THE EFFECT OF STRAIGHTENING AND GRINDING OF WELDS ON TRACK ROUGHNESS

BY MELISSA E BONA

BE, (QUT)

Thesis Submitted for the Degree of Master

School of Civil Engineering

Queensland University of Technology

July 06

QUEENSLAND UNIVERSITY OF TECHNOLOGY

MASTER THESIS EXAMINATION

CANDIDATE NAME	***Melissa Ellen Bona***
CENTRE/RESEARCH CONCENTRATION	
PRINCIPAL SUPERVISOR	***Dr Martin Murray (QUT)***
ASSOCIATE SUPERVISOR(S)	***Prof Luis Ferreira (QUT)*** ***Mr Simon Shelley (QR)***
THESIS TITLE	***The effect of straightening and grinding of welds on track roughness***

Statement of original authorship

The work contained in this thesis has not been previously submitted for a degree or a diploma at any other higher education institution. To the best of my knowledge and belief, the thesis contains no material previously published or written by another person except where due reference is made.

Signature:____________________________

Date:________________________________

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Rail is a very expensive component of the railway track. Therefore, research methods extending rail life have great economic importance. During the past thirty years and, particularly during the past ten years there has been an increasing awareness throughout most rail networks in the world of the need to introduce improved design criteria, better construction techniques and higher standard track generally. This implies that quality control at all levels is mandatory if these objectives are to be achieved.

With the improved understanding of degradation of track, a more complete comprehension of the costs associated with different operating and infrastructure conditions should also be developed, aiding in the determination of efficient maintenance costs and their contribution to access charges. Track and structures together account for 60% of maintenance costs, with 50% of the total being track. The UIC has done a lot of work on comparative performance indicators, and these show what potential savings much be out there for the taking, just by adopting current best practice. The old wisdom is that it’s not enough o do things rights; we have to make sure that we do the right things.

These developments have largely resulted from the demand for higher speeds particularly in passenger services and the demand to accept heavier axle loads of freight traffic. Whilst the conventional railway track structure is not likely to change significantly over the next ten years there will be a requirement over that period for better quality track infrastructure. This means less rail surface defects, less internal defects and less wheels irregularities.

The presence of rail surface defects generally increases the roughness of the track leading to a poor passenger ride and increased safety risk with freight traffic. In addition, rail surface defects will generally increase the degradation rate of other track components; however, not all defects will produce visible track deterioration.

Dynamic impacts produced by the rollingstock running over rail surface defects, such as poor welds, will, over time, create continuous rail defects, loosening of fastenings, abrasion and skewing of sleepers, crushing of ballast and loss of formation geometry. It is only in the recent years that the importance of poor welds in track has been identified. Dips and peaks must be recognised as a severe track irregularity that needs to be addressed and removed.

Current maintenance activities have little effect on removing misaligned welds in track and the improvement obtained after the maintenance works is generally short lived. On the other hand, straightening operations have proven to solve the problem and maintain the results following 7 months of traffic.

As part of this project, a six kilometre test section was selected on the Mt Isa Line and all welds located in this region were monitored for over 9 months to increase the understanding of the effect of individual maintenance activities on the track roughness. Three 2km *Divisions* were established; each *Division* had different maintenance activities and levels of intervention completed over the duration of the project. Over 15,000 readings were recorded and analysed. The following conclusions were drawn.

The effect of cycle tamping was clearly identified when comparing the means of weld located in *Division 1, 2* to the mean of welds in *Division 3*. Cycle tamping showed to have a significant positive effect on the dipped welds geometry and an increase in severity of peaked welds prior to their correction.

Straightening operations completed in *Division 1* and *2* reduced the overall mean of weld misalignments. These *Divisions* were subjected to different levels of straightening intervention however they produced similar results. *Division 1* all dips were straightened and *Division 2* only dips >0.3mm were straightened. This means that no additional benefit, in terms of overall misalignment of welds, can be gained when straightening operations target dips with a misalignment smaller than 0.3mm.

Cycle grinding proved to have little effect on the removal of both dips and peaks. In fact, due to the configuration of the grinding machine, grinding operation produced a slight worsening of the dips misalignments and only a minor improvement of peaks.

Although long term monitoring of the site may show minor variations in weld geometry performance, after approximately 3.9 Mgt of traffic the mean of dipped welds in *Division 1* and *2* appeared to remain unaltered, as *Division 3* showed a minor worsening. Furthermore, the mean of peaked welds in *Division 1* and *2* appeared to remain unaltered, as *Division 3* showed a minor worsening.

DEFINITIONS

Ballast – the selected material placed between the sleepers and the formation for the purpose of holding the track to top and line.

Corrugation – a rail defect of regular wave-like depressions on the top of the rail head.

Continuous Welded Rail (CWR) – consists of lengths welded together to form a rail longer than 220m.

Flashbutt welds – welds in which the heat of fusion is provided by an electric arc between the ends of the rail to be jointed.

Formation – the prepared surface on which the ballast is laid.

Gauge – the distance between the running faces of two rails, measured a nominal distance below the tops of the railheads.

Kilometre post – a post placed every kilometre along the track to satisfy the distance from a known point.

Long Welded Rail (LWR) – rail welded together into lengths greater than 110m, but less than 220m long.

Maintenance machines – includes on-track machines and section cars working singly or as a group.

P_2 *forces* – static plus low frequency dynamic force exerted at discontinuity in rail such as a dipped weld.

Rail – track component that the wheels run on.

Rail grinder – a piece of equipment used to grind rails.

Resonance – increase in the oscillation energy absorbed by a system when the frequency of the oscillation matches the system's natural frequency of vibration.

Rollingstock – any vehicle which operated on or used a rail track, excluding on- and off-track use when not operating on the track.

Sleeper – a cross member which supports the rails and maintains gauge.

Speed board – a sign placed beside the track indicating the maximum nominal speed for that section of track.

Tamping machine – track equipment used for tamping ballast.

Track Condition Index (TCI) – the sum of the PCI’s of each parameter for the length of track under evaluation.

Thermite weld – aluminothermic weld used to join rail in the field.

Top and line – the horizontal and vertical alignment of the rails.

Top defects – vertical alignment defects.

Track – the combination of rails, rail fasteners, sleepers, ballast and points and crossings.

Track monuments – permanent markers placed beside the track to provide information for maintaining track curves and transitions in their correct position.

Track Recording Car (TRC) – track equipment used for recording track geometry.

Welded track – track in which the rails are jointed by welding (LWR and CWR)

LIST OF ACRONYMS

CETS – Civil Engineering Track Standards

CWR – Continuous Welded Rail

FBW – Flash Butt Welds

HTT – Harsco Track Technology

LWR – Long Welded Rail

QR – Queensland Rail

QUT – Queensland University of Technology

RIC – Rail Infrastructure Cooperation

TRC – Track Recording Car

TCI – Track Condition Index

UIC – International Union of Railways

NOTATION

$m =$ Mass [kg]

$t =$ Time [s]

$a =$ Acceleration [m/s2]

$P_0 =$ Static wheel/rail contact force [kN]

$P_1 =$ Dynamic wheel/rail contact force [kN]

$P_2 =$ Dynamic wheel/rail contact force [kN]

$2\alpha =$ Total dip angle at the weld [rad]

v = Train speed [m/s]

$k_H =$ Linearised Hertzian contact stiffness [N/m]

$m_{T1} =$ Effective track mass for P_1 calculation [kg]

$m_u =$ Unsprung mass [kg]

$m_{T2} =$ Effective track mass for P_2 calculation [kg]

$k_{T2} =$ Equivalent track mass for P_2 calculation [N/m]

$c_T =$ Equivalent track damping for P_2 calculation [Ns/m]

$\lambda =$ Dimensionless factor depending on the track damping (for P calculations)

$k =$ Track stiffness [N/m]

$\delta_1 =$ Overall vertical displacement over 1 m length rail section

$\delta_2 =$ Localised dip/peak at the weld

$\lambda =$ Rail heat-affected-zone

ACKNOWLEDGEMENT

The researcher wishes to thank Dr Martin Murray, School of Civil Engineering, QUT, for his time and valuable suggestions in supervising this thesis. The researcher also wished to thank the following for their support and suggestions throughout the study: Simon Shelley, John Powell, Gerard Buckett, Scott Ryan, Glen Graham, Graham Creese, Geoffrey Ries, David Schonfeld and Queensland Rail (QR). The researcher wishes to extend her appreciation to those people of QR and QUT, not individually mentioned above, for their co-operation and support in this study.

The thesis was made possible by the financial support from the QR.

The researcher is indebted to her family for their patience and moral support during the course of this study.

1.0 INTRODUCTION

Within both the government and private sectors, there is increasing pressure to reduce budgets to maintain rail infrastructure to improve the viability of the relevant business. To address this need, rail organisations are looking to optimise maintenance and renewal activities so that better performance can be extracted from their asset at lower operating costs.

The presence of rail surface defects, such as misaligned welds, can cause an increase in track roughness which will create a bouncing motion of the bogies leading to a poor passenger ride or an unsafe travel of freight loads. This project focuses on the removal of such defects by using common maintenance activities.

Discrete defects such as misaligned welds on track not only create points of impact with consequent damage to rails but also can lead to cracking of sleepers and breakdown in the ballast structure and particles, leading to a loss of track geometry. Such deterioration can lead to loss of support of the rail which can accentuate the defected weld. It all results in a vicious circle, if the defects are not removed.

It has only been in relatively recent years that the effect of certain rail and track geometry defects, such as misaligned welds between sections of rail, has been identified. Misaligned welds often result in the two pieces of rail not being connected at exactly 180^o apart in a vertical plane, meaning there is a dip or peak in the longitudinal running surface of the rail at the location of the weld. With the presence of such rail geometry irregularities and the continuous increase in train speed and loads, the dynamic effects of trains imposed to the track structure are inevitably increased.

Welds between sections of rail can become dipped or peaked in numerous ways such as via:

- Manufacturing processes where the weld alignment is not correct to begin with;
- Manufacturing processes where, after welding, the area is ground while the steel has not satisfactorily cooled and hardened;

- High volumes of traffic causing constant impacts at the weld will induce work hardening and plastic deformation around the weld.

A variety of track maintenance activities are used to relieve the track from these and other rail head irregularities, including cycle tamping, cycle grinding and weld straightening.

Significant quantities of data can now be easily collected, stored and summarised. This, coupled with the accurate high-speed acquisition of rail geometry data, is providing the information to better understand the effect of maintenance and renewal on the rates of deterioration in terms of defects and geometry. The present project comprised an investigation of the effects of a number of maintenance activities on rectification of misaligned welds with a view to providing information on which better maintenance planning and costing could ultimately occur.

1.1 AIMS OF THE PROJECT

The main objectives of the projects were as follows:

- Understanding the effectiveness of weld straightening operations on slowing the rate of increase of track roughness.
- Understanding the effectiveness of rail grinding and of tamping of track on weld rectification with regards to slowing the rate of increase of track roughness.

1.2 METHODOLOGY

A six kilometre test site was selected in the QR (Queensland Rail) network near Mt Isa and the effect of various track maintenance activities monitored over a period of 9 months. The present project outlines the findings. In order to achieve the proposed aims, the project was divided into three main stages. These are:

(1) Stage 1 – Development of Field Trials, Data Collection and Data Analyses

> <u>Establish Test Sites</u> on the Mt Isa Line within the boundaries of an existing QR Weld Straightening Project
>
> <u>Review of Available Data</u>, especially data collected by the following means:

- *Track Recording Car* data which reports on the condition of the track by measuring the track geometry (in particular the parameters known as Top, Twist, Gauge and Versine)
- *Programmed Track Audits* data which reports on the overall track (Visual Inspection, Manual Measurements)

Program Data Collection from established test sites with the use of the Track Recoding Car and Visual Inspections before, during and after the Weld Straightening Project on the Mt Isa Line.

(2) Stage 2 – Review the Past and Current Industry Practice in rail maintenance

Review of Australian and Overseas literature.

Establish what data is required to achieve the objectives of the project.

(3) Stage 3 – Submission of Final Thesis Document

Compile the results from the analyses of measurements from the test sites with the findings from the review of National and International Literatures.

1.3 CONTENTS OF THE THESIS

Chapter 1 – Introduction

The aim of the project and the methodology that was followed to achieve the objectives of the projects is detailed in Chapter 1.

Chapter 2 – Forces, Defects and Maintenance

The progressive increases in speed, loads and frequency of travel on railways, especially over the last 20 years, has shown that rail defects, in particular more localised rail geometric defects such as poorly aligned welds, can cause very high dynamic forces at the wheel/rail interface which, over time, will increase the degradation rate of associated track components.

Chapter 2 reviews the following:

- Principle of dynamic forces and the amplification effect of rail geometry on the magnitude of the dynamic loadings;
- Discrete geometric rail surface defects, particularly of misaligned welds, and their effect on the initiation and propagation of continuous geometric defects;

- Track components' degradation due to the presence of poor welds in track and maintenance activities currently adopted for the rectification of track condition.

Chapter 3 – Field Test Section

The track structure is part of a complex dynamic system and as such the loadings it experiences are directly dependent upon the tolerances to which it was built. QR conducted an investigation on the Mt Isa Line that identified the need for a better defect management system so that the track infrastructure could better sustain future traffic tasks with minimal maintenance cost. Misaligned welds were identified as one of the major causes for poor track quality and therefore were targeted for removal using a rail straightening machine produced by the company Harsco Track Technology.

Chapter 3 describes and reviews the followings topics:

- Mt Isa Line and QR's investigation findings;
- Selection of the 6km test region, the division and monumenting of the region;
- Quality control limits used for the straightening operations;
- Detailed description of the track maintenance activities completed in the test area.

Chapter 4 – Measuring and Processing of Data

In total, over 15,000 readings were recorded during the duration of the project. It is common practice within the railway industry to use a 1m straight edge and taper gauge to evaluate the degree of vertical weld misalignment. However, due to the configuration and process followed by the RASTIC straightening machine, a longer straight edge was adopted.

Following a repeatability test the data was analysed and actual readings were converted to angle changes to identify if the RASTIC straightening machine had created additional defects to the rail head during the rail bending operations.

Furthermore, all of the data collected was converted to a 1m straight edge reading to comply with the standard work practice. The conversions processes and the findings have been outlined in Chapter 4.

Chapter 5 – Outcomes from the Project Data Analysis

The presence of poor welds in track gives rise to larger dynamic forces by moving rollingstock. These impacts create large vibrations which, over time, can induce ballast compaction or even crushing with consequent loss of track top.

A detailed investigation of the effect of straightening activities has been completed, as part of this project. In addition, a comparative analysis of tamping, straightening and grinding works has been conducted to establish the most efficient maintenance operation for the removal of poor welds in track, both short and long term. The findings have been detailed in this chapter.

Chapter 6 – Conclusions and Recommendations

Only in recent years has the importance of dipped/peaked welds on track degradation been realised. The straightness of the welds is important to prevent high dynamic force increments and particularly to reduce defect growth, noise propagation and poor vehicle ride.

Chapter 6 summarises the overall outcomes of the project, particularly:

- The effect of cycle tamping on misaligned welds;
- The effect of weld straightening on misaligned welds;
- The effect of grinding operations on misaligned welds; and,
- The efficiency of using the Track Recording Data to forecast track roughness due to the presence of localised discrete rail geometric irregularities such as poor welds.

Furthermore, Chapter 6 identifies the need for future studies in specific areas that have not currently been investigated.

2.0 FORCES, DEFECTS AND MAINTENANCE

2.1 INTRODUCTION

The cost of construction and maintenance of permanent way (railway track) are very substantial and form a large part of the total infrastructure expenditure. Any reduction of these costs has a significant impact on the overall efficiency of infrastructure management. It is of primary importance to those responsible for the condition and maintenance of the track to keep the cost as low as possible whilst maintaining a given track quality level for the period required.

The principal function of the rail is to act as a hard and unyielding surface to carry a rigid tyred wheel without rutting or abrasion. Additional functions are to act as a beam and thereby transmit wheel loads to the sleepers, and to act with the tread and flange of the wheel in steering the vehicle in the desired direction (Esveld 2001).

The progressive increases in speed, loads and frequency of travel on railways, especially over the last 20 years, has been shown (Zhai, Cai et al. 2001) to increase the magnitude of impact forces due to irregularities on the rail head and to raise track degradation rates. Generally, more localised defects such as poor weld geometries between sections of rail can cause very high dynamic forces at the wheel/rail interface which, over time, will increase the track degradation rate of surrounding track components. By constructing and maintaining the track to high standards, track owners can eliminate or at least minimise this scenario.

Much research and practical experimentation (Bogdaniuk, Massel et al. 2003) as been devoted to the complex problems involved in understanding the mechanisms by which rail wear and development of rail head defects take place, and of selecting the proportions of the alloying elements which will give the best possible resistance to rail head damage without making the rails less serviceable in other ways. However, very little research has been published on the effect of discrete rail surface defects on the degradation of all track components.

Not all defects will produce visible track deterioration. Corrosion and mechanical damage can produce a sufficient stress concentration to initiate fatigue cracks and cause them to grow. Thermal damage in the form of accidental heating can produce a very brittle structure, which easily forms cracks that can propagate further by fatigue until the rail breaks (Esveld 2001).

However, the defects that are most important to the present study are the discrete rail surface defects. In fact, the presence of such irregularities on the rail surface amplifies the dynamic impacts of the rolling wheels which will eventually increase the degradation rate of all of track components (UIC 1979). For example, weld defects, alone, can amount to one third of the total rail defect scheme (UIC 1979) in the international union of railways classification of rail defects, as shown in Appendix A.

For the purpose of the present research, a detailed review of the literature relating to discrete rail geometric irregularities has been undertaken. This chapter discusses the findings of this review in reference to the following:

- Dynamic forces in track and their effect to track structure;
- Discrete rail geometrical defects, their effect on the generation of higher dynamic impacts, and their effect on the initiation and/or propagation of defects;
- Rectification operations used to relieve or remove discrete geometric irregularities present in track.

Dynamic loads are the forces that are of most interest in the present project. Their effects on all track components are considerable, even more so if geometric irregularities are present. Dynamic forces can be greatly amplified by such irregularities, as discussed in the following sections.

2.2 DYNAMIC FORCES IN TRACK

Railway tracks are subjected to a wide range of vertical and horizontal forces from the moving rollingstock change in temperature and material properties. The higher the dynamic impact forces at localised rail surface defects in general, the more rapidly the track and its components, at that location, deteriorate. It is important to fully understand the causes of these induced forces to be able to remove them from the track and therefore extend the life of the track assets (Grassie 1996). Misaligned welds between rail sections are the types of defect which are at the heart of this thesis, and their particular relationship to dynamic forces is investigated in this section.

The forces acting on the track as a result of train loads are considerable, sudden and dynamic in nature. The loads can be categorised in three main groups:

- Vertical loads;
- Lateral loads, transverse to the track; and
- Longitudinal loads, parallel to the track.

Loads can then be divided into two groups depending on their nature:

- Quasi-static loads, generally caused by the vehicle body mass reacting to the track variations; and
- Dynamic loads caused by reaction of the vehicle/track system to:
    - Track geometry irregularities (horizontal and vertical) due to irregular track stiffness due to variable characteristics and settlement of ballast bed and formation;
    - Discontinuities at welds, joints etc;
    - Irregular rail running surface (eg. corrugation, wheel burns), and
    - Rollingstock defects such as wheel flats, natural frequency etc.

2.2.1 DYNAMIC PRINCIPLE

The aim of this section is to outline the principle of operation of dynamic forces in order to understand the amplification effect that some rail geometric defects may have on dynamic loadings.

Considerable research has been undertaken in order to understand the loads that exist between the wheel and rail, which are the source of many of problems, such as noise and track degradation (Zarembski 1991). When dealing with track structures most of the problems are related in one way or another to dynamics.

With increase in train speeds, wheel-rail interaction becomes more complicated and the dynamic effects of trains on tracks generally will increase, especially for the speed-raised lines where the track structures have not been altered from the state they were in when constructed for lower speed trains (Zhai, Cai et al. 2001).

In dynamic systems, however, an increase in speed can at times decrease the impacts created by moving rollingstock, for wheel flats can impose less force at higher speeds (Zhai, Cai et al. 2001). This emphasises the importance in understanding the dynamic systems.

