c}] / (1+r)^i\} * (1 - (1/(1+r_y))) * (1+r_y) / (1 - (1/(1+r_y)^{y_j})) \tag{6.10}$$

where $P_i(B)$ and $P_i(A)$ can be estimated based on n_{NDTq}, the number of *NDT* detected potential rail breaks, n_{RB_q} the number of rail brakes in between two *NDT* inspections and n_{A_q} the number of accidents in between two *NDT* inspections.

6.4.4 Modelling inspection cost

Non-destructive testing is widely used in track to detect rail defects. Ultrasonic inspection is one method used for this purpose. Inspection intervals are set in accordance with operational conditions. Selection of inspection intervals largely depends on number of defects found, and number of rail breaks and derailments. German railways specify inspection intervals from 4 to 24 months. North America railways inspect a 40 million gross tonnes (MGT) freight line two to three times in year and very heavy line over 140 MGT per year may be for every 30 days. Inspection intervals can be as frequent as every 7 days, similar to Australian 37 tonnes axle load lines (Cannon et al., 2003). Annual inspection cost over the rail life can be modelled as:

$$c_i = \{\sum_{q=1}^{N_I} (i_c / (1 + r_i)^q\} * r_y / (1 - (1/(1+r_y)^{y_j})) \tag{6.11}$$

where

$$N_I = Integer[\frac{M_N}{I_f}] \tag{6.12}$$

and r_i is discounting rate associated with interval of Non Destructive Testing *(NDT)*.

6.4.5 Modelling cost of lubrication

This can be based on lubricant, application equipment (whether wayside or on board) and lubrication strategy whether it is continuous or stop/ start lubrication based on weather condition. Therefore if the applicator and lubricants are selected then there are three possibilities:

- No lubrication: the wear occurs more in sharp curves and the replacement of rails occurs too frequently.
- Lubrication is continuous: per MGT cost of lubrication in curves is more; however there is no cost of switching for stop/start mechanism. There may be environmental cost due to lubrication contaminating ground water.
- Start/ Stop Lubrication: per MGT cost of lubrication is less; it can reduce RCF to some extent however there is cost of switching stop/start mechanism and also some risk of spalling. There may be reduced impact on environmental damage.

$$c_{l_j} = \{\sum_{i=1}^{N_j} (c_j M_j + Y_j c_s)/(1+r)^i\} * r_y / (1-(1/(1+r_y)^{y_j})) \qquad (6.13)$$

As already mentioned

j = l means lubricated

= s means start/ stop lubrication

= nl means no lubrication

In no lubrication, cost of lubrication is nil. In this case rail replacement cost may rise. From the field experiments it is found that the wear rate at non-lubricated sharp curves for 300 to 400 meters radius has ten times higher than the lubricated curves. For curve radius 600 meters and above the wear rate is about two to five times higher than lubricated curves (Jendel, 2002).

In start/stop lubrication, lubrication is effective periodically according to the requirement. This method may have aesthetic and economic appeal but it is not a valid option particularly in areas with high moisture. From the field experiments it is found that the wear rate during the autumn, winter and spring is higher than the wear rate during the fall. It is also found that the average daily precipitation is about 1.4 milli meters then the wear rate may reach to 35 - 50 mm^2/MGT in dry conditions. With the continuous lubrication it is possible to reach the wear rate between 7 to 10 mm^2/MGT. Precipitation and air temperature are important parameters that influence the rail wear rate under non-lubricated conditions. Increased precipitation reduces the rail wear rate at non-lubricated conditions and increased air temperature increases the wear rate. High rail temperature may cause lubrication to become more liquified and vanish more easily from wheel-rail contact zone. It may also cause the lubrication to get dried up to reduced effect of the lubrication.

6.4.6 Modelling replacement costs of worn-out rails

Rail life can be increased to 1500 MGT of traffic in straight track and over 300 MGT in highly curved track by adopting appropriate rail lubrication. Head-hardened (HH) rail also plays a role in this. In modelling cost of replacement it is assumed that replacements are occurring at the beginning of each year and the annual spread over of investment of new rail, then can be modelled as:

$$c_{re\,j} = I*(1-(1/(1+r)))/(1-(1/(1+r_y)^{y_j})) \tag{6.14}$$

6.4.7 Modelling total cost of rail maintenance

Total cost of rail maintenance with j^{th} strategy (C_{tot_j}) is the sum of the rail grinding cost with j^{th} strategy (c_{g_j}), down time due to rail grinding with j^{th} strategy (c_{d_j}), cost of rectification based on NDT with j^{th} strategy (c_{i_j}), rail breaks and derailment with j^{th} strategy (c_{r_j}), cost of lubrication with j^{th} strategy (c_{l_j}) and replacement cost of worn-out unreliable rails with j^{th} strategy (c_{re_j}). It is then modelled as:

$$C_{tot_j} = c_{g\,j} + c_{d_j} + c_i + c_{l\,j} + c_{r_j} + c_{re_j} \tag{6.15}$$

6.5 Numerical Example

Data related to cost and life is collected from Swedish Rail and Queensland Rail. The simulation model is developed by including lubrication cost. Results from investigation at SJ Track division (Swedish State Railways) found that rail wear in curves has been reduced substantially with a very small amount of grease, only 17 grams (0.06 oz.)/1000 wheels. The measurement also showed that the wear on wheel flanges decreased with as much as 50% after a large-scale installation of SRS CLICOMATIC.

ZETA-TECH Associates Inc. (USA) found that the different combinations of axle load and train weight have significant influence on rail track maintenance costs. Table 6.1 shows the operating scenario

Table 6.1: Operating scenario of Heavy haul trains

	Base case	Heavy Axle load	Longer Train Case
Cars per Train	52	68	85
Net weight	4160	6800	6800
Axle load	25	30	25
Tonnes Ore/Yr	22900000	22900000	22900000

Table 6.2: Characteristics of Freight wagons

	Base Wagon	High Capacity Wagon
Length	8400 mm	10300 mm
Tare weight (Wagon weight)	20 tonne	20 tonne
Net Capacity (Goods)	80 tonne	100 tonne
Gross weight	100 tonne	120 tonne

Table 6.2 shows the characteristics of freight wagons and is used to estimate average number of cars for each freight train, average weight of freight train, amount of lubrication required for each train and number trains for each MGT. From the above data we have:

- Average number of cars for heavy axle load = 68
- Number wheels for 68 cars = 68*8 = 544 wheels
- Amount of lubrication per train = (17*544)/1000 = 9.248 grams.
- Average gross weight of train is given by = 68*100 = 6800 tonne
- Number of trains per MGT = 1*1000000/6800 = 147 trains
- Amount of lubricant/MGT = 147*9.248 = 1360 grams
- Amount of lubricant/23 MGT = 147*23 =3381 trains

Lubrication cost is collected from supplier of lubricants (Australasia) is on an average $AUD 4.5 per kg of grease based lubricant (Zarembski and Paulsson, 2000).

6.5.1 Lubrication cost

Lubrication cost is estimated based on MGT and number of wheels.

- For 0 to 300 meters curve radius the length of rail in which each lubricator ($L_{lubrictor}$) placed is given by = 300*3.14/180*36.4 = 190.50 meters.
- For 300 to 450 meters curve radius the length of rail in which each lubricator ($L_{lubrictor}$) placed is given by = 450*3.14/180*36.4 = 285.74 meters.

- For 450 to 600 meters curve radius the length of rail in which each lubricator ($L_{lubrictor}$) placed is given by = 600*3.14/180*36.4 = 380.99 meters.

Number of lubricators used can be estimated with the length of rail for each curve radius:

- Number of lubricators for 0 to 300 meters curve = 1318/190.50 = 7 approximately.
- Number of lubricators for 300 to 450 meters curve = 1384/285.74 = 5 approximately.
- Number of lubricators for 0 to 300 meters curve = 36524/380.99 = 96 approximately.

6.5.2 Lubrication cost/meter (23 MGT)

Analysis of lubrication cost/meter for 23, 12, 18 and 9 MGT of curve radius 0 to 600 meters. Results are shown in Table 6.3.

Table 6.3: Lubrication cost/meter for curve radius 0 to 600 meters

MGT		23	12	18	9
Length (meters)	Radius (meters)	**Lubrication cost/meter ($AUD)**			
1318	0-300	0.75	0.75	0.75	0.75
1384	300-450	0.51	0.51	0.51	0.51
36524	450-600	0.37	0.37	0.37	0.37

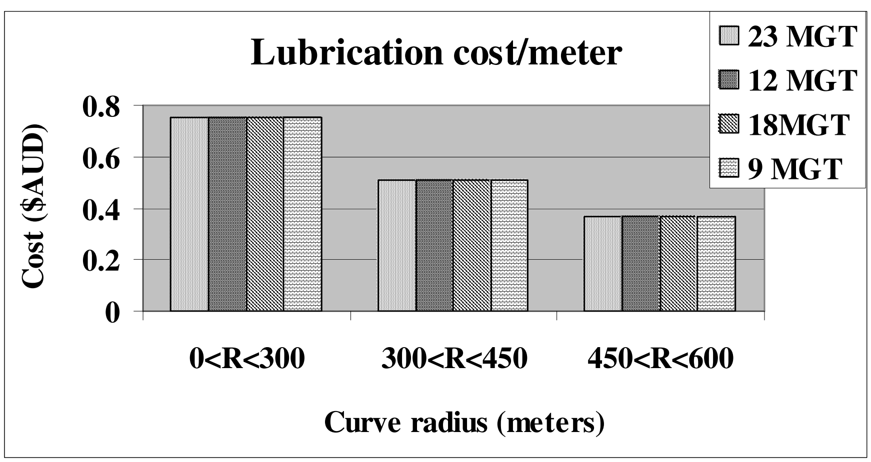

Figure 6.5: Lubrication cost/meter for curve radius (0 to 600 m)

Figure 6.5 shows the analysis of lubrication cost/meter for 23, 12, 18 and 9 MGT of curve radius from 0 to 600 meters. It is observed that lubrication cost/meter is higher for curve radius 0 to 300 meters compared to other curves. This is due to excess amount of lubrication used to control traffic wear and noise at sharp curves. Lubrication cost is same for all MGT intervals if the volume of traffic is assumed to be same every year.

6.5.3 Total annuity cost/meter for lubrication

Total annuity cost/meter for lubrication for 23 MGT, 12 MGT, 18 MGT and 9 MGT are estimated. Results for lubrication costs are compared for different curves. Analysis of annuity costs/meter for lubrication results is shown in Table 6.4.

Table 6.4: Total annuity cost/meter for lubrication 23, 12, 18 and 9 MGT.

MGT		23	12	18	9
Length (meters)	Radius (meters)	Total annuity cost/meter ($AUD)			
1318	0<R<300	0.68	0.67	0.67	0.65
1384	300<R<450	0.46	0.46	0.45	0.45
36524	450<R<600	0.33	0.34	0.32	0.33

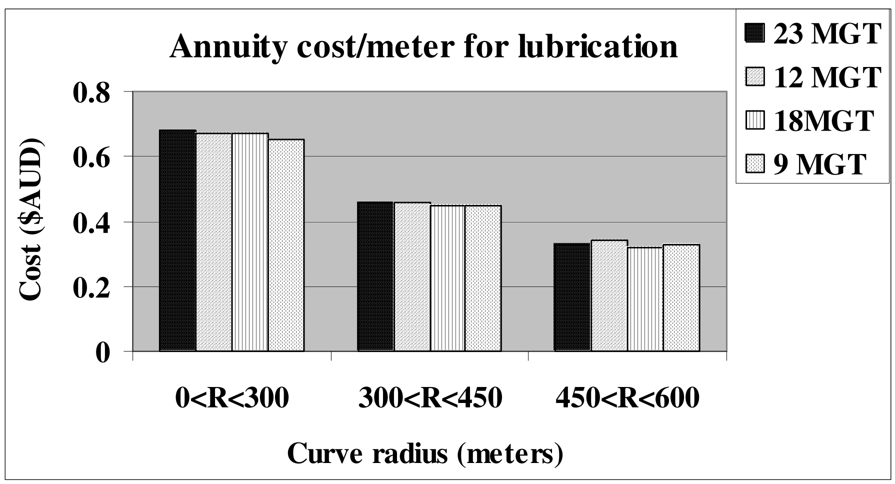

Figure 6.6: Annuity cost/meter for lubrication of curve radius (0 to 600 m)

Figure 6.6 shows the analysis of annuity costs/meter for 23, 12, 18 and 9 MGT curve radius from 0 to 600 meters. It is also found that the annuity costs/meter is higher for curve radius 0 to 300 meters compared to curves with radius over 300 meters. This is due to excessive usage of lubrication to control traffic wear and noise in sharp curves.

Comparison of total annuity cost/meter for curve radius from 0 to 600 meters with lubrication, without lubrication and stop/start lubrication is analysed. Total annuity cost/meter for non-lubricated curves is estimated on the basis of increase of traffic wear for 0 to 300 meters curve by 10 times, 300 to 450 meters curve by 5 times and 450 to 600 meters curve by 2 times.