As described by Esveld (2001):

> "Dynamic behaviour occurs in a fairly wide band ranging from very low frequencies of the order of 0.5-1 Hz for lateral and vertical car body accelerations to 2000 Hz as a consequence of geometrical irregularities in rails and wheel treads." (Esveld 2001)

This dynamic interaction is represented in Figure 2.1. The first spring/damper combination to reduce vibrations originating from the wheel/rail interaction is the suspension system between either:

- The wheel set and bogie

This is called 'primary suspension'. The 'secondary suspension' consists of either:

- The bogie and car body

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

Figure 2.1 Dynamic Model of Vehicle/Track Interaction (Grassie 1992)

From basic mechanics, the dynamic behaviour is governed by the law of momentum, which says that force equals the rate of change of momentum or:

$$F = \frac{\partial(mv)}{\partial t} \qquad \textbf{Equation (2.1)}$$

With a constant mass, Equation 2.1 transforms into Newton’s law, which implies that force equals mass times acceleration:

$$F = ma \qquad \textbf{Equation (2.2)}$$

So the objective is to evaluate the accelerations in the components making up the train and track. However, there is a huge number of interacting components in this system, so complex models are needed to attempt to determine the forces induced. In an attempt to simplify the situation, Jenkins’ Model (Jenkins, Stephenson et al. 1974) categorises all forces imposed on the track following vehicle/track interaction into two main types: P_1 and P_2 forces. Jenkins’ Model suggests that these forces can be mathematically calculated with various equations, namely:

$$P_1 = P_0 + 2\alpha \mathrm{v} \sqrt{\frac{\mathrm{k_H m_{T1}}}{1 + m_{T1}/m_u}} \qquad \textbf{Equation (2.3)}$$

$$P_2 = P_0 + 2\alpha v \sqrt{\frac{m_u}{m_u + m_{T2}}} \left[1 - \frac{\mathrm{c_T}\ \pi}{\sqrt{\mathrm{k_{T2}}\left(\mathrm{m_u} + \mathrm{m_{T2}}\right)}} \right] \sqrt{\mathrm{k_{T2}\ m_u}}$$ **Equation (2.4)**

Where:

$P_0 =$ Static wheel/rail contact force [kN]

$2\alpha =$ Total dip angle at the weld [rad]

v = Train speed [m/s]

$k_H =$ Linearlised Hertzian contact stiffness [N/m]

$m_{T1} =$ Effective track mass for P_1 calculation [kg]

$m_u =$ Unsprung mass [kg]

$m_{T2} =$ Effective track mass for P_2 calculation [kg]

$k_{T2} =$ Equivalent track mass for P_2 calculation [N/m]

$c_T =$ Equivalent track damping for P_2 calculation [Ns/m]

Alias Equation

$$P \approx P_0 + \lambda 2\alpha v \sqrt{k m_u}$$ **Equation (2.5)**

Where:

$\lambda =$ Dimensionless factor depending on the track damping

$k =$ Track stiffness [N/m]

P_1 forces represented in this model, which generally give rise to high frequencies (greater than 100 Hz), are due to wheel/rail interaction on the Hertzian contact spring (or stiffness). The combination of motion of the wheel (unsprung mass) and rail on the ballast spring gives rise to the P_2 forces, which generally produce lower frequencies (less than 50 Hz) (QR 1998b). The effects of these dynamic forces on the track structure are outlined in Section 2.2.2, and the amplification of these dynamic loadings due to misaligned welds is discussed in Sections 2.2.3 and 2.2.4.

All structures are characterised by their frequency response function which is governed by mass, damping and stiffness. These parameters determine the amplitude of the structure, in other words those frequencies in which the structure likely to vibrate. These frequencies can be largely amplified by the presence of track irregularities; the irregularities will provide excitation of the structure to which the structure will respond. If the loads contain matching frequency components to the natural frequency of the structure, large dynamic amplifications may occur. The general term used for this is resonance (Grassie 1992).

The effect of resonance in track can be detrimental to the life of track components. Individual track components respond differently to the passing of rollingstock and its applied forces. The following section details the effects of such forces on the track structure.

2.2.2 EFFECT OF DYNAMIC IMPACTS ON THE TRACK STRUCTURE

The work of Jenkins and his colleagues at BR in the 1970s (Knothe and Grassie 1993) arose from the need to understand why fatigue cracks propagating from bolt holes at the rail ends, had become more prevalent after running electric locomotives at speeds over 160 km/h on the BR West Coast Main Line. The mathematical model not only demonstrated that impacts associated with movements of the wheel and rail on the contact stiffness were responsible, but also that a satisfactory treatment was to reduce the unsprung mass of the offending locomotives using wheels with resiliently supported rims (Grassie 1996).

There are at least four (4) dynamic problems with the existing track structure caused by raising train speeds. Firstly, increased speed brings about impacts and vibrations on turnout structures. Secondly, much attention needs to be paid to jointed tracks and welded rail joints on the speed-raised lines, because the short-wavelength irregularities on the welded rail may lead to intense wheel-rail dynamic effects at higher speeds. The third problem lays in the bridge-subgrade transition sections. When a train passes through these sections at high speed, the dynamic wheel loads will fluctuate and the vehicles will respond in such a way as to influence the riding comfort. This is because the track stiffness and deformation are different from the supporting conditions on the bridge and on the sub-grade. Last, the prominent problem of the effect of wheel flats on track can be increased at higher speeds (Grassie 1996).

The general response of the vehicle to track geometry irregularities is the primary dynamic issue. However, there are without doubt, other dynamic problems originating from other defects which are not discussed in this thesis. High frequency dynamic loads give rise to several problems with components of the track (refer to Section 2.5). The high frequency P_1 force is important as far as wheel/rail contact is concerned. This can cause plastic flow of the rail steel usually found almost on top of a weld's centreline. P_1 forces, however, are not detrimental as far as rail and sleeper strains are concerned because the inertia of the rail ensures these high frequencies forces are not transmitted to the underlying track structure.

P_2 forces, on the other hand, are very important as far as rail and sleepers are concerned, as well as the ballast itself as the wheel and rail mass oscillates on its stiffness (refer to Section 2.5) (Jenkins, Stephenson et al. 1974).

To simplify the effects and initiation source of such forces, the cause, the symptoms, how they may be diagnosed and the remedy have been summarised in Table 2.1.

The response of track to defects and irregularities can also be calculated using numerous dynamic models. In fact, in the last 20 years there has been a greater interest in applying mathematical models to understand and perhaps even solve practical problems (Knothe and Grassie 1993).

Table 2.1 Vertical Track Forces (Shelley and Williams 1990)

CAUSE	FORCE	SYMPTOM	DIAGNOSIS	REMEDY
Impact at Rail Welds	$P_1r + P_2r$ [1]	Rail fatigue/failure Corrugations Pad degradation Sleeper cracking/movement Ballast degradation Weld fatigue	Ultrasonic inspections Manual inspections	Weld straightening Rail grinding Lower unsprung mass Lighter axle loads
Vehicle/Track Interaction	Quasi Static Dynamic Forces (D)	Track geometry deterioration Rail failure/fatigue Ballast failure/degradation Subgrade failure/degradation	Track recording car Ultrasonic inspections Manual inspections	Tamping Mud hole rectification Ballast cleaning Ballast regulating Formation/ballast design
Wheel irregularities	$P_1w + P_2w$ [2]	Sleeper cracking Rail breaks Wheel cracks Ballast deterioration	Wheel impact detector	Wheel turning program More frequent inspections
Static	P_0	All of the above	Weighbridge Manual checking	Lighter axle loads No over loading

[1] r = rail

[2] w = wheel

Many railway engineers like Grassie, Jenkins, Zhai and Cai have investigated the various dynamic models available to railway networks. For further details on the subject, refer to Grassie (1993), Jenkins (1974), Zhai and Cai (1997; 2001) published research articles, and Steffens (2004) thesis.

For the purpose of this project, no dynamic modelling was undertaken. Instead an extensive field analysis on the rectification of misaligned welds in track was completed. The results are detailed in Chapter 5.

The following section discusses one of the primary aims of the project: discrete geometric rail surface defects – misaligned welds; their contribution to creating and or propagating continuous rail surface defects and their effect on dynamic loadings.

2.2.3 DYNAMIC FORCES AT WELDS

It is only in recent times that the importance of rail weld geometry has been realised. Dipped/peaked welds must be recognised as very important track irregularities. If welds are allowed to become severely dipped, they can potentially cause derailment or very high impact forces leading to rail fracture and severe ballast, sleeper and sleeper components damage (discussed in Section 2.5).

With the increase in axle loads, the presence of dipped welds has become an important safety issue. The unsprung mass of vehicles can cause significant variation in wheel load; dipped welds in track commonly accentuate this motion. This vibration can be further accentuated when the weld passing frequency is such as to build up resonant motion of the body on its springs (refer to Section 2.2.1).

The dynamic P_2 loads imposed by the vehicle on the track at welds can be over three (3) times the static axle load (Figure 2.2) as shown by the experiments carried out by Australian National in 1985/86 (Shelley and Williams 1990).

As shown by the Jenkins' equation (Equation 2.4), P_2 forces are sensitive to a few factors; these are:

v = Train speed

$\sqrt{m_u}$ = Effective unsprung mass

2α = Effective dip angle at the weld

To maintain adequate levels of P_2 type forces when increasing the axle loads of vehicles requires one of the following:

- Reduction in speed, generally not feasible;
- Reduction in the effective change of angle at welds through weld straightening and grinding (refer to Section 2.6); or
- Reduction of unsprung mass of the vehicle.

International researchers have analysed the wheel/rail interaction combined with the detrimental effects of dynamic forces on track due to the increasing speeds and axle loads. A number of studies are discussed below.

A study conducted in China supported the importance of keeping the rising vehicle speed under control. Chai and Zhai (1997) researched the already well studied area of vehicle and track interaction for several years. With the increasing demand for high speed and heavy haul transportation in the Chinese railways, the scope of the research was to develop a new mathematical model to investigate the dynamic effects at the wheel/rail interfaces on typical Chinese mainline tracks. They developed a model called VICT (vertical interaction between cars and track) which was validated by field experiments in the Chinese mainline tracks. The simulation of a train passing a rail weld can demonstrate the application of the VICT model. Figure 2.2 shows the predicted response of a passenger train running at a range of speeds through a typical dipped weld (Zhai and Cai 1997).

The data plotted in Figure 2.2 illustrates how the two peaks forces, P_1 and P_2, of the wheel/rail impact at the weld, increase rapidly with increasing speed. It is obvious then that P_1 and P_2 impact forces are proportional to the increase in speed of the passing vehicle. However, it must be noted that this is only true for certain defect geometry (eg. a ramp).

Figure 2.2 Simulated Dynamic Effect of a Typical Weld (Zhai and Cai 1997)

This is consistent with the well-known fact that wheel/rail dynamic interaction due to wheel or rail irregularities generally will intensify as the train speed increases. It is also important to illustrate that dynamic forces are related to any increase of unsprung mass of the vehicle, as shown in Figure 2.3.

The figure indicates that the increase of P_2 force is more pronounced that in the P_1 force especially when the unsprung mass is greater than 5000 kg (Zhai and Cai 1997).

It has been demonstrated by many researchers that a significant portion of the P_2 force is transmitted to the track formation and is a primary damaging source to adjacent sleepers and the underlying ballast (Shenton 1978). The effect of dynamic forces on track components degradation is detailed in Section 2.5.

The current Chinese standard for rail weld irregularities is that the ordinate of concavity or convexity (peaked or dipped weld) should be less than 0.3 mm in the 1 m length range, however, dynamic analysis shows that the dynamic effects of such irregularities on track components are relatively small if a train does not run at very high speeds (Zhai and Sun 1994). On the other hand, there is a general trend to increase train speed of railway transportation all over the world causing much larger dynamic effects at these irregularities (Zhai, Cai et al. 2001).

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

Figure 2.3 Simulated Effect of Unsprung Mass on P_1 and P_2 Forces (Zhai and Cai 1997)

A further study (Zhai, Cai et al. 2001) illustrated that irregularities of the form shown in Figure 2.4 were very common in their continuously welded rail (CWR) track both in Japan and in the Chinese railway lines. δ_1 represents the overall vertical displacement over 1 m length rail section, δ_2 corresponds to the localised dip/peak at the weld and λ symbolises the length of the rail heat-affected-zone.

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

Figure 2.4 Model of Irregularity on a Rail Weld (Zhai, Cai et al. 2001)

If $\delta_2 > 0.2$ mm in Figure 2.4, the wheel may lose contact with the rail for a very short time and then exert a large impact on the rail, which is harmful to all of the track components.

The short-wavelength irregularities produce much larger dynamic forces than long-wavelength irregularities. It is necessary to restrict the concavity or convexity of welds with short-wavelength to avoid worsening of all track components due to these dynamic effects near the defect (Zhai, Cai et al. 2001).

An additional study conducted by Australian National in Australia, highlighted the relationship between faster and heavier trains with the increase in P_2 forces at welds and increase of deterioration of track components due to this (Shelley and Williams 1990). This supports the many other studies conducted around the world on the relationship between speed and P_2 type dynamic forces, as shown in Figure 2.2.

It was identified by Shelley and Williams (1990) that the P_2 forces exerted by the locomotives with high unsprung mass over the Australian National network were the cause of long-wave rail deformation (corrugation) problems. These deformations in time spread along the rail away from the welds in both directions at wavelengths associated with the P_2 force frequency. The study also demonstrated that P_2 type impact forces at dipped welds were found to be the most likely cause of ballast breakdown into smooth “river pebble” type shape. This breakdown not only caused the ballast to loose its load bearing capacity but the abrasion causes drainage problems at dipped welds.

It is seen in Figure 2.5 that while the effect of the ballast density on the P_2 force is insignificant, the vibration level in the ballast is largely reduced as the ballast density increases. This illustrated the importance of maintaining a firm ballast layer below the track in order to reduce the vibration level in the ballast, and ultimately in the subgrade (Zhai, Cai et al. 2001). On the other hand, if the ballast layer has deteriorated due to poor maintenance and high dynamic impact, the pumping of a mixture of water and fines will cause rapid deterioration of timber sleepers. Concrete sleepers will also degrade faster due to the P_2 impacts, which will initiate cracking of the sleeper (Shelley and Williams 1990).

Figure 2.5 Simulated Effect of Ballast Density on Ballast Vibration Level and P_2 Force (Zhai and Cai 1997)

2.2.4 DYNAMIC EFFECT OF WELD MISALIGNMENTS

All shapes of poor welds must be considered, as all will generate dynamic loadings with the passing of rollingstock. Figure 2.6 shows an example of load distribution as a function of time during wheel passage over a poor weld.

Figure 2.6 Dynamic Wheel Load during Passage over a Poor Weld (Esveld 2001)

The sharp peak in Figure 2.6 is much more pronounced than in Figure 2.2 and represents the P_1 force mentioned earlier; it has a local influence on the wheel/rail contact stress, internal rail stresses and consequently internal rail defects. Following that peak is the second, much broader, P_2 force peak which penetrates the whole track structure (Esveld 2001).

Mutton and Alvarez (2003) agreed with Esveld (2001) and showed that the dynamic impact factor of these forces will be significantly increased with the increase of vehicle speed for dips and peaked welds, as represented in Figure 2.7.

Figure 2.7 Dynamic Impact Factor Vs Train Speed – tangent track (Esveld 2001)

Welds can become dipped due to plastic deformation occurring at the weld depending on the loads it experiences (Frederick 1978). If the rail profile is rough, the dynamic forces will be higher and the localised plastic deformation at the weld will be higher leading to an increase of dip. Two types of rail irregularity are important in creating dynamic loads: continuous and discrete defects. Long wave irregularities are spread over several metres and create P_2 forces while discrete irregularities over a few hundred (100) mm create P_1 type forces. These latter type of irregularity may rise from inadequate smoothing of the weld profile or from differential settlement (Shelley and Williams 1990).

As discussed in Section 2.2, the P_2 dynamic impacts are closely proportional to the speed of the passing vehicle, to the unsprung mass of the vehicle and the change of angle of the weld. A study conducted at QR in 1998 verified the relationship of these parameters to the dynamic impacts on the track (QR 1998b).

A section of track on the Queensland Rail network, the North Coast Line, was selected to be part of QR's test site and three different defects were manufactured to re-create in-situ irregularities. The three purpose-made dipped welds had a target rail dip greater than the maximum allowed dip of 3 mm over 1 m length. The final defect angles were more severe than specified. They were classified as follows:

Defect A $2\alpha =$ 0.0193 rad

Defect B $2\alpha =$ 0.0200 rad

Defect C $2\alpha =$ 0.0276 rad

A range of vehicles at different speeds passed over the test site and the results have been summarised in Table 2.2.

The study was carried out to validate the limit for P_2 type forces on track. The limit for P_2 forces, in 1998, was 200 kN for a rail dip of 0.012 radians (3 mm over 1 m of rail length) in both rails. This limit was selected on the basis of theoretical calculations only (see Jenkins Equation 2.4). Confirmation of this limit by on track testing was never performed due to the difficulty and cost of field testing.

Table 2.2 Vertical Forces P_2 Vs Speed and Axle Load (QR 1998b)

---

* EMD – InterCity Express (ICE) Unsprung mass = 580 kg; Axle = 12.50 tal

^ TTT – Tilt Train Unsprung mass = 736 kg; Axle = 11.15 tal

‘ PCZY(G) – Freight Container Wagon Unsprung mass = 750 kg; Axle = 20 tal

It is obvious from the results in Table 2.2 that for constant speed and unsprung mass, the dynamic impact of P_2 forces increases with the greater change of angle (i.e. greater dip). It is apparent that with an increase of speed, greater P_2 type forces will impact the track given the same axle load and defect.

Standards utilised by different railway networks to control the degree of dips of new or old welds in track allow different tolerances depending on the use of the railway lines, risk assessments and maintenance costs.

The Civil Engineering Track Standards (CETS) (QR 2001a), utilised by QR has a tight quality assurance checklist to certify the optimal alignment of welds. On completion of grinding a weld, the weld is required to be re-checked for alignment, which must be within the tolerances specified in Figure 2.8 and Figure 2.9. Welds that do not comply with the stipulated tolerances must be reground or removed and re-welded so that the required tolerances are achieved.

Figure 2.8 Weld Misalignment Tolerance in Vertical Plane (peak) (QR 2001a)

Figure 2.9 Weld Misalignment Tolerance in Vertical Plane (dip) (QR 2001a)

Similarly, other railway networks (RIC 2003) follow the same tolerance limits for vertical weld misalignments. The risk of having irregularities at welds is very high to both safety of passenger and freight vehicles and damage to other components.

It is also important to maintain these defects within the recommended limits to minimise the risk of accidents and to reduce the track degradation rate and therefore increase the service life of track components.

2.3 DISCRETE GEOMETRIC RAIL SURFACE DEFECTS

Discrete rail surface defects are generally referred as localised geometric irregularities on the surface of the rail, such as dipped and peaked welds. The degree of defect misalignment will give rise to a nominal dynamic impact which will then accelerate, slightly or more significantly over time, the rate of degradation of the track (refer to Section 2.2.2). It is important to understand the causes and the consequences of having discrete defects in track.

Continuous welded rail (CWR) has reduced the high maintenance requirements normally associated with jointed track. When combined with other improvements in track design and maintenance procedures, increased rail life, as well as the life of other components is achieved.

The following sections will outline the types of welds used in track, their effect on the creation of new and propagation of existing defects and their effect on dynamic loadings.

2.3.1 WELDS

Historically, the track structure consisted of the rail ends being jointed together mechanically with a gap between the rails to allow thermal expansion in summer. These joints weaken the track structurally, increase the track maintenance cost and power consumption of the running train (Cope 1993).

Factors like increasing train frequency, higher axle loads, and higher train speeds have resulted in an increase in track loads and the associated stresses. Fishplated rail joints exhibit considerable impact forces when the wheel passes the gap of the joint. CWR track avoids such weak points, leading to higher reliability and safety of the track. The use of CWR track not only reduces the track maintenance cost, but also increases the life cycle of the track components. Therefore, the use of the CWR track has increased consistently worldwide (Lim, Park et al. 2003).

However, it is important to remember that if the rail lengths are not correctly aligned prior to welding, both vertically and horizontally, the final outcome will result in the creation of a much localised geometric defect. A range of processes are used to weld lengths of rail; they can be divided into two main areas of operation: depot welding and site welding.

Depot, or workshop, welding consists of flash-butt welding processes (FBW), which enables longer lengths of rail to be welded together to specified lengths. Depot welding tends to produce fewer irregularities at welds as the welding process is completed in a more controlled environment. This, however, does not imply that welds constructed in track are all defective.

Two types of site welding processes are widely used: the alumino-thermic welding of long welded rail (LWR) strings on site to form CWR. Other site welding processes are used, but the most cost-efficient method to join rail on site is still the alumino-thermic weld (Esveld 2001).

The following section describes in more details the process involved with both flash-butt and alumino-thermic rail welding.

2.3.2 TYPES OF WELDS

The flash-butt welding, or electrical resistance welding principle, characterised by current, travel and pressure is shown in Figure 2.10. After evenly flashing of both rail end sections, preheating commences. Here the energy input should be high and the flashing time short. The heat input should be uniform throughout the cross-section. At the end of the preheating phase the temperature, right at the joint should drop abruptly from a high level in towards the rail (Esveld 2001).