6.5.4 stop/start lubrication

Stop/start lubrication reduces lubrication costs during wet/snow season and reduces RCF by controlled wear. The micro cracks caused by ratchetting beyond 5 MGT can initiate spalling in heavy tonnage lines. Let α be reduction of rail grinding cost for controlling RCF. For modelling start/stop lubrication let Y_j be decision variable for lubrication strategy.

where $Y_j = 1$, for j = S and decision is switching off and on if the lubricators,

$Y_j = 0$, for not using stop/start lubrication option.

Let cost for switching on or off = $AUD 250

Total annuity cost/meter for start/stop lubrication = Total annuity cost/meter with lubrication + Number of switching * cost/switching/meter – Cost of lubrication * $\sum_{N=1}^{n_s} Lub_i$ - α * saving in rail grinding annuity cost/meter + probability of spalling * annuity cost/meter for risk + % of increase in wear during the stop period (increase in replacement cost)

Where i = index

Let $\alpha = 0.05$, where α is percentage of saving in cost/meter for grinding.

Total annuity cost/meter with lubrication = Grinding cost +inspection cost +down time cost + risk cost + replacement cost + lubrication cost.

Number of switching per stop/start = 2

Where n_s = Number of stop periods.

It is assumed that number of stop periods are 1 per year.

Stop period per year in percentage = 16%

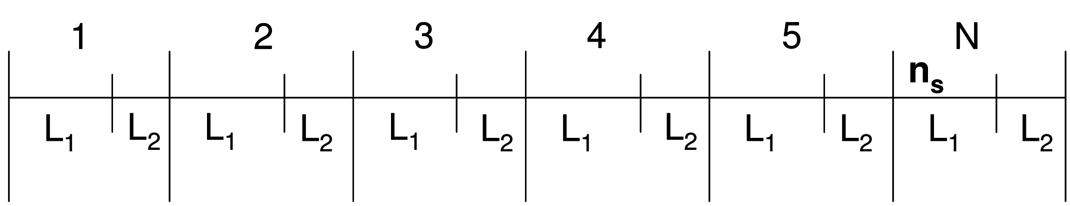

Figure 6.7: Stop/start lubrication for N periods

Savings in lubrication = 16%

Lub_i = Lubrication amount during i^{th} stop periods.

Let probability of spalling due to stop/start lubrication strategy = 0.02

Increase of wear during the stop period = 130% = 1.3

Figure 6.7 shows the stop/start lubrication for N periods. L_1 is the period when lubrication is switched on and L_2 is the period when the lubrication is switched off. For the analysis it is assumed that there may be 5% savings in grinding cost/meter and 16% reduction in lubrication cost/meter for stop seasons. However, there may be increased risks of rail break and rail failures.

6.6 Total annuity cost/meter for 23, 12, 18 and 9 MGT

6.6.1 Total annuity cost/meter for 23 MGT

Analysis of total annuity cost/meter for 23 MGT with lubrication, no lubrication and stop/start lubrication is shown Table 6.5.

Table 6.5: Total annuity cost/meter for 23 MGT curve radius (0 to 600 m)

Total annuity cost/meter for 23 MGT ($AUD)				
Length (meters)	Radius (meters)	With lubrication	no lubrication	Stop/start lubrication
1318	0-300	24.65	171	28.32
1384	300-450	22.51	168	25.66
36524	450-600	23.38	87	26.38

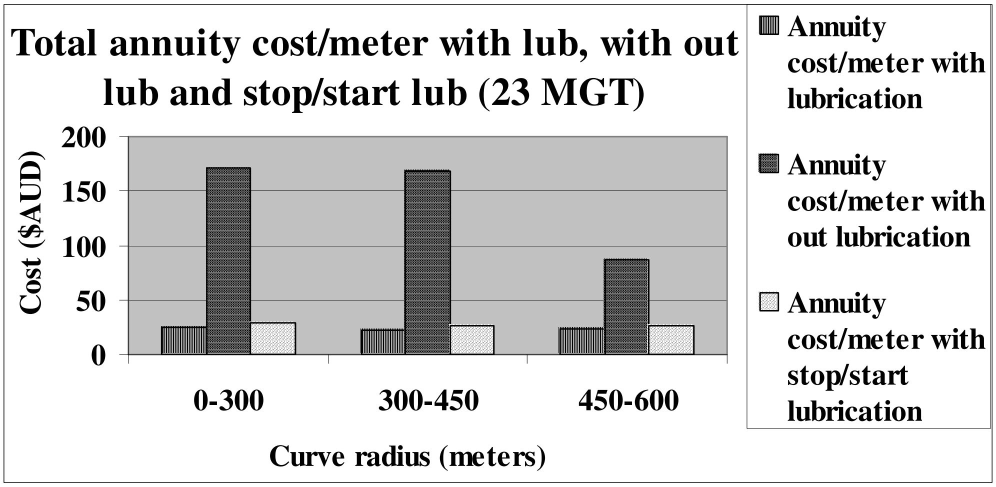

Figure 6.8: Total annuity cost/meter for 23 MGT curve radius (0 to 600 m)

Figure 6.8 shows the analysis of total annuity cost/meter for 23 MGT with lubrication, without lubrication and stop/start lubrication from curve radius 0 to 600 meters. From the analysis it is observed that the cost/meter is higher for curves without lubrication. This is due to early replacement of rails at the sharp curves due to increase of RCF and traffic wear. The costs are very close for both lubrication and stop/start lubrication strategy.

6.6.2 Total annuity cost/meter for 12 MGT

Analysis of total annuity cost/meter for 12 MGT with lubrication, no lubrication and stop/start lubrication is shown Table 6.6.

Table 6.6: Total annuity cost/meter for 12 MGT, curve radius (0 to 600 m)

Total annuity cost/meter for 12 MGT ($AUD)				
Length (meters)	Radius (meters)	With lubrication	no lubrication	Stop/start lubrication
1318	0-300	24.06	73	27.11
1384	300-450	20.62	60	23.33
36524	450-600	20.23	54	22.25

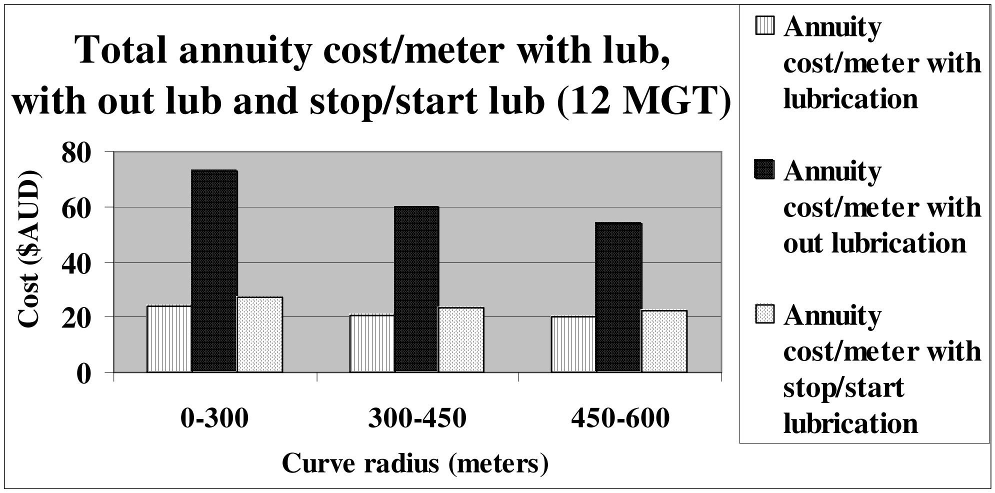

Figure 6.9: Total annuity cost/meter for 12 MGT, curve radius (0 to 600 m)

Figure 6.9 shows the analysis of total annuity cost/meter for 12 MGT with lubrication, without lubrication and stop/start lubrication from curve radius 0 to 600 meters. It is found that the cost/meter is higher for curves without lubrication.

6.6.3 Total annuity cost/meter for 18 MGT

Analysis of total annuity cost/meter for 18 MGT with lubrication, no lubrication and stop/start lubrication is shown Table 6.7.

Table 6.7: Total annuity cost/meter for 18 MGT of curve radius (0 to 600 m)

Total annuity cost/meter for 18 MGT ($AUD)				
Length (meters)	Radius (meters)	With lubrication	no lubrication	Stop/start lubrication
1318	0-300	29.8	168	32.83
1384	300-450	36.77	127	41.5
36524	450-600	45.78	60	51.85

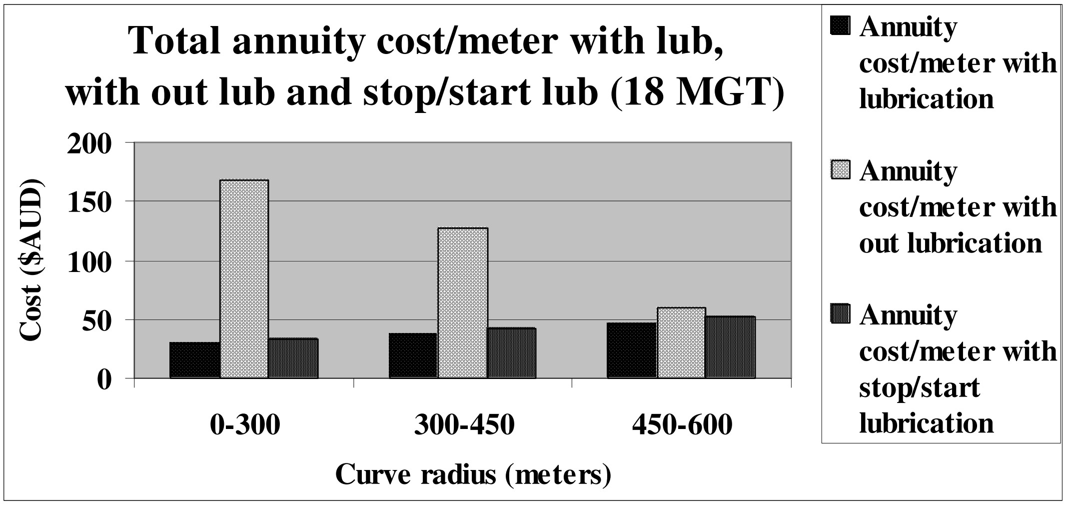

Figure 6.10: Total annuity cost/meter for 18 MGT, curve radius (0 to 600 m)

Figure 6.10 shows the analysis of total annuity cost/meter for 18 MGT with lubrication, without lubrication and stop/start lubrication from curve radius 0 to 600 meters. The cost/meter is higher for curves without lubrication.

6.6.4 Total annuity cost/meter for 9 MGT

Analysis of total annuity cost/meter for 9 MGT with lubrication, no lubrication and stop/start lubrication is shown Table 6.8.

Table 6.8: Total annuity cost/meter for 9 MGT of curve radius (0 to 600 m)

Total annuity cost/meter for 9 MGT ($AUD)				
Length (meters)	Radius (meters)	With lubrication	no lubrication	Stop/start lubrication
1318	0-300	37.07	91	40.93
1384	300-450	39.68	67	44.57
36524	450-600	40.35	55	45.63

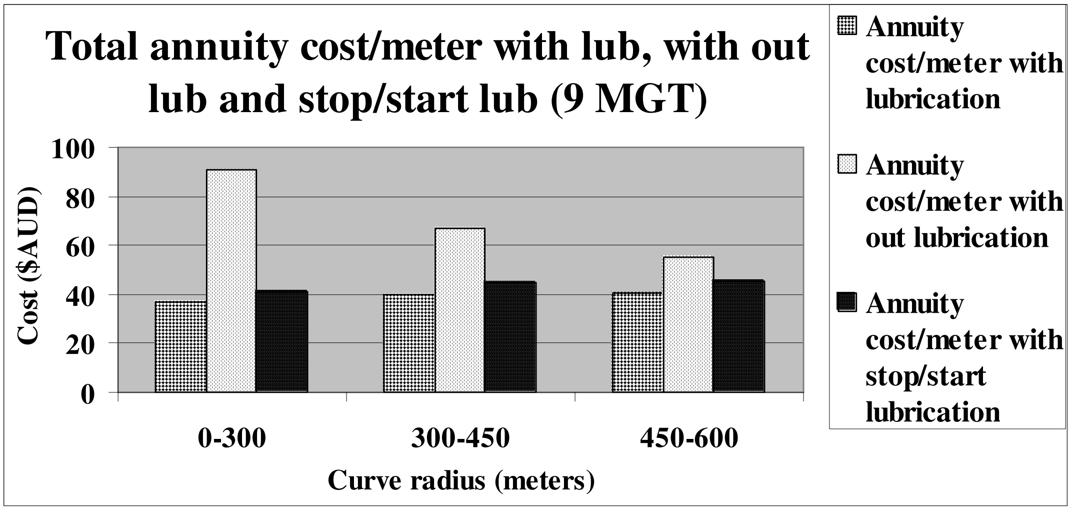

Figure 6.11: Total annuity cost/meter for 9 MGT, curve radius (0 to 600 m)

Figure 6.11 shows the analysis of total annuity cost/meter for 9 MGT with lubrication, without lubrication and stop/start lubrication from curve radius 0 to 600 meters. The cost/meter is higher for curves without lubrication.

6.7 Total annuity cost/meter for curve radius from 0 to 600 meters

This section estimates total annuity cost per meter for curves from 0 to 600 meters.

6.7.1 Total annuity cost/meter for 0 to 300 meter curves

Analysis of total annuity cost/meter for 23 and 12 MGT curve radius from 0 to 300 meters with lubrication and stop/start lubrication is shown Table 6.9.

Table 6.9: Total annuity cost/meter for curve radius 0-300 m

MGT	Total annuity cost/meter for 0-300 meters ($AUD)	
	With lubrication	Stop/start lubrication
23	24.65	28.32
12	24.06	27.11

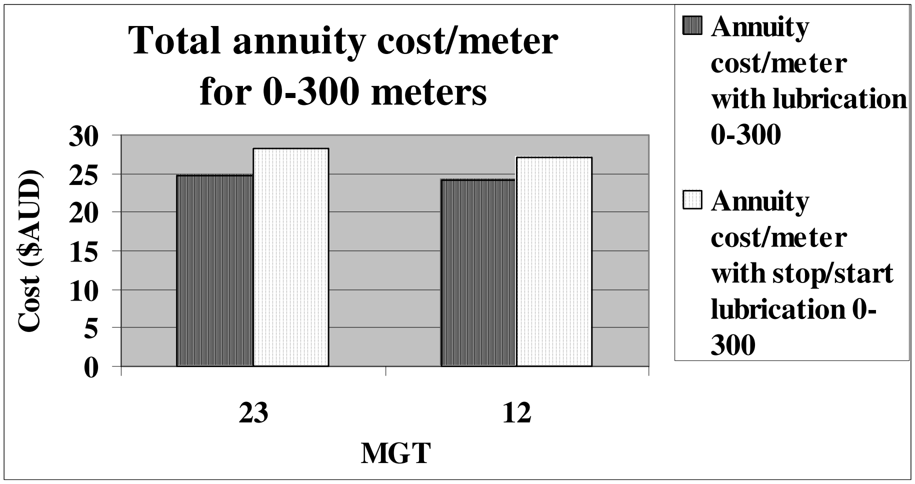

Figure 6.12: Total annuity cost/meter for 0-300 m

Figure 6.12 shows the analysis of total annuity cost for 0 to 300 meter curves with lubrication and stop/start lubrication. It is observed that the effect of stop/start lubrication does not show savings in track maintenance and is not practiced other than snow zones where lubrication is forced to switch off. However, there is not enough data available in this area and therefore a huge scope remain in carrying out research on stop/start lubrication.

6.7.2 Total annuity cost/meter for 300 to 450 meter curves

Analysis of total annuity cost/meter for 23 and 12 MGT curve radius from 300-450 meters with lubrication and stop/start lubrication is shown Table 6.10.

Table 6.10: Total annuity cost/meter for curve radius 300-450 m

MGT	Total annuity cost/meter for 300-450 meters ($AUD)	
	With lubrication	Stop/start lubrication
23	22.51	25.66
12	20.62	23.33

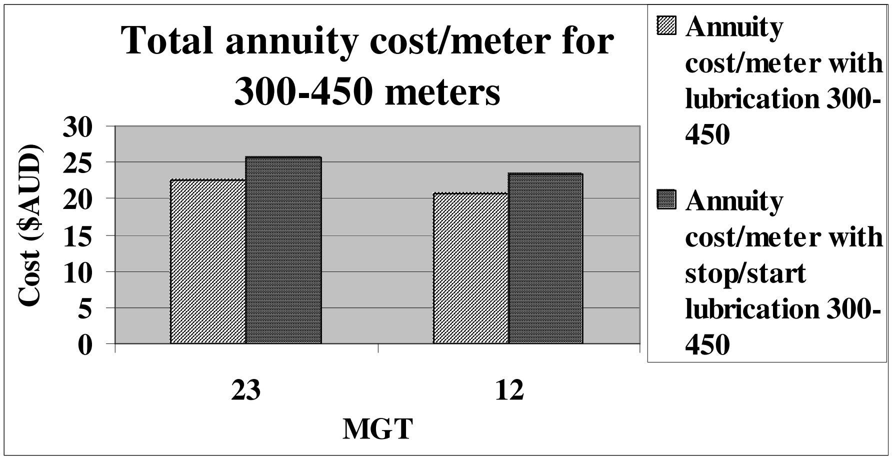

Figure 6.13: Total annuity cost/meter for 300-450 m

Figure 6.13 shows the analysis of total annuity cost/meter for 300 to 450 meter curves with lubrication and stop/start lubrication. It is observed that cost with lubrication for 12 MGT interval is minimum.

6.7.3 Total annuity cost/meter for 450 to 600 meter curves

Analysis of total annuity cost/meter for 23 and 12 MGT curve radius from 450-600 meters with lubrication and stop/start lubrication is shown Table 6.11.

Table 6.11: Total annuity cost/meter for curve radius 450-600 m

MGT	Total annuity cost/meter for 450-600 meters ($AUD)	
	With lubrication	Stop/start lubrication
23	23.38	26.38
12	20.23	22.25

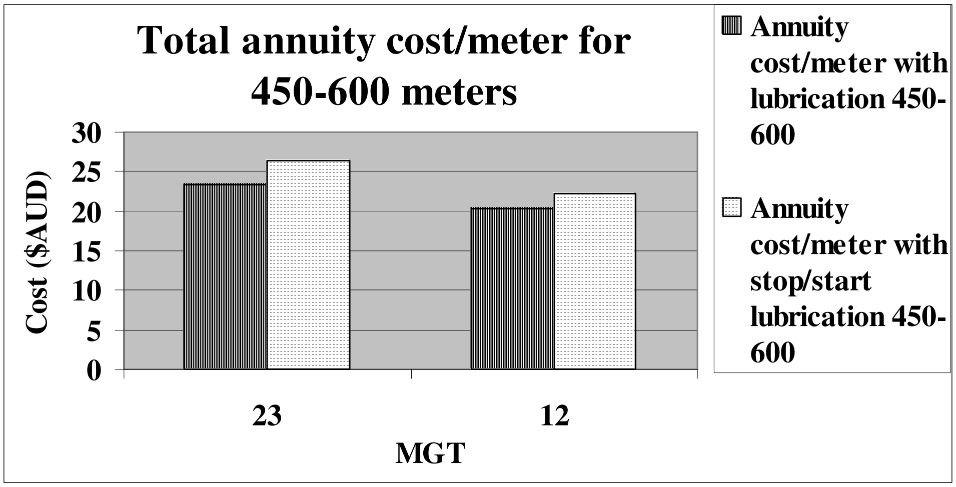

Figure 6.14: Total annuity cost/meter for 450-600 m

Figure 6.14 shows the analysis of total annuity cost for 450 to 600 meter curves with lubrication and stop/start lubrication. It is observed that cost for 12 MGT intervals with lubrication is economical.

From the analysis it is found that the costs are higher for curves without lubrication. The curves without lubrication wear at faster rate and needs early replacement. The curves with lubrication and stop/start lubrication show significant influence in reducing rail degradation (and also noise). Costs may vary with the variation in grinding costs and increase the risk due to spalling with stop/start lubrication. It is found that total annuity cost/meter with lubrication for 12 MGT interval is economical. Economical solution is useful for long term benefit of rail players for reliability and safety of rail operation. However, there is an element of environment pollution due to ground water contamination from excessive lubrication. This is not considered in this research due to lack of appropriate data and is left for future work.

6.8 Summary

Cost models developed in this chapter present an integrated approach for rail maintenance based on Rolling Contact Fatigue (RCF), traffic wear and lubrications. Results from this investigation can be applied to enhance rail life, reduce noise and improve the safety of rail operations. There is enormous scope for developing integrated decision support systems for optimal rail lubrication and rail grinding strategies for various rail segments based on the signature of the rail which includes speed, axle loads, Million Gross Tonnes and trains length along with traffic density, wheel/rail interaction, and wheel/rail wear. Other elements such as rolling contact fatigue, effect of rail grinding and lubrication, curve radius, rail material, track geometry, rail dynamics and inspection intervals are important for future work in those areas.

Chapter 7

Conclusions and Scope for Future works

7.1 Introduction

Rail track maintenance plays an important role in reliability and safety of rail operation. The Office for Research and Experiments (ORE) of the Union International des Chemins de Fer (UIC) has noted that maintenance costs vary directly (60–65 per cent) with change in train speed and axle load. It was also found that the increase in these costs with increased speed and axle load was greater when the quality of the track was lower (ORR, 1999). Failures during operation are costly to rail players due to loss of service, property and loss of lives. Technical and economical analysis of related maintenance decision is needed by rail players to reduce operating costs and improve reliability and safety of rail networks.

Over the past few years, there have been major advances in terms of increased speed, axle loads, longer trains, along with increased traffic density in corridors. This has led to increased risks in rail operation due to rolling contact fatigue (RCF) and rail wear. The infrastructure providers now have less incentive to maintain a given infrastructure standard if its access charge is rigid when the wheel standard is not achieved. It has been estimated that between 40 to 50 per cent of wagon maintenance costs and 25 per cent of locomotive maintenance costs are related to wheel maintenance (Railway Gazette International, 2003). The economic analysis of Malmbanan indicates that about 50% of the total cost for maintenance and renewal were related to traffic on rails and 50% not related to traffic, such as signalling, electricity, snow-clearance etc. Costs for maintenance and renewal of rails, on some lines, account for more than 50% of the total costs. The results from the analysis have made it possible for the mining company LKAB to start up the 30 tonne traffic with new wagons and locomotives on the Malmbanan line in year 2001 (Åhrén et al 2003). The rail infrastructure providers have challenges to maintain infrastructure due to government control on access charges and train operators not doing their part of wheel maintenance.

The aim of my research was to:

- Develop maintenance cost model for optimal rail grinding for various operating conditions.
- Develop integrated rail grinding and lubrication strategies for optimal maintenance decisions.

Out line of this Chapter as follows: Summary of the thesis is discussed in section 7.2. Section 7.3 provides conclusion. In section 7.4 limitations of this research are discussed. Scope for future work is explained in section 7.5.

7.2 Summary

Chapter wise summary of this research is given below:
In Chapter 1, background of the study, aims and objectives, research methodology was presented along with significance of the research work.

In Chapter 2, overview of the literature on railway track and maintenance models was discussed. It covered track characteristics and various operating and traffic conditions under which rails operate.

Analysis of failure mechanisms for rail track degradation was discussed in Chapter 3. Variables such as speed, Million Gross Tonnes (MGT), axle loads, wheel/rail interaction, wheel/rail wear, rolling contact fatigue, effect of rail grinding and lubrication were explained in this Chapter. Effect of curve radius, traffic density, rail material, track geometry, rail dynamics, inspection intervals, and wear limits are also discussed in this Chapter.

Integrated framework for rail track degradation modelling in deciding optimal maintenance strategies was explained in Chapter 4. Real life data from North American Rails, Swedish National Rail and Queensland Rail in Australia were analysed. An integrated approach was developed for controlling fatigue initiated surface cracks and carrying out effective rail track maintenance. These models considered crack initiation and growth rate along with wear influenced by traffic; grinding and lubrication.

Modelling of preventive rail grinding for optimal decisions to control RCF and traffic wear was discussed in Chapter 5. This chapter was focused on the rail breaks, rail degradation, grinding, inspection, down time, risks and rail replacement costs to develop economic models for cost effective rail grinding decisions. Real life data was collected and analysed from industry for these models. Illustrative numerical examples and simulation approaches were used for the analysis of the RCF and traffic wear for various MGT intervals.

Integrated rail grinding and lubrication strategies for economic maintenance decisions were discussed in Chapter 6. Lubrication vs. no lubrication and stop/start strategies were modelled and analysed.

7.3 Conclusions

This research has developed integrated cost models considering rolling contact fatigue (RCF), wear, down time, inspection, operating risks, and replacement for rail grinding and lubrication strategies. Results can be used for the analysis of costs and benefits of maintenance strategies to improve reliability and safety of rail operation by enhancing rail life. Technical input and statistical data from industry related to rolling contact fatigue, Traffic wear, rail breaks, down times, cost of non-destructive testing (NDT), grinding performances, and risks due to derailments were used for development and analysis of annuity cost/meter for grinding, risk, down time, inspection, replacement and lubrication. Results for 23, 12, 18 and 9 MGT of curve radius from 0 to 300, 300-450, 450-600 and 600-800 meters are modelled in Chapter 5 and 6 for grinding and lubrication strategies. Summary of the findings of Chapter 5 are:

- Analysis shows that total annuity cost/meter for 0-300 meters for 23 MGT AUD $ is 23.96, for 12 MGT is AUD $ 22.91, for 18 MGT is AUD $ 29.24, for 9 MGT is AUD $ 36.78. It shows that rail players can save 4.58% of costs with 12 MGT intervals compared to 23 MGT intervals.
- Analysis shows that total annuity cost/meter for 300-450 meters for 23 MGT AUD $ is 22.09, for 12 MGT is AUD $ 20.15, for 18 MGT is AUD $ 36.59, for 9 MGT is AUD $ 38.87. This shows that rail network providers can save 9.63% of costs with 12 MGT intervals compared to 23 MGT intervals.