The subsequent flashing should be done progressively at an increasing travel rate and with growing current. In this way metal vapour is produced which protects the abutting surface against oxidation, thus preventing the formation of non-metallic inclusions (Frederick 1978).

Figure 2.10 Welding Process (Esveld 2001)

It is critical to obtain straight welds when producing new welds. As described in Section 2.2.4, the greater the degree of dip (change in angle) of a weld, the greater will be the dynamic impacts on to the rail.

If the flash butt machine produces welds with an angular irregularity, it is possible to correct this to a large degree by three-point bending using a hydraulic ram. However, it is important to remember to let the weld cool prior to performing corrective work on new welds. For instance, in short welding lines, the weld will still be hot when leaving the bending machine. The head will be hotter than the foot of the rail due to its slower rate of cooling; as a result the rail weld will dip as it cools after it has left the line. If grinding was performed on a hot weld to smooth the geometry, it is possible to remove too much material and after cooling and contracting, creating a permanent dip.

These problems indicate the need to produce straight welds with a smooth top in cold conditions (Frederick 1978).

Thermit welding is a welding process that produces coalescence of metals by heating them with superheated liquid metal from a chemical reaction between a metal oxide and aluminium with or without the application of pressure (Figure 2.11).

Figure 2.11 Thermit Weld (QR 2000)

The parts to be welded together are aligned and enclosed in a sand mould with a defined gap between the rail faces and preheated to temperatures, which are suitable for both the materials and the process. The parts are then welded together by allowing the molten steel, produced by the reducing effect of the aluminium on the heavy metal oxide, to lower into the mould. The process is governed by the following chemical reaction included in Figure 2.12 (Esveld 2001).

The alumino-thermic mixture is ignited in a high refractory crucible using a special igniter. After the exothermic reaction, lasting a few seconds, approximately equal amounts of molten steel and fluid Al_2O_3 are separated at a temperature of about 2400 ^{0}C (as shown in Figure 2.12). The thermit iron obtained from such a reaction is, however, too soft for practical use, and therefore, steel-forming alloying additions are added to the thermit mixture to harden and improve wear resistance, while cold metal (mild steel) reduces the reaction temperature and improves the steel yield (Esveld 2001).

Figure 2.12 Thermit Reaction (Esveld 2001)

After solidification, the excess weld metal required to compensate for shrinkage, can be removed almost completely in the region of the rail head while still red hot. This is normally done with a manual grinding machine.

As investigated by Mutton and Jeffs (1992), alumino-thermic welds are responsible for over 50% of all defects detected during in-track ultrasonic inspections. The thermit process is both a casting and a fusion welding process and, as such, is dependant on control of temperature in order to produce a sound, defect-free weld (both steel casting temperature and rail-end pre-heat temperature). Lack of pre-heat (for example incorrect gas pressure) or low steel temperature (for example long tapping time) can result in a poor quality weld (lack of fusion, shrinkage defects).

In addition, to obtain straight alumino-thermic welds requires a great deal of care in the setting up of the weld. The rail ends are typically set 1 mm high (over a 1 m chord) before welding since thermal contraction of the head occurs later than in the foot and produces a downward deflection which should then leave a level weld profile. However, the behaviour in service of these welds is very erratic. After one month of passing traffic up to 0.6 mm in dip has been measured over a 1.5 m section (Frederick 1978).

Factors that contribute to rail failure include the presence of weld defects when casting, high residual stress levels, variable metallurgical quality and mechanical properties (eg Hardness).

Corrective measures that may lead to improved performance, especially of alumino-thermic welds include:

- Post-weld thermal treatments to reduce residual stress levels and improve metallurgical quality;
- Alternative collar designs to reduce the incident of weld defects; and
- Improved surface quality through the use of alternative mould materials (Mutton and Moller 1994)

2.3.3 INITIATION AND/OR PROPAGATION OF CONTINUOUS GEOMETRIC DEFECTS DUE TO POOR WELDS

The presence of poor welds in track generating high dynamic loadings has been identified as a possible initiator of continuous rail surface irregularities, such as corrugation. As part of this literature review, corrugation due to poor welds is briefly investigated.

Continuous rail surface defects correspond to a repetitive rail misalignment (i.e. poor vertical alignment). Such defects may induce periodic dynamic impact onto the rail head creating wear patterns which result in a wavy-like deformation of the rail. Continuous rail surface defects include defects such as corrugation, rail contact fatigue, and more.

Initiation causes of continuous defects range from the presence of localised geometric defects on the rail surface, which exacerbate the vibration of rollingstock creating higher dynamic impacts onto the rail, to the presence of wheel defects, which creates small cracks on the running surface.

The rail is initially uncorrugated, but the profile has components of roughness, and inevitably, some irregularities are larger than others. This 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, thereby modifying the initial profile.

Provided sufficient traffic passes over the site at a similar speed, the wavelength at which the dynamic load varies is similar from one train to another. The same irregularities excite each train, and the damage caused by one train tends to exacerbate vibration of subsequent trains, leading to further damage at a specific wavelength (Grassie and Kalousek 1993).

Grassie and Kalousek (1993) reviewed over 40 references and published a paper which summarised the work that was undertaken to understand the causes and characteristics of corrugated rail. Based on their experience, corrugations were classified into six groups based on differences in wavelength-fixing and damage-mechanisms. These are listed in Appendix B. However, corrugation can be simply classified in two groups: short and long pitch corrugation.

The type of corrugation that is most relevant to this study as it propagates from welds, joints and other discrete railhead geometric irregularities is long-pitch corrugation (Grassie and Kalousek 1993). Long-pitch corrugation is characterised by depressions in the running surface which are more or less pronounced and uneven in relation to an ideal rectilinear profile (Figure 2.13). The wavelength varies between 200 and 300 mm (Grassie and Kalousek 1993) or 200-1500 mm (Clark 1984). The ridge-to-valley depth can reach 5 mm in severe cases and is generally associated with heavy haul lines, where there are high wheel loads (in excess of 15 tonnes), unit trains and low, consistent speeds.

At corrugation sites, the ballast around the sleepers can be much disturbed due to high dynamic loads and excessive sleeper vibration (refer to Section 2.5). This can lead to the crushing of the ballast stones under the vibration of the sleepers causing pumping of the ballast which generally leads to a loss of geometry and higher degradation rate of the track (Kalousek 1989). It’s therefore important to reduce the magnitude, or remove altogether, weld misalignments by straightening the rail or grinding the rail head to minimise deterioration of all track components.

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

Figure 2.13 Long-pitch Corrugation (QR 1998a)

There are different treatments for the different types of corrugations. Rail grinding is used to remove existing corrugation and to re-profile the rails transversely. The use of a lubricant on the railhead which modifies the friction characteristics between wheel and rail, in particular to make the sliding co-efficient of friction greater than the limited static co-efficient thereby eliminating a fundamental requirement of stick-slip vibration (Grassie, Gregory et al. 1982).

The practical treatment for long-pitch corrugation is to select a sufficiently hard rail steel and to hope that railhead irregularities are sufficiently small to maintain the contact force below the level which can be beared by the rail. The treatment most commonly adopted for existing long-pitch corrugation is to grind the rail and to straighten the welds, thereby minimising the initial roughness which excites vibration of the vehicle on the track stiffness and gives rise to high dynamic loads (Grassie, Gregory et al. 1982).

Nevertheless, it is important to fully understand all of the causes that induce rail corrugation, in order to remove the source of the problem and not just the consequences.

2.4 WHY REMOVE DISCRETE GEOMETRIC DEFECTS

From a mechanical point of view, the train vehicle and the rail track can be treated as two separate dynamic systems. However, they are dynamically coupled as an integral entity at the point of wheel/rail contact where the common source of excitation to both systems takes place. Severe dynamic disturbances at the wheel/rail interface occur when geometric irregularities exist, either along the rail head surface, such as at rail joints, dipped and peaked welds and rail corrugation, or around the wheel circumference, such as wheel shells and wheel flats (Zhai, Cai et al. 2001).

These enlarged dynamic forces may lead to increased maintenance costs for both infrastructure and rollingstock administration. In addition, rolling noise is an environmental problem of growing concern that has called for legislation regarding acceptable noise levels (Esveld 2001).

The severity of impact loading depends on the severity of the rail surface irregularity. In most cases, welds that are slightly peaked at installation develop localised batter and spalling in the heat affected zone. However, dynamic forces induced by rollingstock can be seen to affect the track deterioration away from the weld in the direction of travel. Dipped welds perform differently; the constant pounding of the wheel-sets create localised track degradation, leading to ballast breakdown near a dipped weld. This will then result into the loss of track geometry in the form of bad top-and-line and consequent increase in impact force (Mutton and Alvarez 2003).

The existence of a defective spot on the rail surface such as wheel burns and shelling, gives rise to wheel impact forces on the rail, which in turn, causes the existing defect to grow and may initiate other types of irregularities, resulting in a “vicious circle”.

These types of defects are easily detected visually and are dealt with either by replacing the rail or weld repair depending on the economics of the situation. Minimising the presence of rail surface irregularities is a common goal to all railway networks to ensure low maintenance costs, higher safety, and most of all better quality of track.

2.5 TRACK DEGRADATION

The purpose of the track is to support and guide rollingstock and it does this by transferring the loads to the formation. Conventional track systems consist of a discrete elements made up of rail, sleepers, and ballast (Figure 2.14). The ideal track is the one in which the total track structure from the formation through the ballast up to the rail sleeper fastening assembly is free of discontinuities entirely. It is obvious that these conditions do not exist (Holm 1978).

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

Figure 2.14 Conventional Track Structure (Esveld 2001)

Track defects such as poor geometry quality welds, corrugation and other rail surface irregularities are widely spread over all railway networks. They are very detrimental to all track components due to the impact stresses that they impose onto each individual track element. These irregularities will cause hunting of the rollingstock, noise emission, poor vehicle ride and accelerate the degradation of the track components (Esveld 2001).

Track geometry must be maintained to a standard to ensure safety and comfort of all moving trains (i.e. passenger and freight). Track parameters that promote retention of good geometry include (Martin 2003):

- Good quality and clean ballast (including depth and covering layer of sub-ballast); this will maintain good drainage and support to the above track structure.
- Good formation properties; providing a well levelled surface to support the above track structure.

- Good sleeper support with minimal stiffness changes (level crossings, bridge ends etc)
- Good track quality; consisting of low rail surface defects such as continuous and discrete irregularities.
- Good contact band to provide better ride comfort to passenger trains, reduced wear at the wheel/rail interface.

If these parameter are not maintained it may result in more rapid track degradation. Figure 2.15 illustrates the influence of track geometry, axle load and speed on the vertical dynamic component of force exerted on the track.

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

Figure 2.15 Effect of Geometrical Quality (Shelley and Williams 1990)

As previously mentioned, the track structure is part of a complex dynamic system and as such the loadings it experiences are directly dependent upon the tolerances to which it was built. If a track were built with perfectly smooth rail, uniform ballast and a sub-grade of uniform strength, the dynamic factor on the static load would be very small, and the track structure would be much lighter. The fact that rails are not perfectly smooth or straight, ballast is not uniform, and the sub-grade properties vary significantly causes large dynamic forces to be imposed on the track structure as a result of vehicle/track interaction (Holm 1978).

One of the main influences on track forces is the vehicle response to the geometry of the track. Figure 2.15 illustrates how better quality track (i.e. geometry quality = 1) endures smaller dynamic impacts. It is essentially these forces that are responsible for the deterioration in the quality of track geometry (Shelley and Williams 1990).

The track geometry can also be significantly affected by formation failure under the action of heavier axle loads. Well-drained ballast of sufficient depth is essential to prevent formation failure. Without both, formation and ballast will mix, drainage will be lost and sleeper deterioration will be rapid (Shelley and Williams 1990). The effects of these forces on track components are detailed in the next sections and summarised in Table C in Appendix C.

In essence, to maintain good track geometry it is essential to determine the deterioration rate and the factors that influence it.

2.5.1 BALLAST

The condition of the formation is one of the major factors bearing upon the maintenance of a railway to an adequate standard. If high P_2 dynamic forces are present and the quality of the formation is not to standards, the track structure will incur rapid deterioration (refer to Section 2.2).

The modern ballast section consists of ballast depth below the underside of the sleeper ranging from 150-375 mm at the time of construction (Figure 2.16). Ballast shoulders should be a minimum of 300 mm, and the ballast stones must be clean, angular, hard and well graded. Inadequate shoulder widths for a section of track with CWR can cause risk of derailments and this situation must not be allowed to develop. Variable ballast depths, particularly over short distances can cause uneven settlement and track geometry will need to be restored with maintenance work at shorter intervals. These situations in conjunction with rail irregularities will increase the degradation of the remaining track components.

Figure 2.16 Ballast Configurations in Track (QR 2001a)

Ballast is required to perform several important functions within the track structure:

- Provide a firm, even bearing for the sleepers and to distribute the loads imposed by traffic evenly over the formation;
- Reduce pressures from the sleeper bearing area to acceptable stress levels for the underlying sub-ballast and subgrade materials;
- Provide a resilient bed or cushion below the sleepers and absorb some of the impact from the passage of trains over the track;
- Prevent lateral movement of the track by filling the cribs or boxes between the sleepers, providing a shoulder at the ends of the sleepers and by friction on the base and sides of the sleepers;
- Provides free drainage;
- Prevent longitudinal movement of the track (i.e. rail creep);
- It is easily worked to enable top and line of track to be adjusted or improved without the formation being disturbed (Martin 2003).

As axle loads, speeds and traffic volumes increase, particularly on the heavy haul lines, there may be a need to re-assess the requirements of ballast to withstand these loads without crushing or degrading over long periods of time (Martin 2003).

If axle loads of freight vehicles are increased, the general rate of compaction of ballast as well as the dynamic loads induced by wheel/rail force at rail irregularities, especially at welds, will increase (refer to Section 2.2.3). The dynamic increments will cause greater ballast compaction at the sleeper locations than elsewhere. This will lead to the formation of voids beneath the sleepers and a hollow in the track, which will itself cause a further increase in the dynamic wheel/rail interaction (Frederick 1978).

As well as traffic-induced loads, it should be remembered that maintenance activities also contribute significantly to ballast breakdown. The high capacity tampers used nowadays appear to apply quite a high vibrational loading on ballast (refer to Section 2.6.1). The vibration caused by the squeezing of the ballast when tamping, causes the breakdown of the ballast stones which will cause some loss of the ability of the track to maintain its geometric profile, reduced drainage properties and most likely pumping of the formation during traffic movements. Thus, this process of ballast deterioration will continue and the P_2 type forces will increase the rate of deterioration of track geometry giving increased stresses throughout the track structure (Frederick 1978).

2.5.2 SLEEPERS

In ballasted track the rail rests on and is fastened to the sleepers. Together the rail and sleepers form the main structure of the track. The general functions and requirements that a sleeper must have are:

- To provide support and fixing possibilities for the rail foot and fastenings;
- To sustain rail forces and transfer them uniformly to the ballast;
- To preserve track gauge and rail inclination (Esveld 2001).

These conditions entail that formation and ballast are of good quality and most importantly that weld geometry and other rail irregularities are not severe. However, it is sometimes impossible to maintain an even dissipation of the loads without causing the sleeper to degrade. There is no doubt that discontinuities in sleepers and fastenings have created major problems for railways both in operation and in maintenance.

Until more recent years, sleepers have been predominantly selected from native or imported timbers, both hardwoods and softwoods, mostly untreated. Their material structure allows the sleeper to absorb and then dissipate the dynamic vibrations induced by rollingstock to the ballast and underlaying formation. If the dynamic forces are very large, the dissipation of the impact by the sleeper to the ballast will cause crushing of the stones, which will lead to loss of track geometry and degradation of the sleeper by abrasion (Holm 1978).

Modern railway networks now have a selection of sleeper types that can be chosen from: timber, steel and concrete. As technology progresses, new materials, such as composite and plastics, are utilised to create sleepers with similar structural properties to the more traditional timber, steel and concrete types (Ryan 2000). However, to date, these new types of sleepers have only been placed in track for research purposes.

Steel sleepers have a mass considerably less than timber and rely heavily on the interaction with ballast to provide restraint against track movement in the vertical and horizontal direction. A disadvantage of steel sleepers is that if the dynamic impacts are very large and cause the ballast to crush (refer to Section 2.5.1), steel sleepers would loose their anchorage to the ballast, retain a lower vertical resistance to load impacts and increase the degrading impact forces from the passage of rolling stock (Baggott and Mau 1988).

The advantage of using concrete sleepers is that climatic influences have little effect on the quality and function of the sleeper. Concrete sleepers have a service life much longer than timber or steel sleepers, under certain conditions. An important problem associated with concrete sleepers is the greater susceptibility to dynamic loading due to train loads, which, may give cause to the initiation of cracks and fractures in the sleepers, wear and loosening of the fastenings components (Ryan 2000).

In addition, problems caused by the presence of high dynamic loading can cause sleeper “walking” and “skewing”. The first case occurs primarily around rail welds and joints where the sleepers tend to move along the rail, often actually towards the defect. Skewing occurs when one end of the sleeper moves along the rail relative to the other (Jenkins, Stephenson et al. 1974).

2.5.3 FASTENINGS ASSEMBLY

“Fastening systems” generally include all the components that together form the structural connection between rail and sleeper. Some of the fundamental requirements for performance of a fastening system include the following properties:

- Vertical and horizontal supports or transfer of loads – To absorb the rail forces elastically and transfer them to the sleeper. The vertical clamping force of the rail on the sleeper much be sufficient in all load situations, even in the case of wear, in order to provide the necessary longitudinal resistance to limit the breathing length (expansion and contraction of the rail steel) in CWR rail, to limit gaps in the case of rail fractures and to resist creep;
- To damp vibrations and impacts caused by traffic as much as possible;
- To insulate the rail;
- Lateral support of rails – To retain the track gauge and rail inclination within certain tolerances (Ryan 2000).

Depending on the axle loadings and gross annual tonnages for the lines, the fastening can play a major part in the rate of deterioration of the track. A fastener is affected by many factors of varying intensity. Factors such as sleeper type, traffic volumes, speed and loadings, track curvature and gradient, ambient temperatures, track stability, track condition, vandalism, to name a few, impact on the service life of the fastener. In the context of this thesis, the shaking and vibration from impact of wheels on misaligned welds can damage or loosen fasteners, which can then cause the weld defect to deteriorate, accelerating overall degradation of the track. Figure 2.17 demonstrates the influence of dysfunctional rail fastenings on the rail acceleration and the rail deflection response.

The results indicate that there is nearly a 30% increase in the rail acceleration and 60-70% increase in the rail displacement due to damaged rail fastenings. It is imperative that any damaged track components should be promptly repaired or replaced to prevent further damage to the track due to the intensified dynamic track response (Zhai and Cai 1997).

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

Figure 2.17 Simulated Effect of Damaged Fastening on the Rail Vibration (Zhai and Cai 1997)

2.6 MAINTENANCE PROGRAMS

In order to meet competition from other modes of transport, there is an increasing demand upon railways to improve reliability, efficiency and transit times. The resulting requirements for increase in speed and axle load mean that the demands made upon the track are becoming heavier. In order to provide cost-efficient track to meet this need in the future, it is essential to be able to improve the methods by which the performance of the track is monitored and to have reliable methods of predicting maintenance requirements and planning programs (Esveld 2001).

The safe and economical operating conditions for railways vehicles are intimately related to the standard geometry control applied to the rail track structure. Deviations in the vertical and horizontal alignment of the track structure provide inputs to the vehicle motion, the significance of which is dependent on the vehicle type and speed. As discussed previously, relatively small geometry variations repeated at regular intervals can be more severe in their effect than larger isolated geometry irregularities (O'Rourke and Waddington 1981).

Some of the factors affecting the degradation of the track include:

- The basic material properties of the track including sleepers, ballast and formation;
- The distribution of imposed loading throughout the structure;
- Dynamic and vibration effects; and
- Environmental changes (seasonal changes, daily weather changes, location).

The track meets quality and reliability (i.e. safety and punctuality) standards at minimum cost. The quality of the infrastructure (rail, ballast, sleepers, etc) has a major influence on all these factors, so it is important to maintain the infrastructure to an adequate level of quality. The track maintenance activities can be divided into two categories: maintenance and renewal activities. The operations are, in general, scheduled on a demand basis; track recording data, visual inspections and financial-economic data determine the maintenance requirements for individual track sections.

Maintenance is very expensive and budgets for maintenance are always under pressure. For instance, the Dutch government drastically reduced the amount of money spent on maintenance at the end of the nineties with major consequences on the reliability (in particular punctuality) of the railway system a few years later. So it is important to reduce the maintenance costs without reducing maintenance itself (Budai, Huisman et al. 2004).

A cost benefit analysis was not part of the scope of this project, however further investigation should be undertaken to fully quantify the benefits of reducing maintenance cost following the recommendations of this thesis.