- Analysis shows that total annuity cost/meter for 450-600 meters for 23 MGT AUD $ is 23.04, for 12 MGT is AUD $ 19.89, for 18 MGT is AUD $ 44.80, for 9 MGT is AUD $ 39.59. This shows that rail players can save 15.80% of costs with 12 MGT intervals compared to 23 MGT intervals.
- Analysis shows that total annuity cost/meter for 600-800 meters for 23 MGT AUD $ is 21.84, for 12 MGT is AUD $ 19.45, for 18 MGT is AUD $ 37.86, for 9 MGT is AUD $ 40.76. This shows that rail players can save 12.29% of costs with 12 MGT intervals compared to 23 MGT intervals.

In steep curves rail replacement is more due to rolling contact fatigue (RCF) compared to curves with higher radius.

Summary of findings of Chapter 6 are:

- Analysis of effectiveness of lubrication strategies show that the costs of no lubrication are extremely (seven times) higher compared to rail curve with lubrication for all curve radii 0-600 meters. This research shows that for higher curve radius this savings diminished.

For 23 MGT grinding interval costs of

- stop/start lubrication is 14.9% higher compared to rail curve with lubrication for 0-300 meters, 14% higher for 300-450 meter and 12.8% higher for 450-600 meters

For 12 MGT grinding interval costs of

- stop/start lubrication on average 12% higher compared to rail curve with lubrication for 0-300, 300-450 and for 450-600 meters.

From the analysis it is found that rail players with lubrication can save around 2.45% for 0-300 curves, 9.1 % for 300-450 meter curves and 15.5% for 450-600m curves respectively by planning 12 MGT interval for rail grinding compared to 23 MGT intervals. Research shows that technically 12 MGT grinding intervals are economical and effective in controlling rolling contact fatigue. The annuity cost/MGT/meter can be used by rail players for benchmarking rail utilisation. Total annuity cost/meter with lubrication can be further analysed in terms of wayside, on-board lubrication methods for benchmarking applicators and lubricants. The models developed in this research have been considered by Swedish National Rail for analysing the effectiveness of their existing grinding policies. Optimal grinding and lubrication models developed in this research have potential for savings in maintenance costs, improving reliability and safety and enhancing rail life.

7.4 Limitations

The research has produced enhanced knowledge on modelling and analysis of preventive grinding for economic decisions in controlling RCF and rail wear. In spite of the contribution mentioned in above this research has following limitations:

- The assumptions in Chapter 5 are limited to technical aspects. Human factors are not considered. Knowledge skills, motivation and training of people in testing, planning and implementing strategies are of great interest to rail players.
- Models combine lubrication strategies with preventive grinding for economic grinding decisions. But the model needs to concentrate on different types of lubrication methods, lubricants and inspection methods, reliability of applicators and condition of other rail components.
- Axle load, number of axle loads and train speed are major factors for rail wear. Assumptions in degradation model is based mainly on MGT. Better models could be possible by considering axle load and number of axle pass, dynamics and geometry.

7.5 Scope for Future works

There is enormous scope for further research work in many areas related to this research.

Some topics are: Development of models for

- Assessment of operating risks in rail tracks under various operating conditions
- Integrated rail-wheel model for wear, RCF combining grinding and lubrication strategies; rail dynamics and geometry.
- Cost sharing by train operators and rail infrastructure players.
- Analysis from operators and infrastructure players point of view.
- Wheel-rail interface considering wheel-rail profile under various operating conditions.
- Integrated rail grinding, inspection, risk, and weather and environmental conditions.

- Analysis of factors in rail and wheel degradation and assessment of risks associated with rail breaks, rail defects and derailments.
- Management system for risk analysis with “what-if” scenario for decision on inspections, rail grinding, lubrications and rail replacements.
- Effective lubrication and preventive grinding programs to achieve balanced wear rate.

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Appendices

Appendix A
Laser Grind and wear data (Courtesy from Queensland Rail)

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Source: Queensland Rail

Appendix B

Wear limit for Banverket

This appendix is not available online. Please consult the hardcopy thesis available from the QUT library.

Source: Jendel

Source: Larsson, P. O.

Source: Larsson, P. O.

Source: Larsson, P. O.

Source: Larsson, P. O.

Appendix C

Simulation Code

Simulation code for estimating costs and life of rail track

```
clear % Clears the working memory
% Number of data set to study
% DAT file contains data up to 720 that can be used for calculations
ndata = 50; % ndata is the data selected for the calculations.
load C:\Datafile_Reddy\23_03.dat; % Path to import the data of file 23_03.dat
% 23_03 is the data file for 23 MGT of curve radius 0 to 300 meters.
datamatrix(1:ndata,1:13)=X23_03(1:ndata,1:13);
clear X23_03; % Reduces the number of matrix and save some memory
load C:\Datafile_Reddy\23_34.dat;  % Path to import the data of file 23_34.dat
% 23_34 is the data file for 23 MGT of curve radius 300 to 450 meters.
datamatrix(1:ndata,14:26)=X23_34(1:ndata,1:13);
clear X23_34; % Reduces the number of matrix and save some memory
load C:\Datafile_Reddy\23_46.dat; % Path to import the data of file 23_46.dat
% 23_46 is data file for 23 MGT of curve radius 450 to 600 meters.
datamatrix(1:ndata,27:39)=X23_46(1:ndata,1:13);
clear X23_46; % Reduces the number of matrix and save some memory
load C:\Datafile_Reddy\23_68.dat; % Path to import the data of file 23_68.dat
% 23_68 is data file for 23 MGT of curve radius 600 to 800 meters.
datamatrix(1:ndata,40:52)=X23_68(1:ndata,1:13);
clear X23_68; % Reduces the number of matrix and save some memory
load C:\Datafile_Reddy\23_815.dat; % Path to import the data of file 23_815.dat
% 23_815 is data file for 23 MGT of curve radius 800 to 1500 meters.
datamatrix(1:ndata,53:65)=X23_815(1:ndata,1:13);
clear X23_815; % Reduces the number of matrix and save some memory
load C:\Datafile_Reddy\23_1599.dat; % Path to import the data of file 23_1599.dat
% 23_1599 is data file for 23 MGT of curve radius 1500 to 9999 meters.
datamatrix(1:ndata,66:78)=X23_1599(1:ndata,1:13);
clear X23_1599; % Reduces the number of matrix and save some memory
```

```
load C:\Datafile_Reddy\23_10000.dat; % Path used to import the data of file 23_10000.dat
% 23_10000 is data file for 23 MGT of curve radius 10000 meters.
datamatrix(1:ndata,79:91)=X23_10000(1:ndata,1:13);
clear X23_10000; % Reduces the number of matrix and save some memory
load C:\Datafile_Reddy\23_TANG.dat; % Path used to import the data of file 23_Tang.dat
% 23_Tang is data file for 23 MGT for tangent track.
datamatrix(1:ndata,92:104)=X23_TANG(1:ndata,1:13);
clear X23_TANG; % Reduces the number of matrix and save some memory
%The matrix consist of around 700 rows and 13 columns.
%Text files, (not the DAT files) Row 1, Column 1: The MGT step
%Text files, (not the DAT files) Row 2, Column 1-13: Label names
%Text files, (not the DAT files) Row 3, Column 1-13: Data matrix
%Data matrix starts from row 1 - 700
% Column 1: MGT
% Column 2: Traffic wear (mm2)        Low Rail
% Column 3: Grinding wear (mm2)       Low Rail
% Column 4: No of grinding passes     Low Rail
% Column 5: Detected cracks           Low Rail
% Column 6: Rail breaks               Low Rail
% Column 7: Derailments               Low Rail
% Column 8: Traffic wear (mm2)        High Rail
% Column 9: Grinding wear (mm2)       High Rail
% Column 10: No of grinding passes    High Rail
% Column 11: Detected cracks          High Rail
% Column 12: Rail breaks              High Rail
% Column 13: Derailments              High Rail
%***********************************************************
% Input data for the Weibull distribution, Lambda and Beta
% Lambda is between 1/1250 and 1/2350, Beta is 3.6 (Besuner et. al., 1978)
% Lambda = 1/1000;
% Beta   = 3.60;
% g = 2; g is the grinding cost/pass/meter ($AUD) is used for the analysis.
```

% on an average 3 to 5 passes are considered per section. It may be around 2.35 i.e.
% around minimum 2 and average 3 and maximum 5 passes per day depend on the
% rail condition and curve sections.
% Grinding cost is divided by 2 to calculate cost per each rail.
% GS = 10;   % GS is a typical grinding speed of 10 m/s.
% rBV50 = Replacement cost of BV50 rail for one rail
% rBV50 = 151.60; % ($AUD)
% k = 1700; k is cost for planed replace of a rail brake with out an accident
% a is the cost for an accident
% a = 3000000; % ($AUD)
% d = 3136; % d is expected down time cost hour for a train.
% ic = 0.00428; % Inspection cost/Meter/MGT
% If = 23; % Inspection frequency for every year, i.e. for example 23 MGT interval for
% Banverket ore line (Malmbanan)
% nNDT = 120; % nNDT is the total number of detected failures during the Non-Destructive % Testing (NDT).
% nRB = 3; % nRB is the total number of rail brakes in between two NDT inspections.
% $\overline{C}$ = k*1.2 % $\overline{C}$ is cost for unplanned replacement of rail brake with out an
% accident i.e. in emergency case (20 % higher cost for unplanned activity).
% $P_i(B)$ is the probability of detected potential rail brakes in between two NDT
% $(1-P_i(B))$ is the probability of undetected potential rail breaks during the NDT
% leading to derailment
% $P_i(A)$ is the probability of failure to detect the undetected potential rail breaks
% leading to derailment during the NDT
% $(1-P_i(A))$ is the probability of detecting the undetected potential rail breaks during
% the NDT leading to derailment are repaired in an emergency.
% L is the length of segment due to worn out regulation considered for analysis.
ic = 0.00428;   % per meter per MGT
If = 23;
nNDT = 120; % Total number of detected failures
nRB = 3; % Total numbers of rail brakes in between two NDT inspections

```
% Start the program to calculate the maximum life of the rails
BV50area   =585; % 50 kg/m rail used in Sweden, max area that can be worn off
%*******************************************************
% Traffic area loss (TAL) for high rail (HR) from 0 to tangent track
Tarealosshi(1:ndata,1)  = datamatrix(1:ndata,8); % (TAL for HR 0<r<300)
Tarealosshi(1:ndata,2)  = datamatrix(1:ndata,21); % (TAL for HR 301<r<450)
Tarealosshi(1:ndata,3)  = datamatrix(1:ndata,34); % (TAL for HR 451<r<600)
Tarealosshi(1:ndata,4)  = datamatrix(1:ndata,47); % (TAL for HR 601<r<800)
Tarealosshi(1:ndata,5)  = datamatrix(1:ndata,60); % (TAL for HR 801<r<1500)
Tarealosshi(1:ndata,6)  = datamatrix(1:ndata,73); % (TAL for HR 1501<r<9999)
Tarealosshi(1:ndata,7)  = datamatrix(1:ndata,86); % (TAL for HR 10000<r<Tangent)
Tarealosshi(1:ndata,8)  = datamatrix(1:ndata,99); % (TAL for HR Tangent)
% Grinding area loss (GAL) for high rail (HR) from 0 to tangent track
Garealosshi(1:ndata,1)  = datamatrix(1:ndata,9); % (GAL for HR 0<r<300)
Garealosshi(1:ndata,2)  = datamatrix(1:ndata,22); % (GAL for HR 301<r<450)
Garealosshi(1:ndata,3)  = datamatrix(1:ndata,35); % (GAL for HR 451<r<600)
Garealosshi(1:ndata,4)  = datamatrix(1:ndata,48); % (GAL for HR 601<r<800)
Garealosshi(1:ndata,5)  = datamatrix(1:ndata,61); % (GAL for HR 801<r<1500)
Garealosshi(1:ndata,6)  = datamatrix(1:ndata,74); % (GAL for HR 1501<r<9999)
Garealosshi(1:ndata,7)  = datamatrix(1:ndata,87); % (GAL for HR 10000<r<Tangent)
Garealosshi(1:ndata,8)  = datamatrix(1:ndata,100); % (GAL for HR Tangent)
% Total area loss is Traffic area loss + Grinding area loss for the high rail
Sarealosshi  = Tarealosshi + Garealosshi; % Total area loss for High Rail
% Traffic area loss (TAL) low rail (LR) for curve segments from 0 meters to tangent
% track
Tarealosslow(1:ndata,1) = datamatrix(1:ndata,2); % (TAL for LR 0<r<300)
Tarealosslow(1:ndata,2) = datamatrix(1:ndata,15); % (TAL for LR 301<r<450)
Tarealosslow(1:ndata,3) = datamatrix(1:ndata,28); % (TAL for LR 451<r<600)
Tarealosslow(1:ndata,4) = datamatrix(1:ndata,41); % (TAL for LR 601<r<800)
Tarealosslow(1:ndata,5) = datamatrix(1:ndata,54); % (TAL for LR  801<r<1500)
Tarealosslow(1:ndata,6) = datamatrix(1:ndata,67); % (TAL for LR 1501<r<9999)
Tarealosslow(1:ndata,7) = datamatrix(1:ndata,80); % (TAL for LR 10000<r<Tangent)
Tarealosslow(1:ndata,8) = datamatrix(1:ndata,93); % (TAL for LR Tangent)
```

```
% Calculate the Grinding area loss (GAL) for low rail (LR) for curve segments from
0
% meters to tangent track
Garealosslow(1:ndata,1) = datamatrix(1:ndata,3); % (GAL for LR 0<r<300)
Garealosslow(1:ndata,2) = datamatrix(1:ndata,16); % (GAL for LR 301<r<450)
Garealosslow(1:ndata,3) = datamatrix(1:ndata,29); % (GAL for LR 451<r<600)
Garealosslow(1:ndata,4) = datamatrix(1:ndata,42); % (GAL for LR 601<r<800)
Garealosslow(1:ndata,5) = datamatrix(1:ndata,55); % (GAL for LR 801<r<1500)
Garealosslow(1:ndata,6) = datamatrix(1:ndata,68); % (GAL for LR 1501<r<9999)
Garealosslow(1:ndata,7) = datamatrix(1:ndata,81); %(GAL for LR 10000<r<Tangent)
Garealosslow(1:ndata,8) = datamatrix(1:ndata,94); % (GAL for LR Tangent)
% Total area loss = Traffic area loss + Grinding area loss for the low rail
Sarealosslow = Tarealosslow + Garealosslow;
% Calculation of accumulated area loss/MGT for both low and high rail
% Accumulated area loss = Sarealosshi + Sarealosslow; i.e. Total area loss for high %
rail + % Total area loss for low rail.
% j in the for loop represent the eight different segments, i.e. from 0<r<300 meters,
% 301<r<450, 451<r<600, 601<r<800, 801<r<1500, 1501<r<9999,
% 10000<r<Tangent, Tangent).
% The for loop is to set first value in the Accumulated area loss
for j = 1:8,
        Accarealosshi(1,j)  = Sarealosshi(1,j); % Accumulated area loss for High Rail
        Accarealosslow(1,j) = Sarealosslow(1,j); % Accumulated area loss for Low
Rail
end;
% This for loop start with the second value, therefore the first value must
% be set before the sum loop is initiated.
for i = 2:ndata,
  for j = 1:8,
   Accarealosshi(i,j)  = Sarealosshi(i,j) + Accarealosshi(i-1,j);
   Accarealosslow(i,j) = Sarealosslow(i,j) + Accarealosslow(i-1,j);
 end;
end;
```

```
% Calculate the percent of area left (worn out level) for each MGT step and rail
profile
WOLBV50hi   =100*(Accarealosshi)/BV50area; % Worn out level of BV50 profile
WOLBV50low =100*(Accarealosslow)/BV50area; % Worn out level of BV50 profile
mgtstephi50(1:ndata,1:8)=1; % Eight different curve radii 50 kg high rail
mgtsteplow50(1:ndata,1:8)=1; % Eight different curve radii 50 kg low rail
for i = 2:ndata
  for j = 1:8
    if WOLBV50hi(i,j) <= 100
      mgtstephi50(i,j)=1+mgtstephi50(i-1,j);
    end;
    if WOLBV50low(i,j) <= 100
      mgtsteplow50(i,j)=1+mgtsteplow50(i-1,j);
    end;
  end;
end;
% The for loop above is to calculate sum of the MGT steps to a value that is one step
% above the critical value of the 100 critical value, therefore -1 step is subtracted
mgtstephi50=mgtstephi50-1;
mgtsteplow50=mgtsteplow50-1;
g = 2; % Cost of grinding per pass per meter. It is divided by 2 to calculate cost per
rail.
GS = 10; % GS is a typical grinding speed of 10 m/s
d = 3136; % expected cost of down time per hour for a train.
Ltot = 130537;
L0_300   = 1.01/100*Ltot; % Percent Length of the curve radius 0 < R < 300 meter
L3_450   = 1.06/100*Ltot; % Percent Length of the curve radius 301<R<450
L4_600   = 27.98/100*Ltot; % Percent Length of the curve radius 451<R<600
L6_800   = 25.46/100*Ltot; % Percent Length of the curve radius 601<R<800
L8_1500 = 3.50/100*Ltot; % Percent Length of the curve radius 801<R<1500
L15_9999 = 3.50/100*Ltot; % Percent Length of the curve radius 1501<R<9999
L10      = 0.55/100*Ltot; % Percent Length of the curve radius 10000<R
LTangent = 36.94/100*Ltot; % Percent Length of the Tangent track
% length vector to be used in the cost calculations
```

```
L(1)    = L0_300;
L(2)    = L3_450;
L(3)    = L4_600;
L(4)    = L6_800;
L(5)    = L8_1500;
L(6)    = L15_9999;
L(7)    = L10;
L(8)    = LTangent;
% The for loop is to find the number of passes for the grinder in each section.
% The generation of passes in the datamatrix is different for the High
% and Low rail, therefore we need to evaluate and find the maximum value of passes
% in both high and low rail grinding then choose the max value to represent the
% total number of passes needed, see if, else
% Grinding passes for low rail (GPLR) from 0 meters to tangent track.
Grindingpasseslo(1:ndata,1) = datamatrix(1:ndata,4); %GPLR for 0<r<300 meters
Grindingpasseslo(1:ndata,2) = datamatrix(1:ndata,17); %GPLR for 301<r<450 meters
Grindingpasseslo(1:ndata,3) = datamatrix(1:ndata,30); %GPLR for 451<r<600 meters
Grindingpasseslo(1:ndata,4) = datamatrix(1:ndata,43); %GPLR for 601<r<800 meters
Grindingpasseslo(1:ndata,5) = datamatrix(1:ndata,56); %GPLR for 801<r<1500 met
Grindingpasseslo(1:ndata,6) = datamatrix(1:ndata,69); %GPLR for 1501<r<9999 met
Grindingpasseslo(1:ndata,7) = datamatrix(1:ndata,82); % GPLR for 10000<r<Tangent
Grindingpasseslo(1:ndata,8) = datamatrix(1:ndata,95); % GPLR for Tangent
% Grinding passes for high rail (GPHR) From 0 to tangent track.
Grindingpasseshi(1:ndata,1) = datamatrix(1:ndata,10); %GPHR for 0<r<300 meters
Grindingpasseshi(1:ndata,2) = datamatrix(1:ndata,23); %GPHR for 301<r<450 meters
Grindingpasseshi(1:ndata,3) = datamatrix(1:ndata,36); %GPHR for 451<r<600 meters
Grindingpasseshi(1:ndata,4) = datamatrix(1:ndata,49); %GPHR for 601<r<800 meters
Grindingpasseshi(1:ndata,5) = datamatrix(1:ndata,62); %GPHR for 801<r<1500 met
Grindingpasseshi(1:ndata,6) = datamatrix(1:ndata,75); %GPHR for 1501<r<9999 met
Grindingpasseshi(1:ndata,7) = datamatrix(1:ndata,88); %GPHR for 10000<r<Tangent
Grindingpasseshi(1:ndata,8) = datamatrix(1:ndata,101); % GPHR for Tangent.
% The following loop is to get the highest number of Grinding passes from high rail
% and low rail for each section
for i = 1:ndata,
```

```
  for j =1:8,
        if Grindingpasseslo(i,j) >= Grindingpasseshi(i,j);
      ni(i,j) = Grindingpasseslo(i,j);
        else
      ni(i,j) = Grindingpasseshi(i,j);
    end;
  end;
end;
%*****************************************************
```

% Grinding cost

```
% The matrix ni is now the total number of passes needed for each section
% g is the Grinding cost
% Cost_g is a matrix that represents each year
% L is the length for each section
% The following for loop is to calculate the Grinding cost for Eight sections
% ni number of grinding passes increases with defect rate i.e. Beta
for i = 1:ndata,
  for j =1:8,
    Cost_g(i,j) = g*ni(i,j)*L(j); % Grinding cost, L is the length for each section
  end;
end;
% Ctot_g is the total Grinding cost for entire curve
% Set the first year total grinding cost equal to the first year grinding cost
% for each eight sections
for  j =1:8,
  Ctot_g(1,j) = Cost_g(1,j);
end;
% Calculation of the total accumulated grinding cost
for i = 2:ndata,
  for j =1:8,
    Ctot_g(i,j) = Ctot_g(i-1,j) + Cost_g(i,j);
  end;
end;
%*****************************************************
```

% Risk cost

```
% Input data for the Weibull distribution, lambda and beta.
% lambda is between 1/1250 and 1/2350, beta is 3.6
lambda = 1/1000;
beta   = 3.60;
a = 3000000; % a is the expected cost per derailment (accident) in AUD$
k = 1700; % k is the expected cost for repairing rail break.
% M is the total accumulated tonnage
M(1) = datamatrix(1,1);
% This loop is for calculating total tonnage for all the data in the matrix
for i =2:ndata,
  M(i) = M(i-1) + datamatrix(1,1);
end;
% E is the expected numbers of failures for the chosen Weibull
E(1:ndata)=0; % Set the vector values to 0, make sure that it has values in each point
for i = 1:ndata-1,
   E(i) = lambda^beta*(M(i+1)^beta-M(i)^beta);
end;
% Calculation of Detected cracks (DC), Rail Breaks (RB), Derailment (D) for low
% rail, for different curve radii.
Detectedcrackslo(1:ndata,1) = datamatrix(1:ndata,5); % DC for Curve radius 0<r<300
Railbreakslo(1:ndata,1)        = datamatrix(1:ndata,6); % RB for Curve radius 0<r<300
Derailmentlo(1:ndata,1)      = datamatrix(1:ndata,7); % D for curve radius 0<r<300
Detectedcrackslo(1:ndata,2) = datamatrix(1:ndata,18); % DC for radius 301<r<450
Railbreakslo(1:ndata,2)  = datamatrix(1:ndata,19); % RB for radius 300<r<450
Derailmentlo(1:ndata,2) = datamatrix(1:ndata,20); % D for radius 300<r<450
Detectedcrackslo(1:ndata,3) = datamatrix(1:ndata,31); % DC for radius 451<r<600
Railbreakslo(1:ndata,3) = datamatrix(1:ndata,32); % RB for radius 451<r<600
Derailmentlo(1:ndata,3) = datamatrix(1:ndata,33); % D for radius 451<r<600
Detectedcrackslo(1:ndata,4) = datamatrix(1:ndata,44); % DC for radius 601<r<800
Railbreakslo(1:ndata,4) = datamatrix(1:ndata,45); % RB for radius 601<r<800
Derailmentlo(1:ndata,4) = datamatrix(1:ndata,46); % D for radius 601<r<800
Detectedcrackslo(1:ndata,5) = datamatrix(1:ndata,57); % DC for radius 801<r<1500
Railbreakslo(1:ndata,5) = datamatrix(1:ndata,58); %DC for radius 801<r<1500
```

```
Derailmentlo(1:ndata,5) = datamatrix(1:ndata,59); % D for radius 801<r<1500
Detectedcrackslo(1:ndata,6) = datamatrix(1:ndata,70); % DC for radius 1501<r<9999
Railbreakslo(1:ndata,6) = datamatrix(1:ndata,71); % RB for radius 1501<r<9999
Derailmentlo(1:ndata,6) = datamatrix(1:ndata,72); % D for radius 1501<r<9999
Detectedcrackslo(1:ndata,7) = datamatrix(1:ndata,83); % DC for radius 10000<r<Tan
Railbreakslo(1:ndata,7) = datamatrix(1:ndata,84); % RB for radius 10000<r<Tan
Derailmentlo(1:ndata,7) = datamatrix(1:ndata,85); % D for radius 10000<r<Tan
Detectedcrackslo(1:ndata,8) = datamatrix(1:ndata,96); % DC for Tangent
Railbreakslo(1:ndata,8) = datamatrix(1:ndata,97); % DC for Tangent
Derailmentlo(1:ndata,8) = datamatrix(1:ndata,98); % DC for Tangent
% Sum of INSpections, RailBrake and DeRailment. The data used is for low rail
SumINSRBDR = Detectedcrackslo+Railbreakslo+Derailmentlo;
% Calculate the accumulated values for each INSpections, RailBrake and DeRailment
% The following loop is to set the first year accumulated Detectedcracks, Railbreak,
% and Derailment values
for j = 1:8,
    accDetectedcracks(1,j)     = Detectedcrackslo(1,j);
    accRailbreaks(1,j)         = Railbreakslo(1,j);
    accDerailment(1,j)         = Derailmentlo(1,j);
end;
% The following loop start with the second value, therefore the first value must
% be set before the sum loop is initiated
% Set the first value
for i = 2:ndata,
  for j = 1:8,
    accDetectedcracks(i,j)     = Detectedcrackslo(i,j)+accDetectedcracks(i-1,j);
    accRailbreaks(i,j)         = Railbreakslo(i,j)+accRailbreaks(i-1,j);
    accDerailment(i,j)         = Derailmentlo(i,j)+accDerailment(i-1,j);
  end;
end;
%
for i = 1:ndata,
  for j = 1:8,
```

```
PB1(i,j)=accDetectedcracks(i,j)./(accDetectedcracks(i,j)+accRailbreaks(i,j)+accDerail
ment(i,j));
PB2(i,j)                                                                        =
accRailbreaks(i,j)./(accDetectedcracks(i,j)+accRailbreaks(i,j)+accDerailment(i,j));
PB3(i,j)                                                                        =
accDerailment(i,j)./(accDetectedcracks(i,j)+accRailbreaks(i,j)+accDerailment(i,j));
  end;
end;
% Cost_r is Risk Cost
for i = 1:ndata,
  for j = 1:8,
    Cost_r(i,j) = E(i).*((PB1(i,j))*k/2 + PB2(i,j)*k*1.2/2 + PB3(i,j)*a/2);
  end;
end;
% Ctot_r is the total risk cost for the entire curve.
% Set the first year total risk cost equal to the first year risk cost
% for each section.
for  j =1:8,
  Ctot_r(1,j) = Cost_r(1,j);
end;
% Calculation of the total accumulated risk cost for eight sections
for i = 2:ndata,
  for j =1:8,
    Ctot_r(i,j) = Ctot_r(i-1,j) + Cost_r(i,j);
  end;
end;
%**************************************************
% Down time cost
% Calculations of Down Time cost
for i = 1:ndata,
  for j = 1:8,
    Cost_d(i,j) = (ni(i,j).*L(j))./(1000*GS).*d/2;
  end;
end;
```

```
% Calculation of the total accumulated down time cost for
% the First year for curve section 0<r<300
for  j =1:8,
   Ctot_d(1,j) = Cost_d(1,j);
end;
% Calculation of the total accumulated down time cost
% for all other sections
for i = 2:ndata,
   for j =1:8,
      Ctot_d(i,j) = Ctot_d(i-1,j) + Cost_d(i,j);
   end;
end;
%**************************************************
% Inspection cost
% Calculation of Inspection costs
% Cost_i = Cost of Inspection for Rail
% Cost_re = Cost of replacement of rail for segment Lxxxy
% ic = Cost of one Inspection
% If = Inspection frequency in MGT
% L length of the segment for eight sections
% Ltot [m] is the total length of a track studied.
for i = 1:ndata,
   for j = 1:8,
      Cost_i(i,j) = L(j).*If*ic/2;
   end;
end;
%**************************************************
% Replacement cost
% Calculation of the Replacement cost
% maxxxxxx displays the Maximum Rail life of each section for different rail
% profiles
max50hi = max(mgtstephi50); % Maximum Rail life of eight sections for BV50 High
Rail
```