Track maintenance can be divided according to the various aspects of the track; these are:

- Rail geometry
- Track geometry
- Track structure
- Ballast bed
- Level crossings
- Miscellaneous

In addition, maintenance of track can also be classified into incidental and systematic maintenance. Incidental track maintenance includes any activity used to repair local irregularities whilst systematic track maintenance is carried out as a matter of course mainly with heavy track maintenance machines.

Incidental track maintenance operations undertaken to repair local defects is generally carried out manually or with the help of small machines. The most important manual work consists in:

- Levelling and tamping using vibrating compactors or tamping tines; defects in track top level are generally corrected by using jacks to raise the track and the filling the space with new ballast material.
- Measured shovel ballast packing; not widely used as it is a very labour-intensive method.
- Rectifying track gauge.

Systematic track maintenance is generally carried out as much as possible by mechanised machines, such as:

- Tamping machines; to correct track level, cant and alignment.
- Track stabiliser; to compact and stabilise the ballast.
- Rail grinding machines; to remove or relieve discrete and continuous rail surface irregularities.
- Rail straightening machines; to straighten poor welds.
- Ballast cleaner machines; to clean the ballast bed.

Only tamping, rail grinding and weld straightening operations will be discussed in the following three sections as they were the only track maintenance activities conducted as part of the experimental stage of this thesis.

2.6.1 TRACK MAINTENANCE – CYCLE TAMPING

The vertical settlement of rail track leading to a loss of top is a cumulative effect of permanent deformation in the ballast and formation, as described in Section 2.5.1. Vertical displacement increases with traffic tonnage and the presence of irregularities (refer to Section 2.2.3). Discrete irregularities in the rail can only be relieved by defect removal rail grinding or rail replacement; tamping can reduce the effect of continuous defects, such as longitudinal alignment of the track, by restoring good top (Frederick 1978).

Current practice is to maintain track almost exclusively using tamping machines, which correct level, cant and alignment. The nature of the machines is to lift the track to the desired top and alignment and vibrate ballast under the sleepers to hold it there. Irregularities in the track geometry with a wavelength of up to 20 to 30 m are automatically removed with the tamping machine with the aid of an in-built laser measuring system (Esveld 2001). The tamping machine lifts the track up to the level determined by the measuring system which also positions it laterally; then the ballast under the sleepers is packed using the tamping tines, as shown in Figure 2.18.

Figure 2.19 shows a measured rail profile over a distance with two welds and the temporary effect of tamping on the weld irregularities. It has been shown that although tamping temporarily improves the smoothness of the profile, traffic soon re-establishes the weld profile similar to the original, as shown in Figure 2.20 (Shenton 1978).

Figure 2.18 Tamping Principle (Esveld 2001)

It is important to remember that the surface and sub-surface of the rail head is subjected to extremely high and complex loads, which give rise to radical changes to the microstructure of the rail steel. A study conducted by Daves and Fisher (2002) showed that after some few cycles, a highly plastified zone is produced on the surface on the rail. Furthermore, they showed that the deformation rate per cycle would slightly decrease after the first 60 cycles. The deformation of the material has to reach some steady state, as otherwise it would be impossible to load the rail millions of times.

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

Figure 2.19 Weld Shapes Pre- and Post-Tamping (Frederick 1978)

When the rail reaches this steady state, it is almost impossible to alter the deformation as it has passed the elastic region of the material. The materials, in this case the rail steel, will return to this steady state following any type of maintenance or vertical alignment remedial work. This is called “rail memory” (Daves and Fischer 2002). Tamping cycles can temporarily relieve the condition (see Figure 2.19 and 2.20), however only a few months after the maintenance program, the vertical rail alignment has returned to its steady position.

Further investigation should be undertaken to fully understand the extent of the permanent rail deformation to minimise the effect of “rail memory”, which would consequently optimise the results of maintenance programs.

Figure 2.20 Effect of Tamping on the Shape of CWR in Service (Frederick 1978)

In addition to “rail memory”, the constant vibration imposed on the ballast by the tamping tines can break the stones. In the long term, this will introduce problems of loss of geometry, increase in settlement, drainage and other issues. This will reduce the efficiency of tamping cycles giving rise to more severe track components problems.

2.6.2 TRACK MAINTENANCE – WELD STRAIGHTENING

The integrity of the rail is threatened by two visible problems which are intimately related:

- Welds of poor geometry, which results in large dynamic impacts from passing vehicles. When fully developed, these become dipped welds (refer to Section 2.2.3; and
- Corrugations in the rail surface which are in actual fact full section deformations propagated directly from the impacts caused by the presence of dipped welds in track (refer to Section 2.3.3).

In “medical terms” when it is realised that dipped welds are the cause and corrugation is the symptom, then it becomes obvious that not only the symptom needs to be treated but prevention needs also to be addressed (Shelley and Williams 1990).

Up until recent years, the straightening machines, used for treatment of welds, and the grinder machines, for treatment of corrugation, have been used separately. Straightening of the welds has always been seen as the last action to extend the life of the track and its components. The capacity of the straightening machine has always been limited due to the use of manual grinder to smooth the peaks after the lift (Shelley and Williams 1990). On the other hand, grinding has been widely used over railway networks; however, the main aim was to relieve the rail from small surface irregularities.

The idea of integrating these two activities into a maintenance concept should be considered by all railway networks.

The concept has a number of advantages that will cause a revolution in track maintenance practices for railway networks; these are listed as follows:

- The treatment of both cause and symptom are packaged into one activity, hence with each maintenance run the overall dynamic input into the track is reduced.
- The effective operational performance of the track is lifted in one operation. This is very important in both getting the track up to standards for present operating conditions as well as looking past this to future operations.
- The effective capacity of the straightening machine is increased by over 50% because it is no longer tied to manual grinders (Shelley and Williams 1990).

HOW DOES WELD STRAIGHTENING WORKS

The underlying principle of weld straightening can be summarised as follows:

Weld straightening will reduce the effect of dynamic loads by removing all geometrical irregularities in the rail at the weld location. This will not only reduce the development and growth of rail corrugation but also reduce the rate of degradation of the geometry and track component quality (refer to Section 2.2).

To ensure the durability of the correction, it is necessary that directly after bending, the sleepers around the weld be tamped. After bending, the excess material and particularly the peak created by the lift of the weld, must be removed by grinding (Figure 2.21).

The crucial factor in assessing the effectiveness of the weld correction is the durability of the result following a period of normal traffic. Many railway networks have utilised weld straightening programs to improve the service life of their track components, but no one has recoded and analysed the achieved results.

Figure 2.21 Straightening, Tamping and grinding

2.6.3 TRACK MAINTENANCE – CYCLE RAIL GRINDING

Irregularities in rail geometry can give rise to high dynamic impacts with passing rollingstock. These geometry defects partly occur during the manufacture of the rails (known as rolling defects), and partly during operation in the form of corrugations, dipped welds and wheel burns. The presence of contact stresses, between the rail and the wheel, are inevitable.

Originally, railway networks used to rail grind following an aggressive, corrective approach. The defects would be allowed to grow before the grinding machines would run through the area, remove a significant amount of metal from the rail head and hopefully remove most surface rail irregularities. Starting in the early 1980s, nationally and internationally, “corrective” grinding started to give way to “maintenance” grinding, also named “preventative” grinding. This latter approach does not allow surface defects to develop to any significant extent, but rather attempts to eliminate the development of these surface defects before they emerge on the rail head (Grassie 1996).

TYPES OF GRINDING

Amongst the “preventative” grinding, there are essentially two types of grinding: profile and longitudinal grinding. Profile grinding goes beyond the basic defect removal approach and addresses the control of the shape of the rail and the associated interaction between the wheel and the rail, to include the wheel/rail contact (Zarembski 1997). Profile grinding is part of railway networks maintenance programs to maintain optimal contact between wheel and rail to achieve the followings:

- Better resistance to wear
- Better resistance to fatigue
- Reduction of noise emission

Longitudinal grinding, although not widely used, seeks to achieve most of the above aims, however its principal purposes is to make the rail:

- More resistant to corrugation development
- To reduce, if not eliminate, the impact forces induced by rail surface irregularities

The aims of longitudinal grinding are some what more difficult to achieve due to the configuration of most grinding machines together with the vertical alignment of track. Due to this, no relevant literature was found on the topic.

CYCLE GRINDING OF POOR WELDS

More recently, correcting surface conditions, such as dipped weld defects, has become the focal point for railway networks. The purpose of rail grinding at welds includes the following:

- Reduction of the potential development of field side defects, particularly at alumino-thermic welds by preventing the contact between the wheel and the field side of the rail; and
- Reduction of the level of rail corrugation which have become of more concern as the axle loads have increased (Marich, Stewart et al. 1994).

Rail grinding produces tangible results, such as less vibration of the track structure, less noise emission, better riding comfort and above all less damage to the track. However, rail grinding is not a miracle cure; it can only remove small defects (less than 0.2 mm in depth) and relieve the more severe ones.

Although rail grinding achieves numerous short and long term improvements, one disadvantage of this operation is the possible worsening effect of dipped welds following the operation. Due to the configuration of the machine, the grinding stones block units tend to follow the vertical alignment of the track and therefore remove metal at welds. However, excess metal removal at dipped welds is not desirable.

HOW DOES CYCLE GRINDING WORK?

Rail grinding consists of a series of grinding motors driving annular grinding stones. The grinding stones are oriented around the rail head at specific, changeable angles, assuring that metal is taken off where necessary. The grinding stones are generally grouped into block units which are pressed on the rail surface in an optimal balance between metal removals, stone type and rail surface condition.

Two variables determine the effect of grinding (Turner 2003):

- The location of the metal removal is given by the angle of the grinding stones;
- The amount of metal removed depends on:
    - The applied stone pressure

    - The speed of the grinding
    - The type of stones
    - The stones blocking system
    - The stones angle of attack
    - The material type (i.e. hardness)

All of the above influence the finished condition of the rail with respect to the surface roughness and facet width.

However, if grinding was coupled with tamping cycles, railway networks will gain numerous benefits, such as:

- Increase in grinding efficiency if the track is freshly tamped prior to cycle grinding. Tamping will restore a good vertical alignment of the rail giving the grinding stones the opportunity to relieve a greater number of surface irregularities.
- Tamping will become more efficient because rail grinding will decrease the dynamic input to the track (Shelley and Williams 1990).

Railway networks should consider the integration of such activities to increase the overall service life of the track and all of its components.

3.0 FIELD TEST SECTION

Much research has been undertaken to understand the complex problems of rail wear and the development of continuous geometric rail surface defects. As discussed in Chapter 2 very little study has been published on the dynamic effects of discrete rail surface defects on the quality and life or the track components and rollingstock.

The primary focus of the present study is to identify the benefits of removing discrete irregularities using current and new technologies (i.e. tamping and straightening respectively). In order to fully comprehend the effectiveness of the individual and combined maintenance operations, a test section had to be selected. This region was divided into smaller *Divisions* which were subjected to different levels of maintenance.

This chapter describes the followings:

- The location of the test region and the reason for choosing it;
- The intervention limits adopted;
- The sub-division of the test region and the monumenting of the welds present in track, and;
- A detail discussion of all of the work completed in each *Division*.

3.1 WHY THE MT ISA LINE (MIL)

The Mt Isa line is one of the oldest railway lines still fully operational as a mixed freight and passenger line in Queensland Rail (QR). The System starts at Stuart on the North Coast Line, 10 km south of Townsville, and services the industrial and rural communities of North West Queensland with all train being hauled by diesel electric locomotives (QR 2001b).

This single line track carries all types of traffic (passenger, freight and mineral) having different traffic tasks. The size of rail varies considerably from one end of the line to the other (refer to Table 3.1).

Table 3.1 Mt Isa Line System

Location	Total Length (km)	Rail Size (kg/m)	Sleeper Type	Speed (km/h)	Traffic (TAL[1])
Stuart to Hughenden	377	47 and 50	Steel	80	20
Hughenden to Cloncurry[2]	392	41	Steel	60	20
Cloncurry to Flynn	100	41	Steel	80	20
Flynn to Mt Isa	98	47	Steel	80	20

[1] tonne axle load

[2] subject to a blanket speed restriction due to the nature of the formation

Due to increased traffic tasks and speed of trains together with the very harsh environmental conditions of the region, the track, especially the 41 kg rail, has sustained considerable degradation. Conventional maintenance activities, such as rail grinding and tamping, help to relieve the track defects, but not remove them.

In order to ascertain the type, quality and quantity of rail geometric defects (i.e. vertically misaligned welds) on the line, a detailed investigation was conducted by QR's Network Access in late 2000. The overall aim of the study was to strengthen the existing track infrastructure, especially the 41 kg rail, by placing a more robust track structure capable of better supporting the existing 20 tonne axle load (TAL) traffic task. This was required for both current and forecast volumes at a level of operational performance and reliability that is within customer expectations whilst further reducing derailments and operating risks.

Regular maintenance work improves the condition of the track for a specific length of time; however it will not remove the cause of the problem. Current maintenance programs (such as cycle tamping, cycle grinding, and lubrication) improve the quality of the track by only relieving the problem. Having a full understanding of this issue, QR decided to explore alternative maintenance activities which focused on rectifying specific identified defects during the investigation, as being part of the principal causes for track degradation. Weld straightening was selected as the preferred alternative maintenance activity to ensure life extension of the 41 kg rail.

3.1.1 INVESTIGATION OF THE MIL

The investigation conducted by the Network Access group raised a number of issues, the most important of which was management of rail defects such as dipped or peaked welds. Passing of rollingstock over poor welds generates destructive dynamic forces that will, over time, loosen fastenings, damage sleepers, crush ballast and overall increase defect growth and rate of track assets deterioration.

The primary focus of the MIL investigation was to identify the quantity and quality of localised defects, focusing primarily on poor welds. Network Infrastructures utilised data recorded by the Track Recording Car (TRC) to gain a general understanding of the conditions of the track. To identify the locations and degree of weld misalignment severity from the TRC data simple estimation tools were used. Assumptions were made regarding the shape of the misaligned welds and the degree of misalignment, for both peaks and dips, was deduced from the accelerometer data recorded by the TRC.

Various sections of track were recognised as areas with significant problems; the most severe sections were highlighted as possible good test sites to monitor the performance of weld straightening.

In addition to the analytical analysis, a limited field survey was conducted by Harsco Track Technology (HTT) to determine the actual in-situ magnitude and frequency of poor welds. Random one kilometre track sections on the MIL were selected and a sample of welds was measured using the standard, calibrated 1 m straight edge.

The records were then plotted against the TRC analysed data (Figure 3.1) to examine if the exceptions used by the TRC records were acceptable to quantify the magnitude and severity of the defects in track.

The X axis in Figure 3.1 indicates the degree of dip/peak in millimetres and the Y axis shows the distribution of weld misalignments. The continuous pink line represents the data collected by the contractors, HTT, while the blue diamonds represent the Track Recording Car data exceptions. The dotted lines are simply the exponential representation of the respective data (i.e. pink is HTT, and blue is TRC data).

Figure 3.1 Weld Distributions – Track Recording Car vs. Harsco Track Technology (Shelley 2002)

It is apparent from the above graph that both methods of identifying quality and quantity of welds follow similar trends when compared to each other. This appears to show that the exceptions used to analyse the TRC data were correctly identified.

However, from the analysis performed by the author, a large dissimilarity between TRC data results and actual field measurements was found. This issue is further discussed in the next section.

3.1.2 TRACK RECORDING CAR DATA

Railway networks tend to rely on Track Recording Car (TRC) data, traffic task (in Mgt) and visual inspections to schedule annual maintenance activities. High values of Track Condition Index (TCI) calculated from the TRC data are symptomatic of poor track quality requiring maintenance operations. Visual signs such as ballast pumping, powder and loss of rail top alignment are other important indicators of poor vertical track geometry.

The most widely used tool for identification of the overall condition of the track is the set of TCI values calculated from the TRC. The TCI values are generated on a kilometre basis as the sum of a number of parameters (i.e. top, twist, gauge and versine) which combined indicate the overall condition of the track. Consequently, TCI is only a general indicator of track roughness. For further information on how to calculate TCI values please refer to the Track Recording Car Manual (QR 1997).

It was anticipated that the effect of discrete irregularities present in track might be able to be identified by isolating and analysing the rail "Top" parameter from the TRC data as well as data from the accelerometer measuring vertical acceleration of the TRC bogie. An accelerometer based reading represents the impact forces that the wheel experiences whilst travelling through rail surface irregularities. Unfortunately, inspection of the accelerometer data from the TRC showed that the peak accelerations corresponded with known misaligned welds only some of the time. The data was not reliable enough to use as a dependable tool for locating misaligned welds and deriving the degree of their misalignment. Consequently, an attempt was made to identify weld misalignments in just the "Top" parameter data.

Most track recording cars record rail Tops in millimetre measurements over a moving baseline of 6.5 metres (QR 1997). The variation is measured centrally over the chord length and to derive the TCI value, left and right readings are averaged to obtain one value per defined section of track.

Table 3.2 summarises the values of track Top parameter recorded with the TRC since June 2001 over the present project's test section. Table 3.3 reviews the short term and long term changes in values of Top parameter (Δ_{Top}) between certain periods defined in Table 3.2.

From the data in Table 3.2, it is possible to see that the short term effects of cycle tamping operations are positive; the Top parameters having been reduced by 30% or more in all *Divisions* when reviewing the changes from June to September 02 in Table 3.3.

When comparing the short and long term effect on the three *Divisions* between June 2003 and June 2004 in Table 3.3 (the period when all the different maintenance interventions occurred in the three *Divisions*), no significant difference in Top alignment values can be identified. In fact, it appears that straightening and cycle grinding had no impact on the overall quality of the track in this time period, as measured by TRC-derived rail Top.

Because of the 6.5m baseline used by the TRC to derive Top, it seems that the Top parameter is too coarse a measure for trying to isolate discrete irregularities. As such it can not identify the effects of maintenance activities on localised defects such as welds.

The only changes in track Top parameters that were reflected in the TRC data were the improvements achieved by cycle tamping on the overall vertical alignment of the track. Tamping has a greater effect on continuous defects with longer wavelengths (refer to Section 2.6.1).

3.1.3 TEST AREA SELECTION

As previously discussed, the principal aim for the MIL investigation was to identify the feasibility of extending the rail life of 41 kg rail. This was achieved by identifying the occurrence and degree of severity of track defects and methods of rectification. From the investigation, it was established that a 150 km section of 41 kg rail track could be targeted by the straightening operation.

The selection for a suitable test area was largely driven by contractual needs to have the RASTIC (RAil STraightening Intrinsically Controlled) rail straightening machine operational for a minimum of 6 hours per day in 2 hour blocks and not driven by the actual track condition. By choosing a section of track on the MIL close to pre-scheduled renewal activities, like concrete relaying and undercutting (ballast cleaning), allowed the straightening project to benefit from the pre-planned long windows of track possession.

Table 3.2 History of Rail Top Parameters

Division / Sub-Part	Dec 01	Mar 02	Jun 02		Sept 02	Dec 02	Feb 03	Jun 03		Sept 03	Dec 03	Mar 04	Jun 04
1/1	14	13	14	Cycle Tamping	10	14	12	14	Cycle Tamping Weld Corrections Cycle Grinding	7	8	10	12
1/2	14	13	13		9	12	12	13		6	8	10	10
2/1	14	13	14		11	14	13	13		7	8	9	10
2/2	14	13	14		11	11	12	12		7	9	9	9
3/1	15	14	16		10	14	13	13		6	8	9	11
3/2	16	15	17		11	13	14	14		7	8	8	11

Table 3.3 Δ (Change in Mean Value)– Short and Long Term Effects of Maintenance Activities on Rail Top Parameters

Division / Sub-Part	Interventions*	Top (mm) Short Term Pre Current Project	Top (mm) Long Term Pre Current Project	Top (mm) Short Term Current Project	Top (mm) Long Term Current Project
		Jun 02 – Sept 02	Jun 02 – Jun 03	Jun 03 – Sept 03	Jun 03 – Jun 04
1/1	T, S, Tr	-4 (T)	0 (T, Tr)	-7 (T, S, T)	-2 (T, S, T, Tr)
1/2	T, S, G, Tr	-4 (T)	0 (T, Tr)	-7 (T, S, T)	-3 (T, S, T, G, Tr)
2/1	T, S, G, Tr	-3 (T)	-1 (T, Tr)	-6 (T, S, T)	-3 (T, S, T, G, Tr)
2/2	T, S, Tr	-3 (T)	-2 (T, Tr)	-5 (T, S, T)	-3 (T, S, T, Tr)
3/1	T, Tr	-6 (T)	-3 (T, Tr)	-7 (T)	-2 (T, Tr)
3/2	T, G, Tr	-6 (T)	-3 (T, Tr)	-7 (T)	-3 (T, G, Tr)

* S = straightening of dips, manual grinding of peaks, T = cycle tamping, G = cycle grinding, Tr = traffic

Track possession simply means that no traffic is allowed over a specific track section during a pre-determined time frame allowing other work activities to move freely over the section. Track possessions must be confirmed with Train Control; possession times will vary on a daily basis depending on the traffic movements over the line. At the end of each possession, traffic is allowed to travel freely over the line.