max50low = max(mgtsteplow50); % Maximum Rail life of eight sections for BV50 Low Rail

rBV50 = 151.60;

% rBV50 = replacement cost of BV50 Rail for one rail

% L is the length of rail segment for worn out regulation.

Cost_reBV50(1,1:8) = 0;

Cost_reBV50(1,1:8) = L(1:8).*rBV50;

% totalpv_re = is the Total Present value for replacement of BV50 Rail profile

% totalpv_re = Cost_reBV50;

%***

% discounting = The discounting factor of Rail for each year

discounting = 10/100;

% HIGH RAIL BV50

% Calculation of present value of different costs for HighRailBV50 for 8 sections

% i is the number of years

% j is the section

% Introduce a time vector that represent life of rail in years and discount rate

% The time vector will then be different for different sections, High and Low rails

% i.e. the time vector will be a matrix of i and j

pv_ihi(1:max(max50hi),1:8) = 0.; % Define and set values in the matrix to 0 for high rail

pv_dhi(1:max(max50hi),1:8) = 0.; % The size is set to 1 to max-life of each section

pv_ghi(1:max(max50hi),1:8) = 0.; % i.e. if the max life is 15 years for any section (1-8)

pv_rhi(1:max(max50hi),1:8) = 0.; % the dimension is then 1:15 to 1:8

% The following loop do not take into account the different life of rails in the

% different sections. The life is calculated in the vector max50hi for the different high

% rail % sections. Using that value number of steps can be set in the loop.

% When life is maximum the remaining present value of rail is set to 0.

% i = Column length of each section is different in this case it is max(max(50hi), 50

% kg

% high rail

% use the maximum value to set the dimensions of the matrix

```
% In this case it is set max(max50hi), i.e 50 kg high rail for each section (i.e 8 sections) and % also calculating the present values of different costs for each section
% Same cost for both High and Low
for i = 1:max(max50hi),
  for j = 1:8,
    pv_ihi(i,j) = Cost_i(i,j)./(1+discounting)^(i);
    pv_dhi(i,j) = Cost_d(i,j)./(1+discounting)^(i);
    pv_ghi(i,j) = Cost_g(i,j)./(1+discounting)^(i);
    pv_rhi(i,j) = Cost_r(i,j)./(1+discounting)^(i);
  end;
end;
% The following loop stops at 7 column, the 8 has the maximum Rail life
for k = 1:7
  for i = (max50hi(k)+1):max(max50hi),
    pv_ihi(i,k) = 0.;
    pv_dhi(i,k) = 0.;
    pv_ghi(i,k) = 0.;
    pv_rhi(i,k) = 0.;
  end;
end;
% LOW RAIL BV50
% Calculation of present value of different costs for Low RailBV50 for 8 sections
% i is the number of years
% j is the section
% Introduce a time vector that represent life of rail in years and discount rate
% The time vector will then be different for different sections, High and Low rails
% i.e. the time vector will be a matrix of i and j
pv_ilow(1:max(max50low),1:8) = 0.; % Define and set values in the matrix to 0 for low rail
pv_dlow(1:max(max50low),1:8) = 0.; % The size is set to 1 to max-life of each section
pv_glow(1:max(max50low),1:8) = 0.; % i.e. if the max life is 15 years for any section (1-8)
pv_rlow(1:max(max50low),1:8) = 0.; % the dimension is then 1:15 to 1:8
```

```
% The following loop do not take into account the different life of rails in the
% different sections. The life is calculated in the vector max50low for the different
% low rail sections. Using that value to set the number of steps in the loop.
% When life is maximum the remaining present value is set to 0.
% i = Column length of each section is different
% use the maximum value to set the dimensions of the matrix
% In this case it is set max(max50low), i.e. 50 kg low rail for each section (i.e. 8
sections) and also calculating the present values of different costs for each section
for i = 1:max(max50low),
  for j = 1:8,
    pv_ilow(i,j) = Cost_i(i,j)./(1+discounting)^(i);
    pv_dlow(i,j) = Cost_d(i,j)./(1+discounting)^(i);
    pv_glow(i,j) = Cost_g(i,j)./(1+discounting)^(i);
    pv_rlow(i,j) = Cost_r(i,j)./(1+discounting)^(i);
  end;
end;
% The following loop stops at 7 column, the 8 has the maximum Rail life
for k = 1:7
  for i = (max50low(k)+1):max(max50low),
    pv_ilow(i,k) = 0.;
    pv_dlow(i,k) = 0.;
    pv_glow(i,k) = 0.;
    pv_rlow(i,k) = 0.;
  end;
end;
% Sum up the present values of low rail of BV50
sumpv_glow(1:8) = 0.;
sumpv_ilow(1:8) = 0.;
sumpv_rlow(1:8) = 0.;
sumpv_dlow(1:8) = 0.;
% Sum loop to calculate the sum of present values of low rail
for j = 1:8,
  for i = 1:max(max50low),
    sumpv_glow(j) = sumpv_glow(j) + pv_glow(i,j);
```

```
    sumpv_ilow(j) = sumpv_ilow(j) + pv_ilow(i,j);
    sumpv_rlow(j) = sumpv_rlow(j) + pv_rlow(i,j);
    sumpv_dlow(j) = sumpv_dlow(j) + pv_dlow(i,j);
  end;
end;
% Sum up the present values of High rail of BV50
sumpv_ghi(1:8) = 0.;
sumpv_ihi(1:8) = 0.;
sumpv_rhi(1:8) = 0.;
sumpv_dhi(1:8) = 0.;
% Sum loop to calculate the sum of present values of High rail
for j = 1:8,
  for i = 1:max(max50hi),
    sumpv_ghi(j) = sumpv_ghi(j) + pv_ghi(i,j);
    sumpv_ihi(j) = sumpv_ihi(j) + pv_ihi(i,j);
    sumpv_rhi(j) = sumpv_rhi(j) + pv_rhi(i,j);
    sumpv_dhi(j) = sumpv_dhi(j) + pv_dhi(i,j);
  end;
end;
% ****************************************************
% Calculation of Annuity costs
% Calculation of the Annuity cost for Replacement
% The replacement cost of one rail, high or low, in a segment is
% same, i.e. the length of that segment is same for high and low rail.
totalpv_re50 = Cost_reBV50;
for j = 1:8,
anuity_relow(j)=totalpv_re50(j).*(1-1./(1+discounting))./(1-
(1./(1+discounting)^(max50low(j)-1)));
anuity_rehi(j)          =          totalpv_re50(j).*(1-1./(1+discounting))./(1-
(1./(1+discounting)^(max50hi(j)-1)));
end;
totalanuity_re = anuity_rehi + anuity_relow;
% ****************************************************
% Calculation of the Annuity cost for grinding
```

```
% for loop for calculation of annuity cost for grinding.
for j=1:8
anuity_glow(j)=sumpv_glow(j).*(1-1./(1+discounting))./(1-
(1./(1+discounting)^(max50low(j)-1)));
anuity_ghi(j)=sumpv_ghi(j).*(1-1./(1+discounting))./(1-
(1./(1+discounting)^(max50hi(j)-1)));
end;
totalanuity_g = anuity_ghi + anuity_glow;
% ****************************************************
```

% Calculation of the Annuity cost for inspection

```
% for loop for calculating annuity cost for inspection
for j = 1:8,
anuity_ilow(j)=sumpv_ilow(j).*(1-1./(1+discounting))./(1-
(1./(1+discounting)^(max50low(j)-1)));
anuity_ihi(j)= sumpv_ihi(j).*(1-1./(1+discounting))./(1-
(1./(1+discounting)^(max50hi(j)-1)));
end;
totalanuity_i = anuity_ihi + anuity_ilow;
% ****************************************************
```

% Calculation of the Annuity cost for risk

```
% for loop for calculating annuity cost for risk
for j = 1:8,
anuity_rlow(j)=sumpv_rlow(j).*(1-1./(1+discounting))./(1-
(1./(1+discounting)^(max50low(j)-1)));
anuity_rhi(j)= sumpv_rhi(j).*(1-1./(1+discounting))./(1-
(1./(1+discounting)^(max50hi(j)-1)));
end;
totalanuity_r = anuity_rhi + anuity_rlow;
% ****************************************************
```

% Calculation of the Annuity cost for down time

```
% for loop for calculating annuity cost for down time
for j = 1:8,
anuity_dlow(j)=sumpv_dlow(j).*(1-1./(1+discounting))./(1-
(1./(1+discounting)^(max50low(j)-1)));
```

```
anuity_dhi(j)=sumpv_dhi(j).*(1-1./(1+discounting))./(1-
(1./(1+discounting)^(max50hi(j)-1)));
end;
totalanuity_d = anuity_dhi + anuity_dlow;
%**************************************************
```

% Calculation of total Annuity cost

```
%**************************************************
totalanuity50                                                        =
totalanuity_g+totalanuity_i+totalanuity_r+totalanuity_d+totalanuity_re;
sumtotalanuity50 = sum(totalanuity50);
```

Appendix D

Data generated in Microsoft Excel Using Visual Basic code

			Hi Rail					
Section	Curve radii [m]	MGT	Average traffic wear [mm2]	Average grinding wear [mm2]	Average No. Of grinding passes	Detected cracks	Rail Brakes	Derailments
1	0<R<300	23	0.25	12.58	1	80	2	0
2	301<R<450	23	0.24	9.06	4	90	1	0
3	451<R<600	23	0.2	11.04	4	78	0	1
4	601<R<800	23	0.28	13.02	2	85	3	0
5	801<R<1500	23	0.25	14.01	2	85	3	0
6	1501<R<9999	23	0.24	16.98	6	80	1	0
7	10 000<R							
8	Tangential track							
			Low Rail					
		MGT	Average traffic wear [mm2]	Average grinding wear [mm2]	Average No. Of grinding passes	Detected cracks	Rail Brakes	Derailments
		23	0.2	11.32	2	68	2	0
		23	0.19	8.15	5	48	1	0
		23	0.16	9.93	8	57	0	1
		23	0.22	11.72	3	68	3	0
		23	0.2	12.61	4	62	3	0
		23	0.19	15.28	5	50	3	0