The section of track that extends from Richmond to Julia Creek (500-650 km; all kilometre pegs are measured from Townsville) was not considered to be the most severe area of the Mt Isa Line, but it was chosen to be the test area for the weld straightening project due to its vicinity to pre-scheduled track relaying work.

The track section is narrow gauge track formed of 41 kg rail on steel sleepers overlaying a black soil formation. The terrain is fairly smooth and the line is mostly consisting of tangent track. The selection of a narrow gauge track would not affect the applicability of the results to standard or broad gauge tracks. The effect of poor welds on track roughness is a rail dependant issue that is not closely affected by the track structure. However, different rail size may perform differently under similar conditions due to the metallurgy and composition. This issue should be investigated in future studies.

Within this 150 km test area, it was acknowledged that nine kilometres had been undercut in 1999 (section between Nelia and Nonda 580-589km). It was recommended by QR to choose a region within these boundaries to undertake the present investigation. By choosing a track section that had been previously ballast cleaned, allowed the current study to focus primarily on the effectiveness of the straightening and grinding of welds on track roughness, as most track (i.e. below rail) related inconsistencies would have been removed following the undercutting works and therefore could be considered negligible.

Six kilometres, which stretched from the 580 kilometre peg to the 586 kilometre peg, were selected by the author as the test area for this investigation. Further details of this test region are described in Section 3.2.

Figure 3.2 MIL – Project's test area (QR 2001b)

Selection of the 6 km test region for the present study permitted the gathering of over 1200 measurements of weld misalignment during each site visit (each kilometre of track generally includes approximately 100 welds per leg of rail; 1 weld approximately every 10 metres). Statistically, this is considered a large enough sample size to achieve confidence in the results.

In addition, the 6 km test region was further subdivided into three 2km long divisions. Each division was subjected to different quality control intervention measures to enable evaluation of the effectiveness of the straightening process. These intervention limits are discussed in Section 3.2.

3.1.4 QUALITY CONTROL LIMITS FOR THE MIL STRAIGHTENING PROJECT

As stated earlier, the principal aim of the straightening program on the MIL was to extend the life of 41 kg rail by identifying and then removing the defects that were the major cause of the problem. The greater the vertical weld misalignment, the greater will be the dynamic forces applied by rolling wheels on the track structure (refer to Section 2.2.3). However, the effects of these dynamic forces on track components are not always seen by the naked eye until the damage is beyond repair.

Numerous visual track inspections and advices from Track Section Supervisors (TSS) showed that if a weld should have more than 0.5mm dip then there is an obvious degradation of the track components below-rail. However, the Track Section Supervisors believed that damage begins when the dip exceeds 0.3mm, even though immediate visual evidence may not be present.

In order to minimise the dynamic forces due to the presence of poor welds and rectify the problem before all track components are affected, the straightening quality control limits for the whole MIL were initially selected to be: 0.3 mm for dipped welds and 0.5 mm for peak welds (QR 2001c). This means that all welds dipped less than 0.3 mm were not straightened and peaks smaller than 0.5 mm were not ground (Table 3.4). The tolerance following straightening allowed no dip to remain in corrected welds; therefore the final post-straightening tolerance on corrected welds was 0; 0.5 mm peaked as shown in Table 3.5.

However, as the straightening program progressed there were found to be many more welds needing straightening than anticipated. For budgetary purposes therefore the limits were relaxed to 0.5 mm for dipped welds and 0.7 mm for peaked welds. The possible impact of this change in contract tolerance is explored through the detailed analysis presented in Chapter 5.

Table 3.4 Initial MIL Intervention Levels *(Contract AT.1719)* **(QR 2001c)**

Table 3.5 MIL Post Measurement Levels *(Contract AT.1719)* **(QR 2001c)**

3.2 SIX KILOMETRE TEST SECTION

The 6 kilometre test region selected for the present study is located approximately half way on the MIL, between Townsville and Mt Isa. The railway was constructed on black soil territory and as such delays can be expected at times due to soil expansion and contraction. The issue of black soil territory has been a significant problem on the MIL causing a large increase in track degradation due to the constant movement of the formation. Several sections, outside the six kilometre test section project's boundaries, are currently being monitored as part of a formation trial where different types of formation stabilisation are being trailed. This matter was not analysed as part of this study.

Like the entire MIL, the test area track structure is narrow gauge consisting of 41 kg/m rail on steel sleepers allowing 20 tonne axle load (TAL) traffic travelling at a maximum speed of 60kph due to the nature of the formation. The track grade is very gentle; the maximum grade that an "Up" train (travelling west) will encounter is 1 in 55 whilst a "Down" train (travelling east) is 1 in 50, refer to Figure 3.3.

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

Figure 3.3 Track Data and Grade Diagrams (QR 2001b)

The six kilometres allocated to the present investigation were divided into three 2 km divisions, each subjected to different intervention limits (Figure 3.4). All dipped and peaked welds in *Division 1* (580-582 km) were identified to be corrected. *Division 3* (584-586km) was maintained as the control division and no work was to be performed on the track section. Dipped welds equal to or greater than 0.3mm and all peaks present in *Division 2* (582-584 km) were identified to be corrected. *Division 2* was utilised to attempt to establish the optimal intervention level for future straightening work.

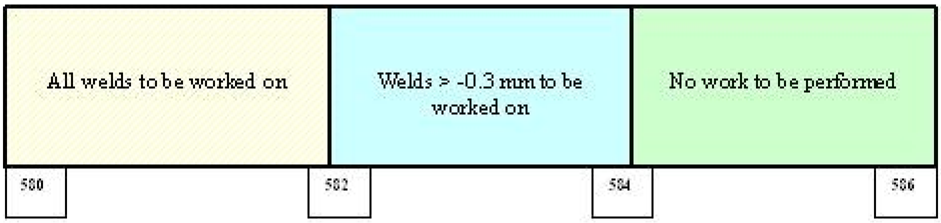


Figure 3.4 Test Areas – Division

A similar approach to the MIL straightening project was adopted for the six kilometre test section where no dips were allowed to remain in track following correction works. However, the tolerance employed in *Divisions 1* and *2* required corrected welds to remain only as peaks having a vertical misalignment of 0.00; +0.2 mm.

3.2.1 DIVISION AND WELDS MONUMENTING

Each weld had to be clearly identified within each division to allow monitoring of a given weld's behaviour with respect to time; the process of identification is known as monumenting.

Coloured steel pegs were utilised to note the beginning or end of the divisions, as shown in Figure 3.5.

Blue pegs were used for *Division 1* (580-582), orange pegs for *Division 2* (582-584) and yellow pegs for *Division 3* (584-586). These colours were selected as they would not interfere with any of the train drivers signalling colours, such as red, green or white.

The peg located at 580 km was chosen as the datum from which all weld positions were measured because it was adjacent to the first weld in the test section. When facing the Up Road direction (i.e. looking west, towards Mt Isa) whilst at the 580 km peg, all welds were identified as follows:

- a sequential number identifying that weld uniquely,
- distance from the 580km post,
- whether the weld was on the left or right rail
- degree of dip/peak using the 1.5 m straight edge and
- type of weld, flash-butt or alumino-thermic

All this information was recorded on 90x90 mm steel plate, which was then glued to the field side of the rail web near the respective weld as shown in Figure 3.6.

When measuring the degree of vertical misalignment of welds, it is standard QR practice to use a 1 m calibrated straight edge and taper gauge, as outlined in the CETS version 2 (QR 2001a). Due to the geometry of the RASTIC straightening machine and the process it uses to straighten welds, a 1.5 m straight edge was adopted for the present study. Detailed discussion of the reasons for using the longer straight edge is outlined in Section 3.3.1.

Additional to the 90x90 mm steel weld information plate, all welds needing correction in *Division 1* (580-582km) and *Division 2* (582-584km) were painted white for easy detection by the straightening gang during the straightening activity (Figure 3.6).

Figure 3.5 Subdivision of Test Area using Coloured Steel Pegs

Figure 3.6 Researcher's Weld Identification Paint

Harsco Track Technology (HTT) followed a similar methodology to identify and monument welds that required straightening operations. Three HTT staff walked the nominated track section generally the day prior to straightening and manually measured all welds in track with a 1 m straight edge and taper gauge. If the weld was identified to be a dipped weld, the rail was painted blue in the vicinity of the weld, if the weld was identified to be a peak, the rail would be painted green in the vicinity of the weld. The colour coding used by HTT to identify the type of weld misalignment was approved by QR for the purpose of the Straightening Project. The actual measurements were then recorded onto the adjacent sleeper using the same colour code (blue for dipped welds and green for peaked welds) and also recorded onto the foot of the rail together with the weld number as shown in Figure 3.7.

Regardless of the fact that the author painted with white paint all welds surveyed in the six kilometre test section that were identified as requiring correction, HTT staff were still required to walk the nominated track division in order to establish the degree of vertical misalignment using a 1m straight edge for the optimal operation of the straightening and manual grinding machine.

Twenty-four hours after straightening had occurred, HTT staff were required to walk the corrected track and confirm by measurement that all corrected welds were within the agreed tolerances (0; +0.2 mm). If the weld was within tolerance no further action was taken. If the weld did not comply with the tolerance, HTT staff painted the fastenings either side of the non-complying weld in pink (see Figure 3.8). This indicated to the other HTT staff that the particular weld required further straightening or manual grinding if dipped or peaked respectively.

Two main causes were found for welds not complying with specified tolerances: steel thermal characteristics and rail memory. These issues are discussed in Section 3.3.3.

3.3 TRACK MAINTENANCE ON TEST SECTION

Rail and weld geometry have a marked effect on the rate at which track quality deteriorates and hence on the cost of maintaining it. It was concluded, from British Rail research (McMichael 1990) that a quick and efficient method of straightening dipped welds was required (refer to Section 2.6.2).

(a) Peak

(b) Dip

(c) Reading

Figure 3.7 HTT – Colour Coding of Weld Classification (a) Peak (b) Dip (c) Reading

Following additional research it was concluded that the straightening process had to include three essential stages:

- Identification and classification of welds
- Controlled three-point vertical bending of the rail
- Effective packing of ballast to support the straightened weld
- A machining process to smooth the running surface across the weld.

Prior to straightening, welds to be corrected were classified by colours and actual readings were recorded on the field side of the foot of the rail by the contractor (refer to Figure 3.7). Additionally, if a weld was identified to be dipped and requiring correction, marking for spot tamping was required and a white cross was painted at three sleeper bays away, on each side, of the to-be corrected weld.

Following straightening, all corrected welds were checked for compliance by the contractor, with the use of a 1 m straight edge. If the weld did not comply, further straightening or manual grinding was undertaken.

In the event that straightening broke a weld, a number of temporary or permanent corrective actions could be taken.

> "Temporary repairs must be a minimum of either:
>
> Fishplates with at least two bolts if suitable or
>
> A closure rail with two fishplates and at least four bolts
>
> Permanent repairs must result in a restoration of continuously welded rail …" *(Clause 16.02-03 – Contract AT.1719* (QR 2001c)

For the MIL straightening contract a maximum daily rail breakage rate of 3% was agreed. Over 5,000 welds were straightened as part of the MIL contract and less than 20 welds were broken over the duration of the project (less than 0.4% breakage). No broken welds were experienced over the six kilometre test section.

Figure 3.8 HTT Weld Classifications – Not within Tolerance

3.3.1 RASTIC – WELD STRAIGHTENING

The Rail straightening bending principle, conducted by the RASTIC machine, involves applying a three-point load centred at the dip to be removed. Unlike most other rail bending machines, RASTIC lifts the welds by the rail head which eliminates the necessity to remove ballast in the vicinity of the weld before straightening and also allows the machine to treat poor welds found on top of sleepers.

RASTIC essentially uses a beam, rail clamp, hydraulic cylinders and instrumentation to correct the dipped welds, as shown in Figure 3.9. The two hydraulic cylinders pushing onto the head rail are 1.1 m apart, and the rail clamp is located half way between them. When correcting dipped welds, small rail head defects may be created at the hydraulic cylinders location due to the nature of the bending process. These defects may not be detected if the standard 1 m straight edge is used. The author selected a 1.5 m straight edge to ensure no additional rail surface abnormalities were created during the bending phase. Detailed description of the 1.5 m straight edge, reliability of the readings and measurement techniques are outlined in Chapter 4.

Figure 3.9 RASTIC Configuration

3.3.2 CYCLE AND SPOT TAMPING

As part of the present project, two types of tamping were undertaken:

- Cycle tamping; which was scheduled to ensure:
    - Reduction of top and line defects in pre-straightening operations
    - Re-establishment of a homogeneous ballast compaction in the corrected track sections
- Spot tamping; as part of the weld straightening operation

A high production tamping machine generally employed to undertake programmed cycle tamping over the entire network was used to restore a good quality track top over the test region. The MMA 60 Fairmont Tamper, manufactured by Harsco Track Technology, was utilised for the cycle tamping operation (Figure 3.10). This machine is QR owned and operated.

Spot tamping was deemed necessary to restore the ballast’s support to the sleepers and thus to the rail following dipped welds corrections. For example, if a 1.0 mm dipped weld was lifted by RASTIC to a +0.5 mm peak, a 1.5 mm gap between the underside of the sleeper and the ballast would be present. Over time, with constant traffic over the weld and no immediate support from the ballast, the rail will bend once again.

A low production machine able to target localised areas was used instead of continuous track section maintenance tamping. The MMA 052 Fairmont Tamper, also manufactured by Harsco Track Technology, was utilised to undertake the spot tamping operations. This machine is owned and operated by QR.

3.3.3 MANUAL AND CYCLE GRINDING

Similarly to tamping, two types of grinding methods were utilised during the project. These are:

- Manual Grinding, as part of the straightening process; used to remove the peaks of peaked welds and of corrected dipped welds.
- Cycle Grinding; to attempt to improve the longitudinal rail profile whilst establishing the transverse rail profile.

Manual grinding was carried out by the contractor, Harsco Track Technology, as part of the straightening process. The machine was operated 500mm either side of the weld to create a smooth running surface over the weld. Figure 3.11 shows one of the manual grinders in operation.

Figure 3.10 MMA 60 – High Production Cycle Tamper

Figure 3.11 Manual Grinder

At the beginning of the MIL straightening project, it was found that manually ground corrected dipped welds would not comply with the allowed project's tolerances if the manual grinding operation was performed during the warmer hours of the day.

Due to the thermal characteristics of steel, welds tend to expand under elevated heat whilst being manually ground (i.e. generating a slight peak) and shrink once cooled down (i.e. generating a slight dip). If manual grinding on corrected dipped welds was completed during the hotter hours of the day and then cooled overnight,, during the re-inspection twenty-four hours post-straightening the same weld may have slightly dipped and not pass the accepted project tolerances.

In addition to the thermal characteristics, due to the presence of internal stresses in the rail, it was apparent that straightened welds were inclined to slightly settle and generate a small dip after straightening. This phenomenon is also known as rail memory, where the internal stresses in the rail attempt to re-establish similar weld geometry to the pre-corrected stage.

When adding the effect of thermal contraction to the rail memory effects, the total settlement of straightened welds was estimated to range between 0.1 to 0.2mm. Over the duration of the present project, it was not possible to quantify the single effect of thermal contraction or rail memory. These issues should be further explored.

For this investigation, it was agreed to schedule the manual grinding operations the morning after the straightening work to take advantage of the cooler conditions, in order to minimise at least the effect of thermal expansion/contraction.

A high production grinding machine was used to improve the longitudinal rail profile. The MMY 019 production grinder, manufactured by Speno, was used (see Figure 3.12). This machine is owned and operated by QR.

Figure 3.12 Cycle Grinder (QR 2001d)

The MMY 019 grinding machine has 40 grinding stones which are placed in unit blocks (10 stones per block) that can pivot with respect to a central axis. This permits the grinding action to focus on specific areas of the rail head. The stones form an angle such that the rail profile approximated the form of a polygon. In this way the rail can be re-profiled.

3.4 WORK PERFORMED ON EACH DIVISION

The climatic and environmental conditions can affect the rate of track degradation by increasing the wear and tear of individual track components. Programmed maintenance work, such as cycle tamping, cycle grinding, ballast cleaning and more, is a vital tool to maintain track, subjected to similar conditions, to the required network standards. During the life of this project, a variety of maintenance and correction activities were undertaken over the three projects divisions. Figure 3.13 illustrates the work performed.

The vertical axis in Figure 3.13 corresponds to the distance, monumented by QR, from Townsville. *Division 1 (580-582km)* is identified by the vertical thin hatching; *Division 2 (582-584km)* is identified by the diagonal hatching and *Division 3 (584-586km)* by the horizontal thin hatching.

The horizontal axis corresponds to the life of the project; commencing on the 26th of June 2003 with the first TRC run and concluding with the last measurement recording (Measurement #4) on the 29th of March 2004.

The orange vertical double-lines represent the Track Recording Car (TRC) runs over the test area. As part of QR maintenance strategy, the TRC runs over the MIL are scheduled to occur four times a year. The TRC program happened to coincide with the present research project's straightening and cycle grinding schedule, providing five sets of TRC data for the project. This data was collected with a view to using it to study the relationship between the degree of misalignment of welds and associated track degradation. However, when trying to correlate the measured positions of welds against the spikes and troughs shown in the TRC "corrugation plots" the results were confusing and erratic. For example, at locations where no weld or defect existed, the TRC data often showed spikes as if large dipped welds were present. Likewise at some known large dipped welds, the TRC data showed nothing. Consequently, the attempt to relate weld misalignment to track degradation was abandoned.

The pink text-boxes in Figure 3.13 represent the cycle tamping programs, which utilised the Fairmont Tamper MMA 60. From the graph, it can be seen that cycle tamping was completed prior to the first set of measurements (Measurement #1) in *Divisions 1 (580-582km)* and *2 (582-584km).* On the other hand, data recorded (Measurement #1) from *Division 3 (584-586km)* was recorded before the cycle tamping.

It is believed that cycle tamping has had an effect on the quality of the weld. This issue is discussed in Section 5.1.1.

The green text-boxes highlight the areas required to have welds straitened.

The blue text-boxes represent the cycle grinding undertaken by the Speno MMY 019 grinding machine. One kilometre of each 2 kilometre divisions was selected to be cycle ground (*Division 1 581-582km, Division 2 582-583km* and *Division 3 585-586km*).

The yellow text-boxes correspond to the actual data collection undertaken by the author. All weld readings (Measurement #2, 3, 4 and 5), except for the ones recorded during Measurement #1 in July 2003, were measured by the author using the calibrated 1.5 m straight edge. Readings in Measurement #1 were taken by the Track Depot Supervisor (TDS) of Richmond. The technique used by the TDS during Measurement #1 was noted carefully by the author and all subsequent Measurements followed the same technique meticulously.

It was anticipated that having weld readings recorded by a different railway skilled staff, whilst being supervised by the author, would not bear any significant influence on the final results. If the same welds were measures by the author and the TDS, the difference between the readings was expected to have the same statistical error as if the same person recorded both of the measurements (refer to Section 4.5).

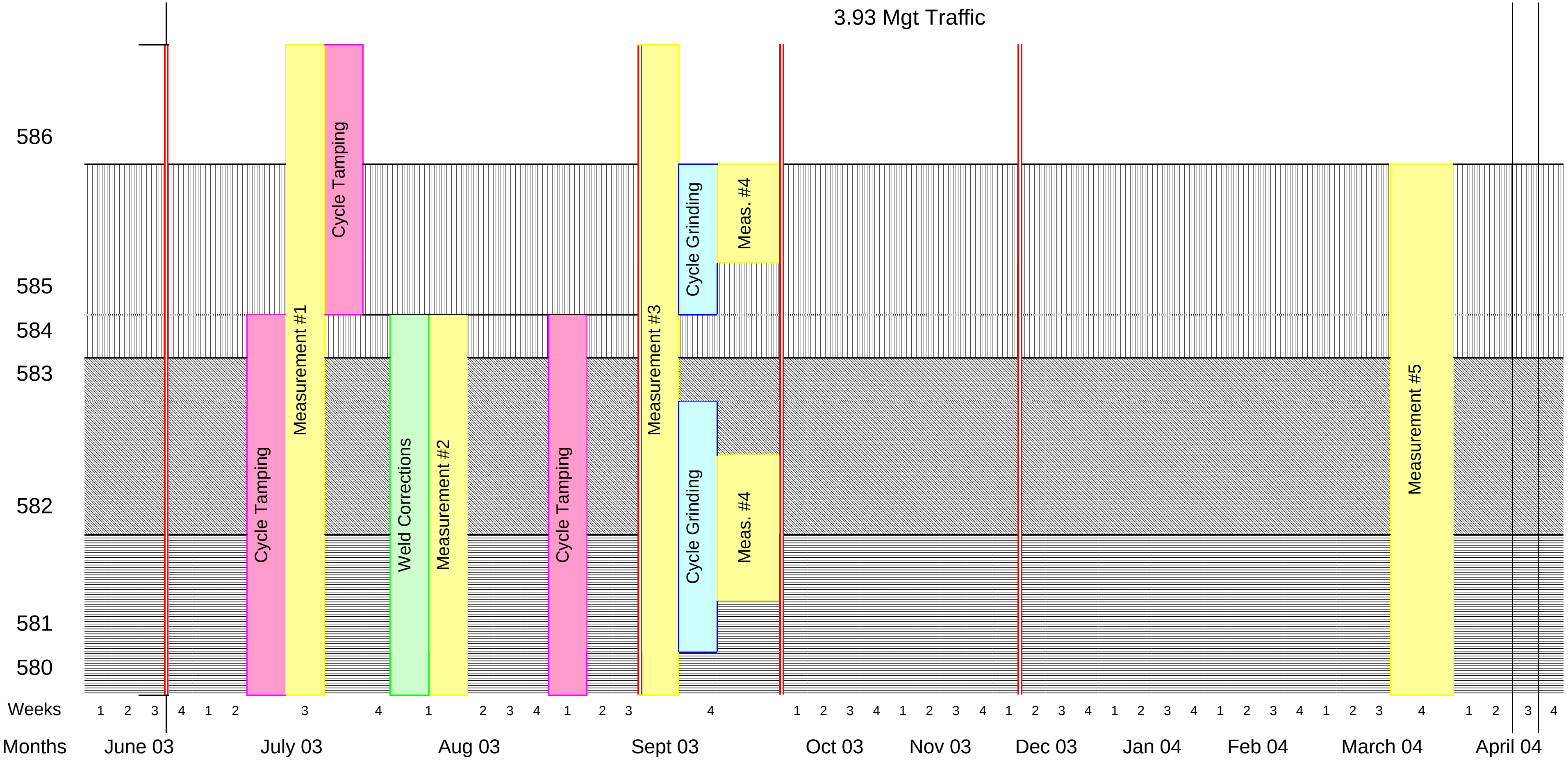


Figure 3.13 Divisions Programmed Work

Measurement #1 was undertaken in July 2003, starting from the 22nd until the 25th of July. This first set of readings gave the base line to which all other visits would be compared. During Measurement #1, all welds within the project's boundaries were monumented (refer to Section 3.2). In addition, comments about the condition of the track near welds were recorded if particular issues such as pumping of sleepers or powder from ballast were present. During the remaining site visits, only the degree of dip or peak was recorded.

The aim of Measurement #2 on August 2003 was to examine the effect of the straightening process on misaligned welds. As only *Divisions 1 (580-582)* and *2 (582-584)* were scheduled to be straightened (refer to Section 3.2); only welds present in these *Divisions* were recorded in Measurement #2.

Measurement #3 and #4, September 2003, were taken to understand the effect of cycle grinding on poor quality welds, dipped or peaked. Two sets of manual and TRC readings were taken only a few days apart of each other, pre and post cycle grinding, to confirm the effect of cycle grinding on welds. Measurement #3 readings were taken over the entire six kilometres test area to record the actual performance of the welds after the straightening works. Measurement #4 includes a small sample size of only the sections of track that was cycle ground by the MMY019 machine.

Following the cycle grinding in September 2003, it was agreed that no further maintenance work would be undertaken over the three *Divisions*. Normal rail traffic across the 6km test section resumed so that the track was subjected only to rollingstock loads for the next 7 months.

In March 2004, after the period of 7 months of normal traffic following the straightening program, approximately 4Mgt of traffic traversed the test area. Measurement #5 was undertaken on the 29th of March 2004, which was the final set of data collected for the project; consequently the entire 6 kilometre test section was measured.

All of the readings recorded during the four site visits were analysed and the results are discussed in Section 5.0.

4.0 MEASURING AND PROCESSING OF DATA

To maintain consistency throughout the entire process of data gathering on the MIL test section, the same measurement technique was used whilst recoding each misalignment at welds. To reiterate, a 1.5m straight edge was used together with this steel taper gauge to measure the dip or peak at a weld. To verify the accuracy of these readings it was necessary to perform a random repeatability test and calculate the statistical error of the data. After establishing the accuracy of the records, it was necessary to convert the 1.5m straight edge readings to the standard 1m straight edge records.

The following sections detail the above issues.

4.1 CALIBRATION OF THE STRAIGHT EDGE

Prior to commencing recording, it is important to establish the straightness of the straightedge in use. Two simple methods were used to calibrate straight edges; these are:

- Spirit Level Calibration – generally completed in-situ prior to using the straight edge
- Laboratory Calibration – completed on an annual bases to maintain the edge within specified tolerances

The spirit level calibration was used to initially calibrate the new 1.5m straight edge prior to Measurement #1 (refer to Figure 3.13). The edge was found to comply with QR tolerance of ± 0.15mm.

To maintain the straightness of the edge, following each recording session (i.e. Measurement #1, #2) the 1.5m straight edge was stored in the Richmond Track Section Supervisor's (TSS) office. The edge was carefully placed on a flat surface and not used by any other staff.

Great care was taken whilst using the 1.5m straight edge during the entire duration of the project. The edge was calibrated in a controlled environment, laboratory, to verify its straightness following the last measurement recording in March 2004.

The laboratory calibration identified the straightness of the used edge by determining the difference, if any, between the reference and used edge using a taper gauge. The reference edge is a 3m long cast iron reference edge regularly calibrated with the use of spirit level. The used edge is places on top of the reference edge and with the use of a taper gauge, the difference between the edges measured.

The 1.5m edge used for the project was found to be marginally within QR allowable tolerance limit of ± 0.15 mm (i.e. ±0.145mm). It is recommended to re-calibrate the edge if it is to be used for future studies of the continuation of the present project.

4.2 MEASUREMENT TECHNIQUE

In order to establish the longitudinal weld profile and measure any defects created by the RASTIC weld straightening machine, the 1.5 m straight edge was divided into four segments of 375 mm each, with the centreline of the straight edge being positioned directly over the centre of the weld (Figure 4.1).

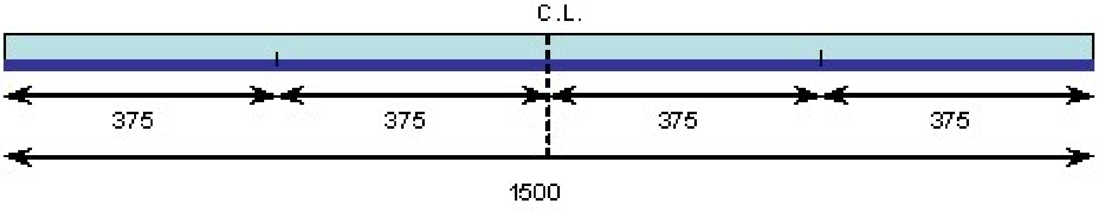


Figure 4.1 Configuration of the 1.5 m Straight Edge

Each dipped weld measured with the 1.5 m straight edge recorded three readings: left (R_{left}), centre (R_{centre}) and right (R_{right}); each peaked weld recorded only one reading which equated to twice the magnitude of the centre peak (2 x R_{centre}), see Figure 4.2. By gently sliding the taper gauge, pictured in Figure 4.3, between the bottom of the straight edge and the head of the rail, the readings were taken.

During the first measurement recording, the information collected was manually recorded into a simple Microsoft Excel generated table, pictured in Figure 4.4. The table was formed by 10 columns; each column detailed a field needed to be completed during the on-site track section recording. The fields included:

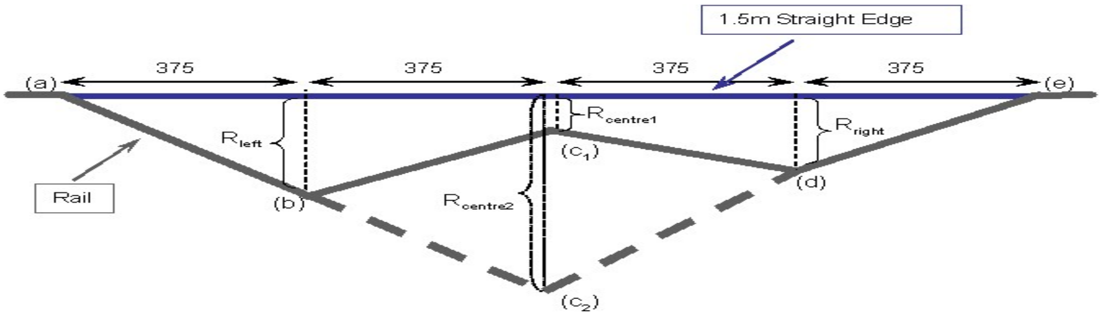
- Distance of a specific weld from the first weld.
- Location of the weld on the left or right side of rail.

- The weld number, assigned sequentially from the first weld measured.
- Degree of weld misalignment. For dipped welds left, centre and right measurement were required; for peaked welds only, the reading recorded with the 1.5m straight edge was halved prior to entering it into the database. The sign convention utilised in the present project gives negative values to dipped welds and positive values for peaked welds.
- Requirement for correction. This column was only included for *Division 2*. Dipped welds equal or greater than 0.3mm and all peaks were identified to be corrected and a "YES" was assigned to them. The remaining welds were documented as not requiring any correction and a "NO" was assigned to them.
- Type of weld, Flash-butt or Thermit.
- Presence of internal defects. If an internal defect was identified to be present in a weld, no correction was to be performed on that weld.
- Comment/notes. This is where starting time of recordings, track conditions, ambient conditions and other comments were recorded.

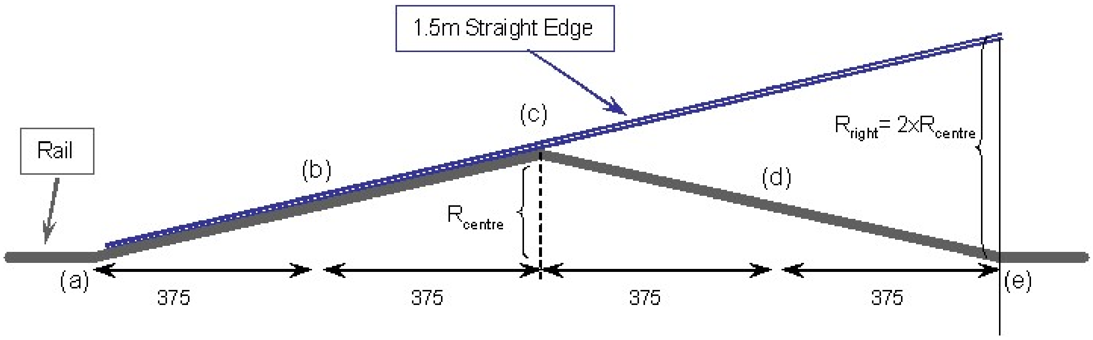
During Measurement #1 (June 2003), all of the above fields had to be completed whilst being out on track. All succeeding measurements (Measurement #2, 3, 4 and 5) required only the weld misalignment and comments/notes columns to be filled out.

On average, each Division contained over 350 welds; and less than 10% of the total count was identified as being alumino-thermic (thermit) welds. The remaining welds were classified as Flash-butt welds. Only two welds over the entire six km test section were identified by QR field testing staff with the ultrasonic laser as having internal defects; and over 550 welds were classified to be corrected.

Overall, over 15,000 readings were manually recorded. This is seen as a significant sample size; statistically there is a confidence that the results calculated during the analysis give a valid representation of the straightening operation with respect to the condition of the track. All recorded data has been saved onto a CD and attached to this document.



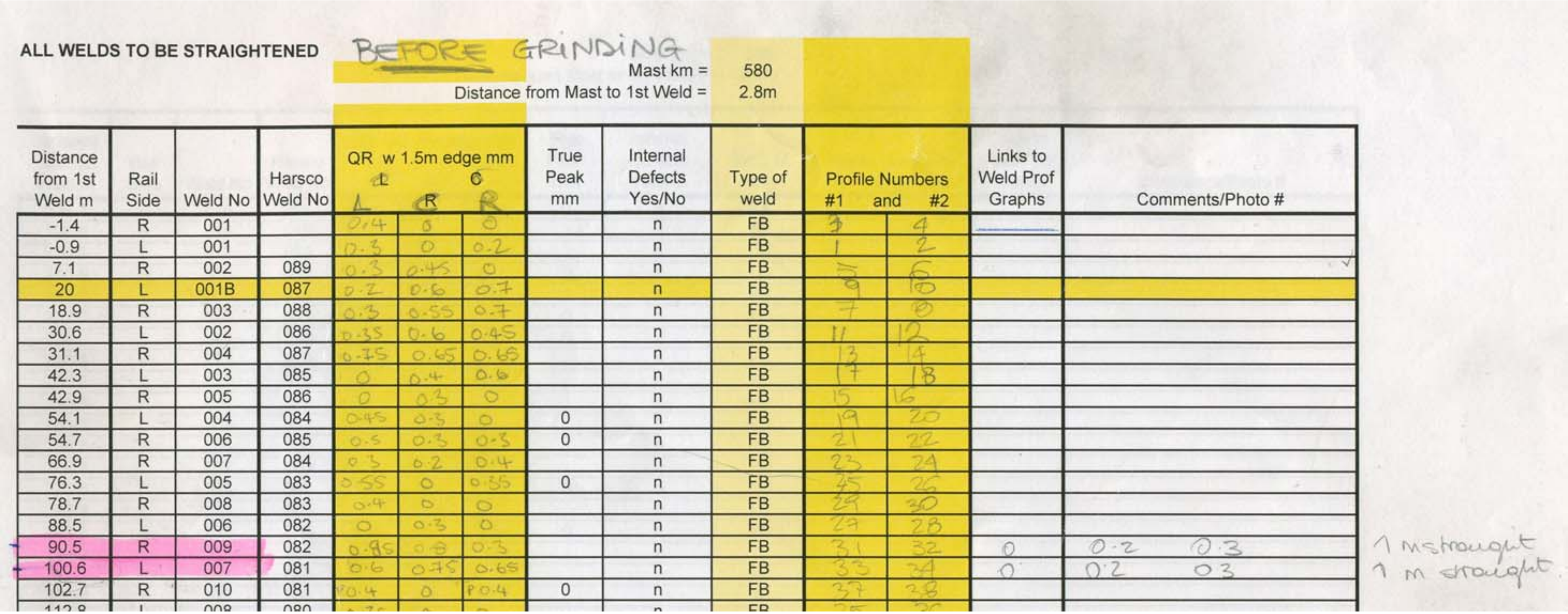
(a) Dipped Weld Profile



(b) Peaked Weld Profile

Figure 4.2 Typical Weld Readings: (a) Dipped Weld and (b) Peaked Weld

Figure 4.3 Taper Gauge



ALL WELDS TO BE STRAIGHTENED BEFORE GRINDING

Mast km = 580
Distance from Mast to 1st Weld = 2.8m

Distance from 1st Weld m	Rail Side	Weld No	Harsco Weld No	QR w 1.5m edge mm L	R	R	True Peak mm	Internal Defects Yes/No	Type of weld	Profile Numbers #1	and #2	Links to Weld Prof Graphs	Comments/Photo #
-1.4	R	001		0.4	0	0		n	FB	3	4		
-0.9	L	001		0.3	0	0.2		n	FB	1	2		
7.1	R	002	089	0.3	0.45	0		n	FB	5	6		✓
20	L	001B	087	0.2	0.6	0.7		n	FB	9	10		
18.9	R	003	088	0.3	0.55	0.7		n	FB	7	8		
30.6	L	002	086	0.35	0.6	0.45		n	FB	11	12		
31.1	R	004	087	0.75	0.65	0.65		n	FB	13	14		
42.3	L	003	085	0	0.4	0.6		n	FB	17	18		
42.9	R	005	086	0	0.3	0		n	FB	15	16		
54.1	L	004	084	0.45	0.3	0	0	n	FB	19	20		
54.7	R	006	085	0.5	0.3	0.3	0	n	FB	21	22		
66.9	R	007	084	0.3	0.2	0.4		n	FB	23	24		
76.3	L	005	083	0.55	0	0.35	0	n	FB	25	26		
78.7	R	008	083	0.4	0	0		n	FB	29	30		
88.5	L	006	082	0	0.3	0		n	FB	27	28		
90.5	R	009	082	0.85	0.8	0.3		n	FB	31	32	0	0.2 0.3
100.6	L	007	081	0.6	0.75	0.65		n	FB	33	34	0	0.2 0.3
102.7	R	010	081	0.4	0	0.4	0	n	FB	37	38		
112.8	L	008	080					n	FB	35	36		

1 m straight
1 m straight

Direct scan from field table to illustrate what was recorded on site

Figure 4.4 Field Data Table

Recording all of the necessary information during each Measurement was an impossible task to be undertaken in a single day. The work was scattered over 4-5 days during each Measurement; requiring the author to walk and record approximately 1.5km of track each day.

During Measurement #1 (refer to Figure 3.13), starting and ending times of recordings were noted. This led to creation of a work schedule for each test section *Division* that required repetition of all subsequent recordings (Measurement #2, 3, 4, and 5) at similar times of the day as the first recording.

The rationale behind this was because the six kilometre test section is located in a region of Queensland with very adverse climatic and environmental conditions, such as:

- The daily air temperature can range between +40^{o}C to -5^{o}C,
- The track is laid on black soil terrain which experiences contraction cracks that can reach up to 80mm in width and over 2 m in depth during the dry season of the year
- The region is subject to regular flooding in the wet season, where the average rainfall can reach up to 500mm in one week. This will generate flash flooding and cause serious damage to the track structure.

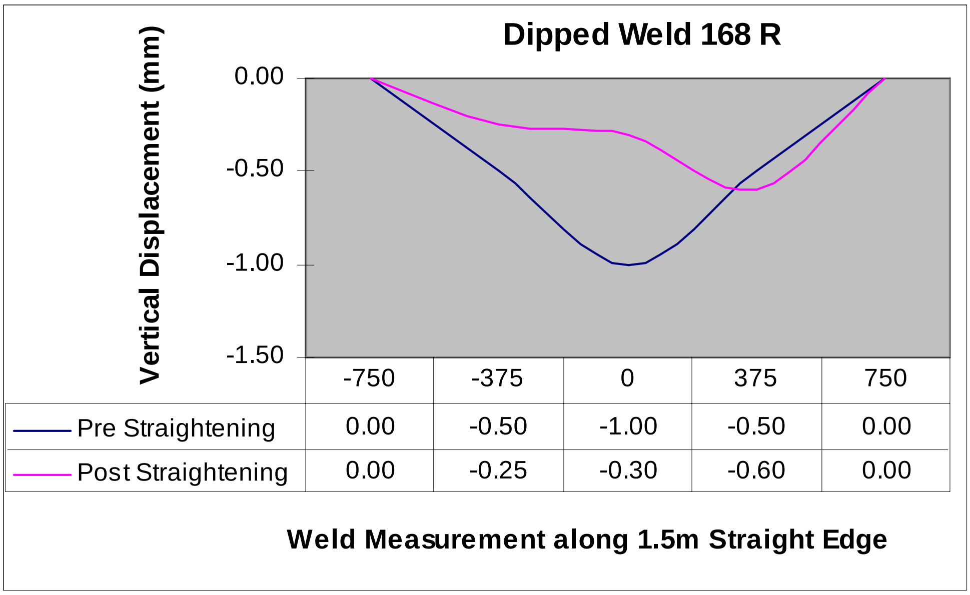
By maintaining similar recording times the possible effects of ambient temperatures on the weld longitudinal profile were reduced. Thermal expansion and contraction characteristics of the rail can influence significantly the measurements recorded with the straight edge. Warmer temperatures will tend to generate more peaks, as cooler temperatures will produce more dips or top defects.

4.3 ANGLE CHANGES

The basis for using the 1.5m straight edge was to detect if any new rail surface defects were created by the pressure applied by the RASTIC's hydraulic rams onto the head of the rail during the bending operations at dipped welds (refer to Section 3.3.1). The RASTIC rams (rail reaction points) were 1.1m apart and so their contact points with the rail were spanned by the 1.5m straightedge.

In order to establish the possible effect of the RASTIC straightening machine onto the rail, the longitudinal profile of welds must be known. Utilising the 1.5m straight edge and recording three readings at 375mm apart per weld, enabled a reasonable representation of the weld longitudinal profiles to be captured (refer to Figure 4.5).

Readings for a typical weld were plotted pre and post straightening operations as shown in Figure 4.57.