Calculated statistics	Max	Min	Average	Step length					Steps		F(x)	Interpolation Mall
Traffic wear	0.28	0.2	0	0.02					10		0.00%	
Grinding wear	16.98	9.06	13	1.58					15		20.00%	10
No of passes	6	1	3	1					20		40.00%	0
Detected cracks	90	78	83	2.4					25		60.00%	0
Rail brakes	3	0	2	0.6					30		80.00%	0
Derailments	1	0	0	0.2			Random =		35		100.00%	0
						High Rail				Low Rail		
					Traffic wear		69.73%	0.25	Traffic wear		22.54%	0.17
Calculated statistics	Max	Min	Average	Step length	Steps	f(x) %	F(x) %	Interpolation	Steps	f(x) %	F(x) %	Interpolation
Traffic wear	0.22	0.16	0	0.01	0.2	0.00%	0.00%		0.1574803	0.00%	0.00%	
Grinding wear	15.28	8.15	12	1.43	0.215	16.67%	16.67%	0	0.1692913	16.67%	16.67%	0
No of passes	8	2	5	1.2	0.23	0.00%	16.67%		0.1811024	0.00%	16.67%	
Detected cracks	68	48	59	4	0.245	33.33%	50.00%	0	0.1929134	33.33%	50.00%	0.17
Rail brakes	3	0	2	0.6	0.26	33.33%	83.33%	0.25	0.2047244	33.33%	83.33%	0
Derailments	1	0	0	0.2	0.275	16.67%	100.00%	0	0.2165354	16.67%	100.00%	0

Grinding wear		11.08%	10.11	Grinding wear		17.54%	9.65
Steps	f(x) %	F(x) %	Interpolation	Steps	f(x) %	F(x) %	Interpolation
9.055894	0.00%	0.00%		8.1503046	0.00%	0.00%	
10.640675	16.67%	16.67%	10.11	9.5766079	16.67%	16.67%	0
12.225457	16.67%	33.33%	0	11.002911	16.67%	33.33%	9.65
13.810238	33.33%	66.67%	0	12.429215	33.33%	66.67%	0
15.39502	16.67%	83.33%	0	13.855518	16.67%	83.33%	0
16.979801	16.67%	100.00%	0	15.281821	16.67%	100.00%	0
No of passes		73.46%	3	No of passes		73.46%	5
Steps	f(x) %	F(x) %	Interpolation	Steps	f(x) %	F(x) %	Interpolation
1	16.67%	0.00%		2	0.00%	0.00%	
2	33.33%	50.00%	0	3.2	33.33%	33.33%	0
3	0.00%	50.00%		4.4	16.67%	50.00%	0
4	33.33%	83.33%	3.41	5.6	33.33%	83.33%	5.24
5	0.00%	83.33%		6.8	0.00%	83.33%	
6	16.67%	100.00%	0	8	16.67%	100.00%	0
Detected cracks		5.00%	78	Detected cracks		20.75%	50
Steps	f(x) %	F(x) %	Interpolation	Steps	f(x) %	F(x) %	Interpolation
78	0.00%	0.00%		48	16.67%	0.00%	
80.4	50.00%	50.00%	78.24	52	16.67%	33.33%	50.49
82.8	0.00%	50.00%		56	0.00%	33.33%	
85.2	33.33%	83.33%	0	60	16.67%	50.00%	0
87.6	0.00%	83.33%		64	16.67%	66.67%	0
90	16.67%	100.00%	0	68	33.33%	100.00%	0

Rail brakes		32.10%	1	Rail brakes		31.76%	2
Steps	f(x) %	F(x) %	Interpolation	Steps	f(x) %	F(x) %	Interpolation
0	16.67%	0.00%		0	16.67%	0.00%	
0.6	0.00%	16.67%	0	0.6	0.00%	16.67%	0
1.2	33.33%	50.00%		1.2	16.67%	33.33%	
1.8	0.00%	50.00%	1.16	1.8	0.00%	33.33%	1.69
2.4	16.67%	66.67%	0	2.4	16.67%	50.00%	0
3	33.33%	100.00%	0	3	50.00%	100.00%	0
Derailments		71.15%	0	Derailments		87.05%	0
Steps	f(x) %	F(x) %	Interpolation	Steps	f(x) %	F(x) %	Interpolation
0	83.33%	0.00%		0	83.33%	0.00%	
0.2	0.00%	83.33%	0.17	0.2	0.00%	83.33%	0
0.4	0.00%	83.33%		0.4	0.00%	83.33%	
0.6	0.00%	83.33%		0.6	0.00%	83.33%	
0.8	0.00%	83.33%		0.8	0.00%	83.33%	
1	16.67%	100.00%	0	1	16.67%	100.00%	0.38

		Traffic Wear			Grinding Wear	
	Total area [mm2]/MGT		Total area [mm2]/MGT		Min Wear [mm2]/MGT	
	High Rail	High Rail	Low Rail	Low Rail	Grinding	
Curve radii [m]	Non Lubricated	Lubricated	Non Lubricated	Lubricated	Min	Max
0<R<300	10.56	2.57	1.14	1.14	0.86	2.15
301<R<450	5.13	1.41	0.63	0.63	0.78	1.94
451<R<600	2.79	0.85	0.38	0.38	0.69	1.73
601<R<800	1.39	0.48	0.21	0.21	0.62	1.56
801<R<1500	0.36	0.15	0.07	0.07	0.56	1.41
1501<R<9 999	0.25	0.11	0.05	0.05	0.51	1.27
10 000<R	0.14	0.06	0.03	0.03	0.47	1.17
Tangential track	0.03	0.02	0.01	0.01	0.42	1.06

	BV Data		BV Data	
	23	MGT	12	MGT
	Traffic	Grinding	Traffic	Grinding
0<R<300	0.37	1.09	0.18	1.52
301<R<450	0.33	1.00	0.17	1.21
451<R<600	0.29	0.89	0.15	1.03
601<R<800	0.22	0.81	0.11	1.08
801<R<1500	0.09	0.73	0.05	0.97
1501<R<9 999	0.07	0.59	0.03	0.68
10 000<R	0.04	0.60	0.02	0.62
Tangential track	0.01	0.55	0.01	0.57

Data for 23 MGT from curve radius 0 to 300 meters

	5.74	27.57	7	67	1	0
			Low Rail			
MGT	Traffic wear	Grinding wear	No of passes	Detected cracks	Rail brakes	Derailments
23.00	5.43	21.10	4.00	62.00	0.00	0.00
46.00	5.93	23.15	2.00	48.00	3.00	0.00
69.00	6.66	25.47	3.00	52.00	1.00	0.00
92.00	6.79	29.43	7.00	48.00	3.00	0.00
115.00	6.77	23.02	4.00	60.00	2.00	1.00
138.00	6.96	23.04	2.00	59.00	3.00	0.00
161.00	5.83	21.20	5.00	51.00	1.00	0.00
184.00	5.77	25.69	4.00	50.00	2.00	0.00
207.00	5.40	26.88	7.00	50.00	3.00	0.00
230.00	6.38	16.84	3.00	50.00	2.00	0.00
253.00	6.00	24.92	3.00	61.00	2.00	0.00
276.00	6.70	25.94	4.00	50.00	1.00	0.00
299.00	7.24	22.56	2.00	63.00	0.00	1.00
322.00	6.66	17.63	5.00	49.00	2.00	0.00
345.00	5.64	16.71	2.00	66.00	3.00	0.00
368.00	7.29	23.04	4.00	53.00	0.00	0.00
391.00	5.45	19.46	2.00	49.00	0.00	0.00
414.00	6.65	29.65	3.00	59.00	3.00	0.00
437.00	6.91	22.13	4.00	64.00	3.00	0.00
460.00	6.80	27.21	2.00	51.00	0.00	0.00

7.31	33.19	5	80	3	0
		High Rail			
Traffic wear	Grinding wear	No of passes	Detected cracks	Rail brakes	Derailments
6.87	27.42	2.00	84.00	1.00	0.00
8.75	31.40	1.00	79.00	3.00	1.00
8.35	26.87	1.00	83.00	3.00	0.00
9.08	33.25	5.00	83.00	0.00	0.00
8.53	23.48	2.00	82.00	3.00	0.00
7.24	33.28	1.00	89.00	3.00	0.00
8.36	20.91	3.00	80.00	3.00	0.00
8.42	32.04	2.00	80.00	1.00	0.00
7.41	19.11	5.00	90.00	3.00	0.00
7.83	24.91	1.00	78.00	1.00	0.00
8.47	25.27	2.00	80.00	3.00	0.00
8.77	29.96	2.00	86.00	2.00	0.00
8.96	29.56	1.00	89.00	3.00	0.00
9.16	26.72	2.00	83.00	1.00	0.00
6.97	27.28	1.00	79.00	2.00	0.00
7.71	18.02	2.00	82.00	2.00	1.00
7.47	19.03	1.00	82.00	2.00	0.00
7.21	33.48	2.00	81.00	3.00	0.00
8.52	26.75	2.00	79.00	3.00	0.00
8.23	18.82	1.00	83.00	2.00	0.00

Appendix E

Generated data for estimation of 23 MGT

Estimation of total annuity cost for grinding, inspection, risk, down time, replacement

Cost of grinding per pass per meter ($AUD)	2	**Section**	Curve radii [m]	Length [m]	Percentage		Length [m]
Grinding production speed	10	**1**	0<R<300	1318	1.01%	Radius<800	51791
Cost of replacement of one rail for segment L due to worn out regulation ($AUD)	152	**2**	300<R<450	1384	1.06%	Radius>800	30526
Expected costs of repairing rail brakes ($AUD)	1700	**3**	450<R<600	36524	27.98%	Tangential track	48220
Expected cost per derailment (accident) ($AUD)	3000000	**4**	600<R<800	33235	25.46%		130537
Expected cost of down time per hour ($AUD)	3136	**5**	800<R<1500	4569	3.50%		
Inspection cost ($AUD)	0.0043	**6**	1500<R<9999	4569	3.50%	Discount rate is 10% is taken as flat rate for 23 MGT	
New rail cross sectional area	2960	**7**	10 000<R	718	0.55%		
Critical area for replacement decision	2520	**8**	Tangential track	16073	36.94%		
Discount rate	0.1		Total length	130537	100.00%		
Weibull constants Beta	3.6	Lubrication Cost		4.5	$AUD per Kg	The costs vary with quality of the lubrication oil.	
Weibull constants Lambda	0.001	Lubrication consumption		1.36	Kg per MGT		

$P_i(B)$ is the probability of detecting potential rail breaks during the NDT and repairing immediately
$(1-P_i(B))$ is the probability of undetected potential rail breaks during the NDT leading to derailment
$P_i(A)$ Probability of failure to detect the undetected potential rail breaks leading to derailment during the NDT
$(1-P_i(A))$ is the probability of detecting the undetected potential rail breaks during the NDT leading to derailment are repaired in an emergency.

Data for 23 MGT of curve radius from 0 to 300 meters low rail

Year	23 MGT	Low Rail Comment	Traffic wear	Grinding wear	No of passes	Detected cracks	Rail brakes	Derailments
1	23		6	25.92	3	50	1	0
2	46		5.38	23.16	3	60	3	0
3	69		7.09	26.92	4	67	3	0
4	92		7.27	16.85	5	64	1	0
5	115		5.9	16.71	4	50	3	0
6	138		6.98	18.11	4	61	3	0
7	161		6.8	27.35	3	65	1	0
8	184		7.21	20.54	4	64	3	0
9	207		7.17	28.82	4	49	2	0
10	230		6.87	17.03	5	51	1	0
11	253		6.76	22.09	4	54	3	0
12	276		7.23	26.24	2	62	2	0
13	299		7.2	19.63	5	61	2	0
14	322		6.56	26.4	5	60	3	0
15	345		7.1	18.85	5	51	3	1
16	368		6.53	24.56	5	52	2	0
17	391	No grinding	6.79	26.62	2	52	1	0
18	414	Replaced	5.4	30.32	5	49	3	0

Estimation of annuity cost for grinding low rail

Grinding cost	Present value	Total PV at Replacement	Annuity cost	Annuity cost/Meter	Annuity cost/MGT	Annuity cost/MGT/Meter
7910.54	7191.4					
7910.54	6537.64					
10547.39	7924.41					
13184.24	9005.01					
10547.39	6549.1					
10547.39	5953.73					
7910.54	4059.36					
10547.39	4920.44					
10547.39	4473.12					
13184.24	5083.09					
10547.39	3696.8					
5273.69	1680.36					
13184.24	3819					
13184.24	3471.82					
13184.24	3156.2					
13184.24	2869.27					
		80390.76	9110.77	6.91	396.12	0.3

Data for 23 MGT of curve radius from 0-300 meters high rail

	23	High Rail						
Year	MGT	Comment	Traffic wear	Grinding wear	No of passes	Detected cracks	Rail brakes	Derailments
1	23		8.76	20.16	2	83	1	0
2	46		7.89	28.44	2	83	1	0
3	69		8.66	32.41	2	80	1	0
4	92		9.02	29.15	3	84	3	1
5	115		9.29	23.42	2	79	2	0
6	138		8.16	19.61	2	80	0	1
7	161		8.41	23.32	1	79	3	0
8	184		8.97	29.7	2	80	1	0
9	207		7.27	24.88	2	79	1	0
10	230		7.22	18.36	4	79	2	0
11	253		6.83	26.01	2	85	2	0
12	276		7.12	32.88	1	87	1	0
13	299		9.29	25.27	4	89	2	1
14	322		8.25	33.75	4	82	2	0
15	345	No grinding	7.71	23.49	4	79	3	0
16	368	Replaced	7.32	22.77	3	79	3	0