	-750	-375	0	375	750
Pre Straightening	0.00	-0.50	-1.00	-0.50	0.00
Post Straightening	0.00	-0.25	-0.30	-0.60	0.00

Figure 4.5 Change of Shape of Dipped Weld Number 168R due to Straightening

The X axis represent the vertical displacement recorded with the use of the straight edge and the taper gauge (refer to Figures 4.1 and 4.3). The interval on the Y axis indicate the location where the recording was taken with the taper gauge (refer to Section 4.2).

From vertical displacement analysis, Figure 4.5, any effects of the RASTIC hydraulic rams onto the rail head could be identified.

From Figure 4.5, it is possible to visualise the changes in vertical wheel/rail force that the wheels experience when passing through a dipped weld. The shape of the weld has a considerable effect on the applied dynamic force. Passing rollingstock experiences changes in rail top vertical alignment at welds' locations, which can best be expressed as changes of angle of the rail top (see Figure 4.6 for typical changes of slope along a weld); dynamic forces are strongly affected by the change in angle of the rail top at such discontinuities.

Each weld is unique; it has a distinctive longitudinal profile. The same vertical misalignment directly over the weld does not correspond to identical longitudinal profiles. Having different profiles will produce different impact forces; the greater the misalignment, the greater will be the dynamic force. As outlined by Esveld (1989), for example, above a certain value of the ratio between the velocity and the length of the defect (V/L) the wheel may not be able to follow the exact alignment of the discrete irregularity and “fly” over the defect. This effect could happen over a dipped weld if the actual depression does not follow a straight line but rather a downward curve.

All 1.5m straight edge readings recorded were converted into angle changes using a simple mathematical conversion. Figure 4.6 represents a typical dipped weld where the rail top is idealised into a series of straight lines. When using the 1.5m straight edge, three readings are being recorded: reading left R_{left}, reading centre R_{centre} and reading right R_{right} (refer to Section 4.2). As the rollingstock moves along the rail, the wheels will experience a change in the angle of the rail top at location (b), (c) and (d). This change can be quantified by calculating the angle changes α, β and γ for each weld. The formulae utilised for the calculation of the angle changes are listed as follow.

Following the conversion to angle changes, the data was analysed to establish if the RASTIC straightening machine affected the rail head at the hydraulic cylinders location. Left and right angle changes were plotted with respect to time in Figure 4.7. The blue line represent the left angle change (α), the pink line represents the right angle change (γ). The red horizontal limit line represents the maximum change of angle allowed in the Civil Engineering Track Standards (QR 2001a).

$$\alpha = -\left[\frac{R_{left}}{375} - \left(\frac{R_{centre} - R_{left}}{375}\right)\right]$$

Equation 4.1 Left Angle Change

$$\beta = -\left[\left(\frac{R_{centre} - R_{left}}{375}\right) - \left(\frac{R_{right} - R_{centre}}{375}\right)\right]$$

Equation 4.2 Centre Angle Change

$$\gamma = -\left[\left(\frac{R_{right} - R_{centre}}{375}\right) - \left(\frac{0 - R_{left}}{375}\right)\right]$$ **Equation 4.3 Right Angle Change**

The Y axis in Figure 4.7 represents the maximum absolute change of angle experience at the R_{left}, and R_{right} locations on the 1.5m straight edge at specific times. The X axis represents the time at which the readings were taken (refer to Section 3.4).

From the mean of angle change in *Division 1*, it appears that the RASTIC machine hydraulic cylinders had no adverse effect (i.e. creation of additional defects such as depressions in the rail head) onto the rail head. In fact, it appears that the overall longitudinal profile of corrected dipped welds has improved following straightening operations. The mean angle change for both left and right readings reduced, by 50% or more, in August 2003.

In conclusion, it was established that the RASTIC straightening machine did not create additional defects to the head of the rail during the bending operations.

4.4 DATA CONVERSION

As detailed in Section 3.2.1, the 1m straight edge is the standard tool required to measure misalignments in welds. To comply with the standard work practice, the readings taken with the 1.5m straight edge during the measurement were converted to an equivalent 1m straight edge reading.

The main difference between using a 1.5m straight edge instead of a 1m edge is that only one reading is recorded when using a 1m straight edge to determine the vertical misalignment of dipped or peaked welds, compared to three for dips and one for peaks when using the longer edge.

The single reading taken with the 1m edge will measure a different weld misalignment compared to the centre reading (R_{centre}) taken with the 1.5m straight edge, as shown in Figure 4.8.

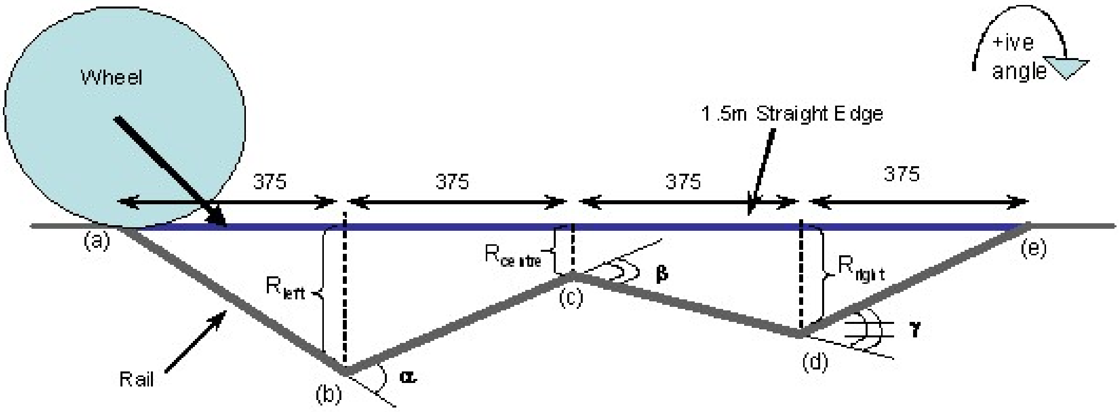
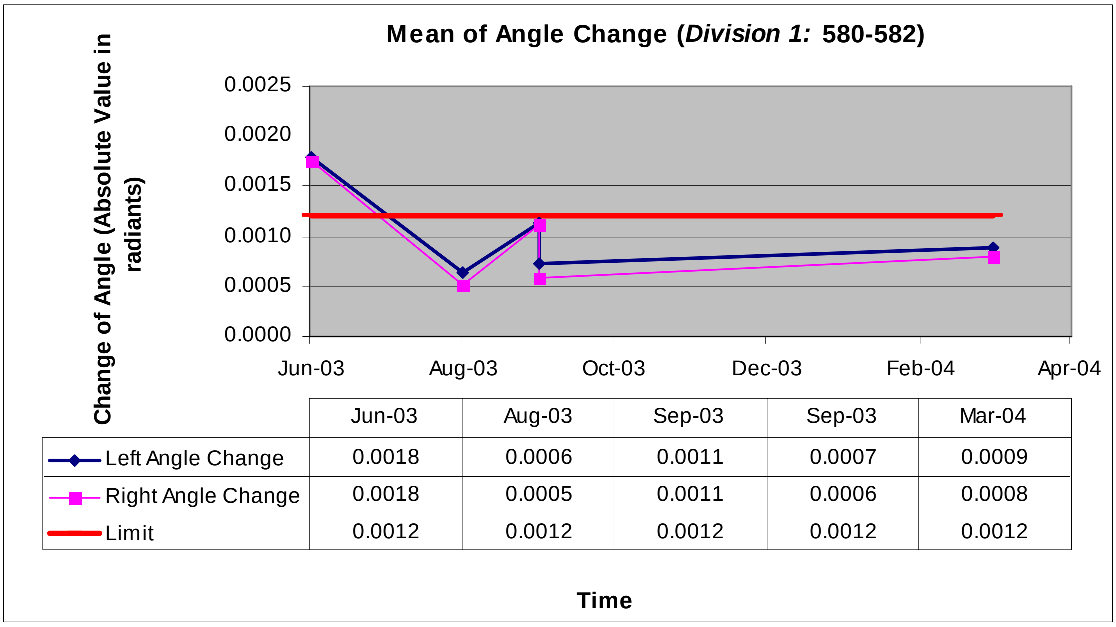


Figure 4.6 Angle Change – Dipped weld



	Jun-03	Aug-03	Sep-03	Sep-03	Mar-04
Left Angle Change	0.0018	0.0006	0.0011	0.0007	0.0009
Right Angle Change	0.0018	0.0005	0.0011	0.0006	0.0008
Limit	0.0012	0.0012	0.0012	0.0012	0.0012

Figure 4.7 Left and Right Angle Changes – *Division 1* (580-582km)

To convert the 1.5m centre reading to its corresponding 1m edge reading, it was necessary to determine the co-ordinates of point $A:(A_x;A_y)$, $B:(B_x;R_y)$ and $C:(C_x;C_y)$**,** which represent the locations where the 1m edge makes contact with the rail head. The 1.5m converted centre reading is equal to the distance BD shown in Figure 4.8. By replacing known values into the co-ordinates for point A, B and C and determining the remaining values using similar triangle rules (see Appendix D) it was possible to calculate the distance BD which is the difference between $B_y - D_y$. Therefore, the converted reading can be calculated as follows:

$$BD:\left(R_{centre} - \frac{250}{375}\left(R_{left} + R_{right}\right)\right)$$ **Equation 4.4 Reading Conversion**

This formula can be used for any shape weld.

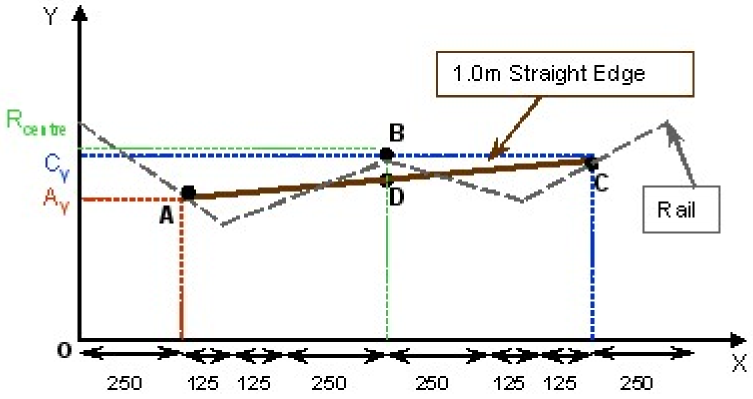
The above conversion process proved to calculate comparable converted readings to the readings recorded by Harsco Track Technology (HTT) using the standard 1m straight edge (refer to Section 4.5).

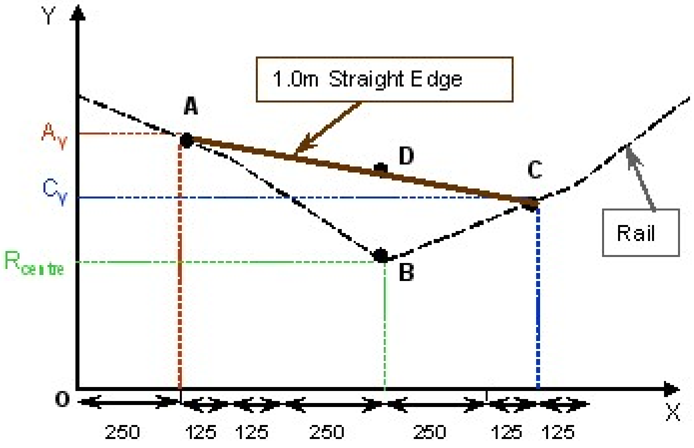
Statistically, the converted data can be assumed to be adequately representative of the centre misalignment of welds and therefore can be used in Chapter 5 to determine the effect of maintenance activities on the geometry of the welds.

4.5 REPEATABILITY VERIFICATION

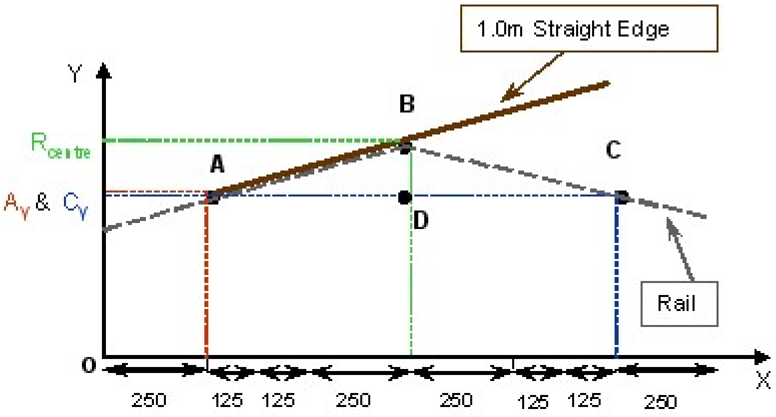
It was essential to ensure minimal “human error” was present in the data collection process. A repeatability test was conducted during Measurement #5 to quantify the reliability of the measurement technique adopted for the present project.

Twenty four hours after recording readings in Measurement #5, over 50 welds in *Division 1* were remeasured following the same measuring technique and reading schedule. Each reading was compared to its corresponding Measurement #5 reading and plotted onto an X-Y graph. Only the centre readings (R_{centre}) taken with the 1.5m straight edge are plotted in Figure 4.9.





(a) Dipped Weld



(b) Peaked Weld

Figure 4.8 Comparisons of Readings from 1m and 1.5m Straight Edges

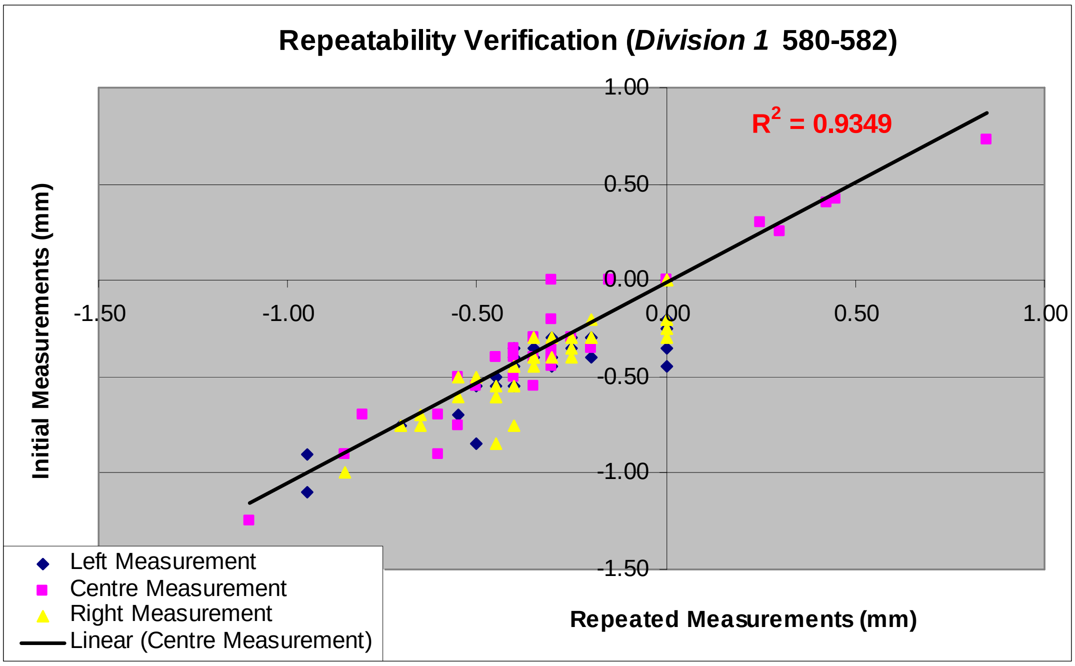


Figure 4.9 Repeatability Verification

The X axis in Figure 4.9 represents the repeated readings and the Y axis represents the original Measurement #5 readings. Overall, the maximum difference between repeated and actual readings is 0.2mm in Figure 4.9; only two welds out of the fifty eight repeated measurements differed by 0.3mm for the centre reading (R_{centre}). The means of each group are very close (0.197mm and 0.215mm respectively).

A linear regression analysis (black trendline in Figure 4.9) of the data was completed and the R-square test calculated. The R-square value is an indicator that reveals how closely the repeated readings correspond to the actual data. A trendline is most reliable when its R-square value is near 1.0. The R-square value calculated for the repeated data come to 0.9349 and with a standard error of 0.09mm (more detail in Appendix E).

Over 15,000 readings were gathered during the duration of the present project and a 93% accuracy of the measurement technique established through the above repeatability test gives a high confidence that the overall data collected is reliable.

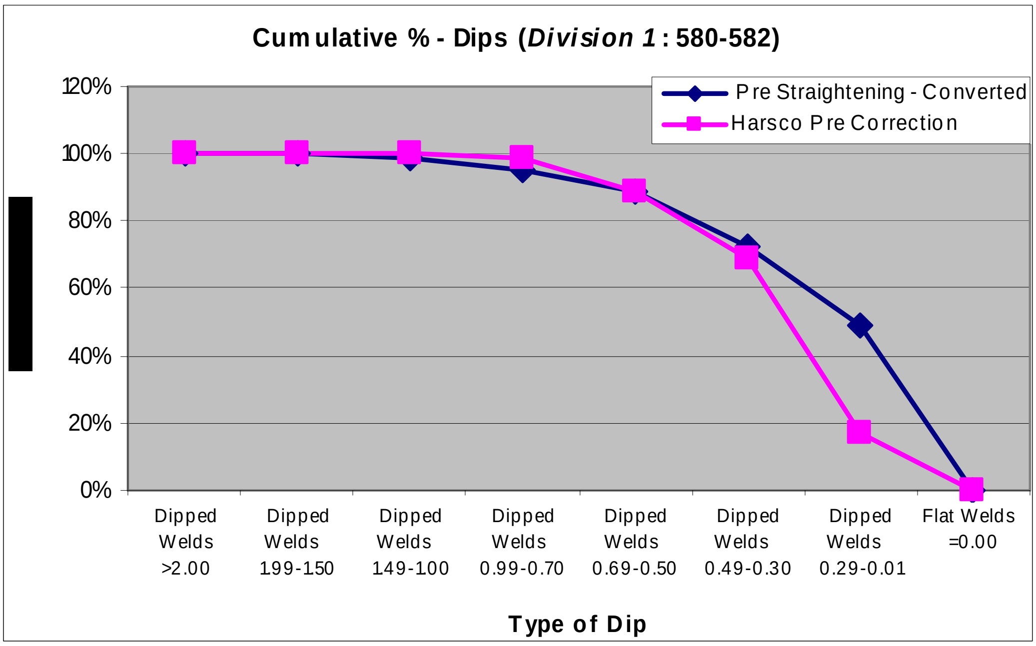
In addition to the repeatability verification, readings collected using the 1.5m straight edge during Measurement #1 (refer to Figure 3.13) were converted to a 1m edge readings and compared against the contractor's, Harsco Track Technology, pre-straightening (June 2003) measurements, as discussed in Section 4.4.

Both the Harsco data and the data converted to 1m straightedge equivalent were separated into dipped and peaked welds and analysed separately, as shown in Figure 4.10**.**

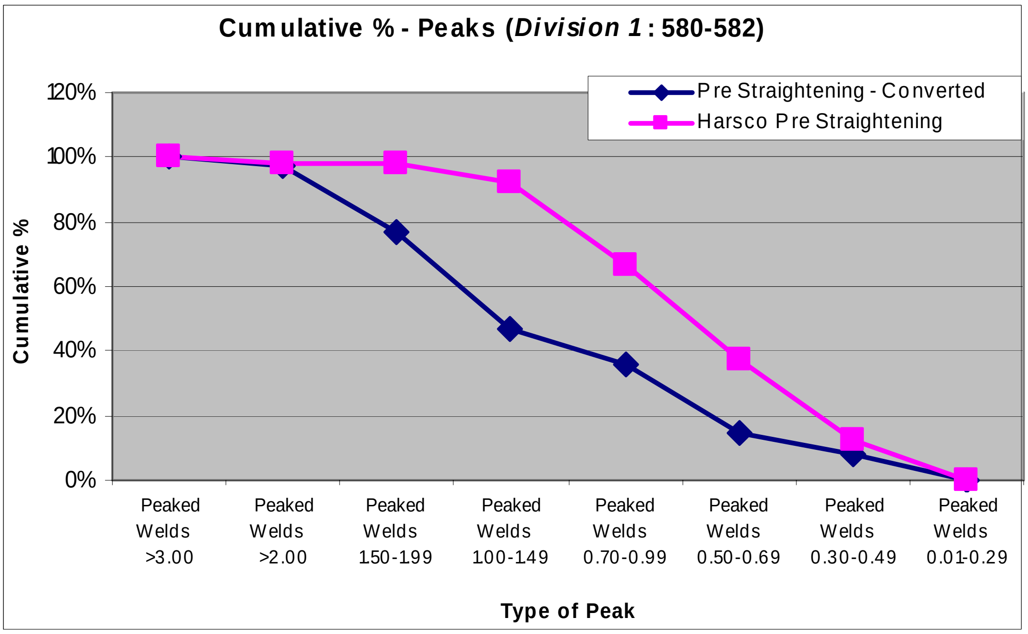
The trends shown in the dipped welds graph (Figure 4.10 (a)), demonstrate that:

- The conversion principle followed to convert the 1.5m straight edge readings to a 1m edge readings is reasonable, and
- The measurement technique and the use of the 1.5m straight edge adopted for the present project gives a comparable representation of the conditions of the welds.