Estimation of annuity cost for grinding high rail

Grinding cost	Present value	Total PV at Replacement	Annuity cost	Annuity cost/Meter	Annuity cost/MGT	Annuity cost/MGT/Meter
5273.69	4794.27					
5273.69	4358.43					
5273.69	3962.2					
7910.54	5403.01					
5273.69	3274.55					
5273.69	2976.86					
2636.85	1353.12					
5273.69	2460.22					
5273.69	2236.56					
10547.39	4066.48					
5273.69	1848.4					
2636.85	840.18					
10547.39	3055.2					
10547.39	2777.46					
		43406.93	5188.07	3.94	225.57	0.17

Average annuity cost for grinding of high rail and low rail for practical purpose

Annuity cost	Annuity cost/Meter	Annuity cost/MGT	Annuity cost/MGT/ Meter	Grinding cost/Meter	Grinding cost/MGT/ Meter
				10	0.43
				10	0.43
				12	0.52
				16	0.7
				12	0.52
				12	0.52
				8	0.35
				12	0.52
				12	0.52
				18	0.78
				12	0.52
				6	0.26
				18	0.78
				18	0.78
				10	0.43
				10	0.43
7149.42	5.42	310.84	0.24		

Data for accumulated area loss for low rail and high rail

			Low Rail				High Rail	
Accumulated Area Loss [mm2]	Worn out level %	Area loss/MGT	Accumulated Grinding Passes	Accumulated Area Loss [mm2]	Worn out level %	Area loss/MGT	Accumulated Grinding Passes	E(M j+1 ; M j)
31.91	7.25%	1.39	3	28.92	6.57%	1.26	2	0
60.45	13.74%	1.31	3	65.25	14.83%	1.42	4	0.0001
94.46	21.47%	1.37	7	106.32	24.16%	1.54	6	0.0001
118.58	26.95%	1.29	12	144.5	32.84%	1.57	9	0.0002
141.18	32.09%	1.23	16	177.2	40.27%	1.54	11	0.0004
166.27	37.79%	1.2	20	204.97	46.58%	1.49	13	0.0006
200.41	45.55%	1.24	23	236.7	53.79%	1.47	14	0.0009
228.17	51.86%	1.24	27	275.36	62.58%	1.5	16	0.0012
264.16	60.04%	1.28	31	307.51	69.89%	1.49	18	0.0016
288.05	65.47%	1.25	36	333.08	75.70%	1.45	22	0.0021
316.91	72.03%	1.25	40	365.92	83.16%	1.45	24	0.0026
350.38	79.63%	1.27	42	405.92	92.25%	1.47	25	0.0032
377.2	85.73%	1.26	47	0	0.00%	0	0	0.004
410.16	93.22%	1.27	52	42	9.55%	0.13	4	0.0048
436.11	99.12%	1.26	57	73.21	16.64%	0.21	8	0.0057
0	0.00%	0	0	103.3	23.48%	0.28	11	0.0067
33.42	7.59%	0.09	2	137.56	31.26%	0.35	12	0.0078
69.14	15.71%	0.17	7	164.87	37.47%	0.4	15	0.009
98.36	22.35%	0.23	10	199.87	45.42%	0.46	17	-0.0508

Estimation of probabilities and annuity cost for risk of low rail

Probabilities of Low rail				Risk cost calculations for low rail			Low rail			
$P_i(B)$	$(1-P_i(B))$	$P_i(A)$	$(1-P_i(A))$	Risk cost	PV Risk cost	Total present value	Annuity Risk cost	Annuity Risk cost/Meter	Annuity Risk cost/MGT	Annuity Risk cost/MGT/ Meter
0.9804	0.0196	0	0.0196	0.024	0.0218					
0.9524	0.0476	0	0.0476	0.087	0.0719					
0.9571	0.0429	0	0.0429	0.2058	0.1546					
0.9846	0.0154	0	0.0154	0.3912	0.2672					
0.9434	0.0566	0	0.0566	0.6627	0.4115					
0.9531	0.0469	0	0.0469	1.0195	0.5755					
0.9848	0.0152	0	0.0152	1.4682	0.7534					
0.9552	0.0448	0	0.0448	2.0435	0.9533					
0.9608	0.0392	0	0.0392	2.7245	1.1554					
0.9808	0.0192	0	0.0192	3.519	1.3567					
0.9474	0.0526	0	0.0526	4.4864	1.5725					
0.9688	0.0313	0	0.0313	5.5479	1.7677					
0.9683	0.0317	0	0.0317	6.7764	1.9629					
0.9524	0.0476	0	0.0476	8.1847	2.1553					
0.9273	0.0545	0.0182	0.0364	26.235	6.2804					
0.963	0.037	0	0.037	11.4265	2.4867					
0.9811	0.0189	0	0.0189			21.8531	2.4766	0.0019	0.1077	0.0001

Estimation of probabilities and annuity cost for risk for high rail

Probability calculations for High rail				Risk cost calculations for High rail						
$P_i(B)$	$(1-P_i(B))$	$P_i(A)$	$(1-P_i(A))$	Risk cost	PV Risk cost	Total present value	Annuity Risk cost	Annuity Risk cost/Meter	Annuity Risk cost/MGT	Annuity Risk cost/MGT/ Meter
0.9881	0.0119	0	0.0119	0.024	0.0218					
0.9881	0.0119	0	0.0119	0.0864	0.0714					
0.9877	0.0123	0	0.0123	0.2045	0.1537					
0.9545	0.0341	0.0114	0.0227	0.6495	0.4436					
0.9753	0.0247	0	0.0247	0.6585	0.4089					
0.9877	0	0.0123	-0.0123	0.9826	0.5546					
0.9634	0.0366	0	0.0366	1.4745	0.7566					
0.9877	0.0123	0	0.0123	2.0304	0.9472					
0.9875	0.0125	0	0.0125	2.71	1.1493					
0.9753	0.0247	0	0.0247	3.5228	1.3582					
0.977	0.023	0	0.023	4.4601	1.5632					
0.9886	0.0114	0	0.0114	5.5259	1.7607					
0.9674	0.0217	0.0109	0.0109	9.4098	2.7257					
0.9762	0.0238	0	0.0238	8.1461	2.1451					
0.9634	0.0366	0	0.0366			14.06	1.6805	0.0013	0.0731	0.0001

Average annuity cost for risk of high rail and low rail for practical purpose

Annuity cost	Annuity cost/Meter	Annuity cost/MGT	Annuity cost/MGT/ Meter	Risk cost/Meter	Risk cost/MGT/ Meter
				0	0
				0.0001	0
				0.0003	0
				0.0008	0
				0.001	0
				0.0015	0.0001
				0.0022	0.0001
				0.0031	0.0001
				0.0041	0.0002
				0.0053	0.0002
				0.0068	0.0003
				0.0084	0.0004
				0.0123	0.0005
				0.0124	0.0005
				0.0199	0.0009
				0.0087	0.0004
2.0786	0.0016	0.0904	0.0001		

Estimation of annuity cost for down time of low rail

Down time cost	PV of Down time cost	Total PV	Annuity cost	Annuity cost/Meter	Annuity cost/MGT	Annuity cost/MGT/ Meter
1240	1128					
1240	1025					
1654	1243					
2067	1412					
1654	1027					
1654	934					
1240	637					
1654	772					
1654	701					
2067	797					
1654	580					
827	263					
2067	599					
2067	544					
2067	495					
2067	450					
827	164	12605	1429	1.08	62.11	0.05

Estimation of annuity cost for down time of high rail

Down time cost	PV of Down time cost	Total PV	Annuity cost	Annuity cost/Meter	Annuity cost/MGT	Annuity cost/MGT/ Meter
827	752					
827	683					
827	621					
1240	847					
827	513					
827	467					
413	212					
827	386					
827	351					
1654	638					
827	290					
413	132					
1654	479					
1654	436					
1654	396	6806	813	1	35	0.03

Average annuity cost for down time of high rail and low rail for practical purpose

Annuity cost	Annuity cost/Meter	Annuity cost/MGT	Annuity cost/MGT/ Meter	Down time cost/Meter	Down time cost/MGT/ Meter
				1.57	0.0682
				1.57	0.0682
				1.88	0.0818
				2.51	0.1091
				1.88	0.0818
				1.88	0.0818
				1.25	0.0545
				1.88	0.0818
				1.88	0.0818
				2.82	0.1227
				1.88	0.0818
				0.94	0.0409
				2.82	0.1227
				2.82	0.1227
				2.82	0.1227
				2.51	0.1091
1121	0.85	48.74	0.04		

Average annuity cost for inspection of High rail and low rail for practical purpose

Inspection cost	PV of Inspection	Total PV	Annuity cost	Annuity cost/Meter	Annuity cost/MGT	Annuity cost/MGT/ Meter	Inspection cost/Meter
65	59						0.049
65	54						0.049
65	49						0.049
65	45						0.049
65	40						0.049
65	37						0.049
65	33						0.049
65	30						0.049
65	28						0.049
65	25						0.049
65	23						0.049
65	21						0.049
65	19						0.049
65	17						0.049
65	16						0.049
65	14						0.049
65	13	510	58	0.04	2.51	0	

Estimation of annuity cost for replacement of Low rail

Replacement cost	PV	Total PV	Annuity cost	Annuity cost/Meter	Annuity cost/MGT	Annuity cost/MGT/ Meter
199873	199873					
0	0					
0	0					
0	0					
0	0					
0	0					
0	0					
0	0					
0	0					
0	0					
0	0					
0	0					
0	0					
0	0					
0	0					
0	0					
0	0	199873	22652	17	985	1

Estimation of annuity cost for replacement of High rail

Replacement cost	PV	Total PV	Annuity cost	Annuity cost/Meter	Annuity cost/MGT	Annuity cost/MGT/ Meter
199873	199873					
	0					
	0					
	0					
	0					
	0					
	0					
	0					
	0					
	0					
	0					
	0					
	0					
	0					
	0	199873	23889	18	1039	1

Average annuity cost for replacement of high rail and low rail for practical purpose

Annuity cost	Annuity cost/Meter	Annuity cost/MGT	Annuity cost/MGT/Meter
23270	17.65	1011.76	0.77

Estimation of annuity cost for lubrication of high rail

Lubrication cost	Present value	Total PV at Replacement	Annuity cost	Annuity cost/Meter	Annuity cost/MGT	Annuity cost/MGT/Meter
985	896					
985	814					
985	740					
985	673					
985	612					
985	556					
985	506					
985	460					
985	418					
985	380					
985	345					
985	314					
985	285					
985	259					
985	236					
		7494	896	0.68	39	0.0295

Estimation of average annuity cost for lubrication of low rail and high rail for practical purpose

Lubrication cost/Meter	Lubrication cost/Meter /MGT	Total annuity cost/meter up to replacement	Total annuity cost/meter with lubrication
0.75	0.03		
0.75	0.06		
0.75	0.1		
0.75	0.13		
0.75	0.16		
0.75	0.19		
0.75	0.23		
0.75	0.26		
0.75	0.29		
0.75	0.32		
0.75	0.36		
0.75	0.39		
0.75	0.42		
0.75	0.45		
0.75	0.49		
0.75	0		
		23.97	24.65

Estimation of annuity cost for stop/start lubrication of low rail and high rail (0-300 meters) for practical purpose

For 0-300 meters	23	12	18	9
Length (meters)	1318	1318	1318	1318
Total Annuity cost including lub/m	24.65	24.06	29.8	37.07
Annuity cost/meter for Lub	0.68	0.67	0.67	0.65
Number of STOP periods/ year	1	1	1	1
Switching cost/ switching	250	250	250	250
Number of switching per STOP/START	2	2	2	2
Switching	0.3793627	0.3793627	0.379363	0.379363
STOP Period, 16%	0.16	0.16	0.16	0.16
Savings in Lub, 16%	0.1088	0.1072	0.1072	0.104
Annuity cost/meter for grinding	5.42	6.82	11.41	14
Savings in grinding, 5%	0.05	0.05	0.05	0.05
Savings in Grinding	0.271	0.341	0.5705	0.7
Annuity cost/meter for risk	0.0015765	0.00023	0.0011	0.00003
Probability of Spalling	0.02	0.02	0.02	0.02
Increase in risk cost	0.000032	0.000005	0.00002	0.0000005
Replacement cost	17.65	15	16	20.62
% increase in wear during stop 130%	1.3	1.3	1.30	1.3
Excessive wear During STOP Period	0.208	0.208	0.208	0.208
Increase in replacement cost	3.6712	3.12	3.328	4.28896
Total Cost with Stop/Start	28.32	27.11	32.83	40.93

Estimation of total annuity cost/meter for 23 MGT of curve radius from 0-300 meters

Total annuity cost/meter up to replacement	Total annuity cost/meter with lubrication	Total annuity cost/meter with stop/start lubrication
24	24.65	28.32