On the other hand, a large difference between the two separate readings plotting peaked welds is evident (Figure 4.10 (b)). This discrepancy between peaked welds readings can be attributed to HTT recording techniques. It was established that HTT measurement technique was required to identify peaked welds only by their location and their approximate degree of misalignment, unlike the dipped welds where HTT needed accurate measurements to identify which welds were to be straightened and which weren’t. It was the manual grinder’s responsibility to accurately measure the peaked welds and grind them to the agreed tolerance; these readings by the manual grinder were not written down. The recorded HTT peaked weld readings are therefore suspect.



(a) Dipped Welds



(b) Peaked Welds

Figure 4.10 Cumulative Percentage Graphs – *Division 1*: (a) Dipped Welds (b) Peaked Welds

5.0 OUTCOMES FROM THE PROJECT DATA ANALYSIS

The presence of poor welds in track, as discussed in Section 2.2.3, gives rise to larger dynamic forces by moving rollingstock. These impacts create large vibrations which, over time, can induce ballast compaction or even crushing with consequent loss of track top. Reduction in the severity of poor welds has been typically targeted by railway networks with the use of maintenance cycle tamping and grinding operations.

Tamping operations renew both track top and horizontal alignment by lifting the track to the desired level and compact the ballast under the sleepers to hold it in position. Tamping activities improves the longitudinal profile of discrete irregularities, such as poor welds, as a secondary benefit. However, the smoother running surface of the discrete irregularities, like dipped welds, is short lived as traffic re-establishes a similar profile to the original (refer to Section 2.6.1).

Cycle grinding has been used over the last few decades in railway networks primarily to relieve rail surface defects, such as corrugation, shelling and cracks, and to establish a good wheel-rail contact patch by profiling the rail head. It has been suggested that a secondary benefit of cycle grinding is its ability to reduce the severity of poor welds present in track. These improvements are achieved by removing a small layer of metal (tenths of a millimetre) from the head of the rail. However, due to the configuration of the grinding machines, particularly of the grinding stone blocks, it has been implied that cycle grinding may worsen the degree of misalignment of dipped welds.

With the constant increase in train speeds and loads, railway networks have the need to specifically target maintenance activities at the removal of poor welds in track. Over the last decade, a number of research and development projects have been undertaken to manufacture machines capable of removing or at least relieving localised defects like dipped or peaked welds. Machines such as the RASTIC straightening machines (McMichael 1990) have been developed to focus on this issue.

As part of the present project, a detailed investigation of the effect of straightening activities on the track geometry has been completed. In addition, a comparative analysis of straightening, tamping, straightening and grinding works has been conducted to establish the most efficient maintenance operation for the removal of poor welds in track, both short and long term.

It is recommended that future work which draws on the results of this project should look towards a cost-benefit analysis of the related maintenance activities.

The data used to determine the effects of individual maintenance activities was the converted 1m straight edge readings (refer to Section 4.4). Primary focus on means and standard deviations of weld measurement did not illustrate the accurate effects of individual maintenance activities completed in the three divisions, as outlined in Section 5.1. A better approach to demonstrate the effects of maintenance works on the quality of weld misalignments is track the history of groups of welds. Outcomes from this analysis are discussed in Section 5.2.

5.1 EFFECT OF MAINTENANCE ACTIONS

As discussed in Section 3.4, each 2km *Division* of the test track was exposed to a number of maintenance activities during the life of the project. Figure 5.1 is a reproduction of the maintenance activities completed in the test section. The data gathered during each measurement was analysed following a time sequence approach. The mean values of weld readings collected during each measurement were calculated and plotted against time (refer to Figures 5.2 and 5.3). Dipped and peaked welds were separated to distinguish the effects of different maintenance activities on different weld geometries.

The overall history of the effects of maintenance activities on weld geometry can be also determined by calculating the difference between means of welds before and after the completion of maintenance activities. To see the full picture, the six kilometre test section was sub-divided into six 1km sub-parts; the means of welds located in each sub-part were calculated and the short and long term effect of maintenance operations summarised in Tables 5.1 and 5.2. Negative values represent improvements in weld misalignments whilst positive values correspond to degradation of welds geometry.

Sections 5.1.1 to 5.1.4 discuss these findings.

5.1.1 PRE-STRAIGHTENING TAMPING – JULY 2003

The entire six kilometre test section was scheduled to be cycle tamped prior to weld straightening operations and especially prior to the recording of Measurement #1, but, discussed in Section 3.4, due to the availability of the cycle tamping machine only in *Divisions 1* and *2* were tamped prior to this first set of readings. *Division 3* was cycle tamped following the recording of Measurement #1 as indicated in Figure 5.1.

A possible effect of this difference in tamping is shown in Figure 5.2 (a) where the means of welds recorded in Measurement #1 representing dips located in *Divisions 1* and *2* were found to be approximately 1/3rd of the mean of dipped welds calculated in *Division 3*. Now, the three *Divisions* were of the same track construction, rail size, sleeper type and size, ballast type and depth and subgrade material. The only factor that could account for the difference in mean dipped welds in Measurement #1 was the difference in tamping of each *Division*. Consequently, it seems that tamping helped reduce dipped welds misalignments, by lifting and aligning the running surface of the rail.

On the other hand, the means of peaked welds calculated from the data recorded in Measurement #1 show a reverse situation. The mean of peaked welds in *Division 3* (i.e. not cycle tamped) is significantly smaller than the means calculated for either *Divisions 1* and *2*, as shown in Figure 5.2 (b). This suggests that packing of the ballast by tamping may have pushed up already peaked rail alignments creating an increase in peaked welds severity.

From the data in Tables 5.1 and 5.2, it can be observed that the mean of dips and peaks in *Division 3* had a significant improvement following cycle tamping. The average improvement in dipped and peaked welds is over 0.5mm. This corresponds to a reduction in weld misalignment of almost half the original condition.

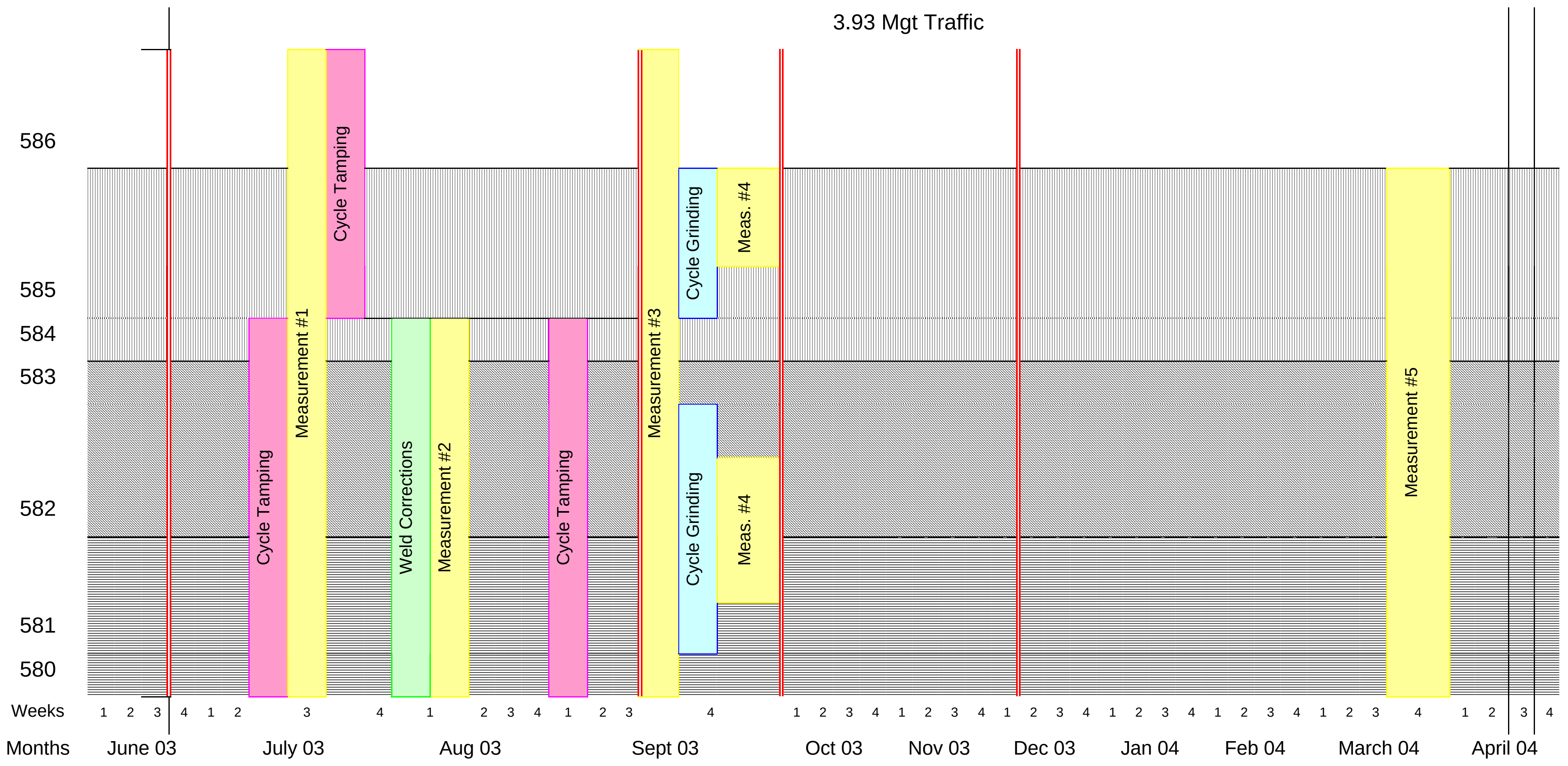
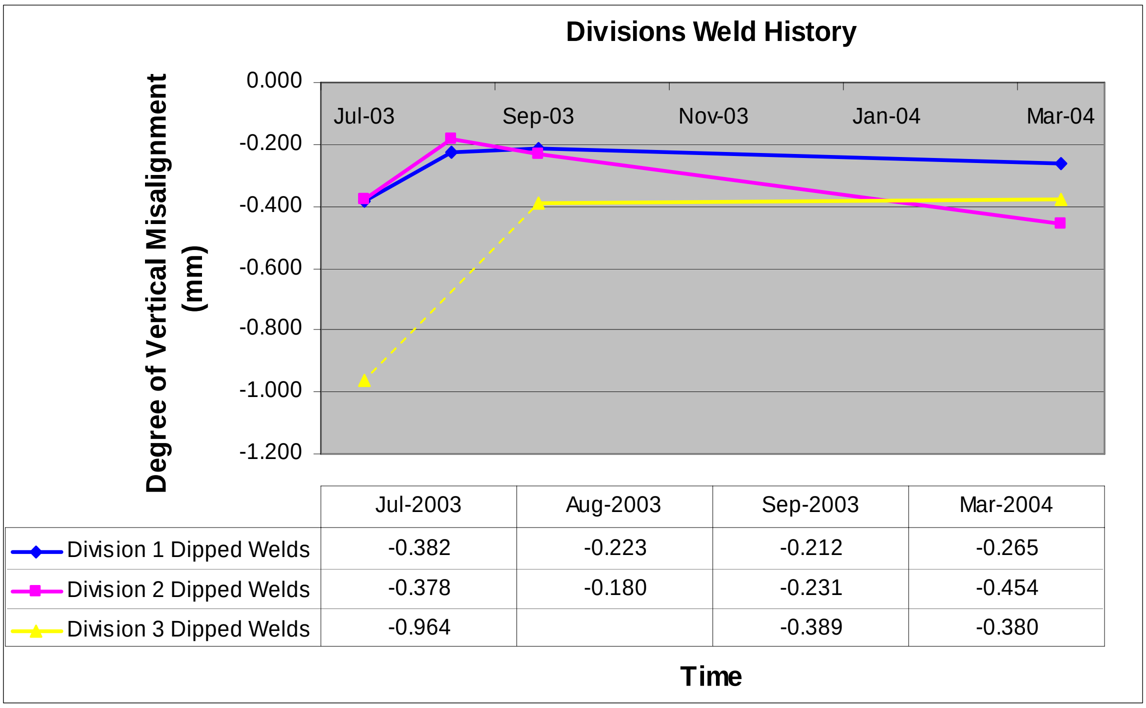
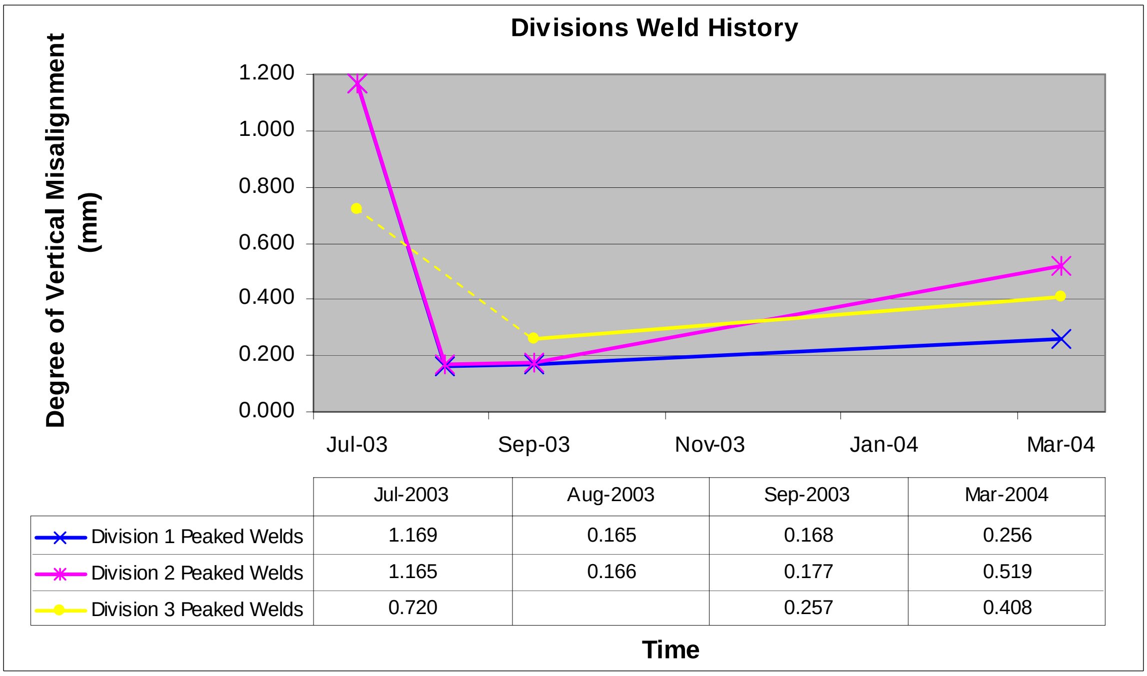


Figure 5.1 Divisions Programmed Work



	Jul-2003	Aug-2003	Sep-2003	Mar-2004
Division 1 Dipped Welds	-0.382	-0.223	-0.212	-0.265
Division 2 Dipped Welds	-0.378	-0.180	-0.231	-0.454
Division 3 Dipped Welds	-0.964		-0.389	-0.380

(a) Dipped Welds



	Jul-2003	Aug-2003	Sep-2003	Mar-2004
Division 1 Peaked Welds	1.169	0.165	0.168	0.256
Division 2 Peaked Welds	1.165	0.166	0.177	0.519
Division 3 Peaked Welds	0.720		0.257	0.408

(b) Peaked Welds

Figure 5.2 Mean of Welds Readings (a) Dipped welds (b) Peaked Welds

Table 5.1 Δ (Change in Mean Value) – Short and Long Term Effects of Maintenance Activities on Dips

Divisions / Sub-part	Interventions[*]	Δ_{means} (mm) Short Term Effect July 03 – August 03	Δ_{means} (mm) Short Term Effect August 03 – September 03	Δ_{means} (mm) Short Term Effect Sept 03 – Sept 03	Δ_{means} (mm) Long Term Effect September 03 – March 04
1/1	T, S, T, Tr	-0.11 (S)	-0.07 (T)	-	+0.12 (Tr)
1/2	T, S, T, G, Tr	-0.21 (S)	+0.05 (T)	-0.01 (G)	-0.01 (Tr)
2/1	T, S, T, G, Tr	-0.16 (S)	+0.04 (T)	+0.10 (G)	-0.10 (Tr)
2/2	T, S, T, Tr	-0.24 (S)	+0.12 (T)	-	-0.08 (Tr)
3/1	T, Tr	-	-0.60 (T)	-	-0.02 (Tr)
3/2	T, G, Tr	-	-0.56 (T)	+0.09 (G)	+0.10 (Tr)

[*] S = straightening of dips, manual grinding of peaks, T = cycle tamping, G = cycle grinding, Tr = traffic

Table 5.2 Δ (Change in Mean Value) – Short and Long Term Effects of Maintenance Activities on Peaks

Divisions / Sub-part	Interventions[*]	Δ_{means} (mm) Short Term Effect July 03 – August 03	Δ_{means} (mm) Short Term Effect August 03 – September 03	Δ_{means} (mm) Short Term Effect Sept 03 – Sept 03	Δ_{means} (mm) Long Term Effect September 03 – March 04
1/1	T, S, Tr	-0.85 (S)	0.00 (T)	-	+0.07 (Tr)
1/2	T, S, G, Tr	-1.14 (S)	+0.01 (T)	-0.01 (G)	+0.12 (Tr)
2/1	T, S, G, Tr	-1.00 (S)	+0.02 (T)	-0.04 (G)	+0.07 (Tr)
2/2	T, S, Tr	-1.00 (S)	-0.01 (T)	-	+0.06 (Tr)
3/1	T, Tr	-	-0.44 (T)	-	+0.23 (Tr)
3/2	T, G, Tr	-	-0.52 (T)	-0.04 (G)	+0.15 (Tr)

* S = straightening of dips, manual grinding of peaks, T = cycle tamping, G = cycle grinding, Tr = traffic

5.1.2 POST STRAIGHTENING – AUGUST 2003

Approximately four weeks after the completion of the cycle tamping operations, straightening works were undertaken in *Divisions 1* and *2*, as illustrated in Figure 5.1.

These two *Divisions* were exposed to different levels of corrections; all welds in *Division 1* were corrected whilst in *Division 2* only dipped welds equal to or greater than 0.3mm in dip and all peaks were corrected. This permitted investigation of the effectiveness of different levels of intervention by straightening operations on the geometry of dipped welds.

The means of dips and peaks from the data recorded during Measurement #2 for these two *Divisions* are shown in Figure 5.2 to be very similar in magnitude. Targeting dips smaller than 0.3mm in vertical misalignment with straightening operations did not appear to result in any additional benefit in terms of overall misalignment of welds. This can be also observed from the data summarised in Table 5.1. The short term improvements calculated following the straightening of dipped welds in *Division 1* and *2* are almost identical. This supports the previous statement indicating that straightening welds smaller than 0.3mm in dip does not result in a better condition of the overall track.

Future straightening operations should investigate whether 0.3mm is the most effective intervention limit for dips or if the limit can be increased to 0.4mm or 0.5mm or more. In addition, further investigation should be carried out to determine the dynamic effects of the dipped welds left in track on the overall deterioration of the track structure.

The annual maintenance expenditure allocated by individual railway systems to rectify misaligned welds can be significantly reduced by now knowing that no additional track quality is achieved by targeting welds with a misalignment lesser than 0.3mm with rail straightening operations.

5.1.3 POST-STRAIGHTENING TAMPING & TRAFFIC – AUGUST/SEPTEMBER 2003

Between early August and late September 2003 (Measurement #2 and #3 respectively), the entire six kilometre test section was subjected to normal traffic condition, but, cycle tamping was undertaken again in *Divisions 1* and *2*, as shown in Figure 5.1.

During this two months period, the mean of dips present in *Divisions 1* and *2* appeared to remain constant, showing very minor changes in weld geometry, as illustrated in Figure 5.2. The means of peaks located in *Divisions 1* and *2* observed a slight “growth” in peak severity.

The effect of the small amount of traffic in this time was expected to be small, so it is almost certain that the re-tamping of *Divisions 1* and *2* made very little effect upon the already straightened welds. Comparing this outcome with the large effects of tamping discussed earlier, it seems that tamping has an influence only over the more severe weld misalignments.

In addition the variance in weld misalignments, shown in Table 5.1 and 5.2, of the four corrected kilometres of track due to 8 weeks of normal traffic and cycle tamping are within the calculated standard error of the writer’s measurements of ± 0.09mm discussed in Section 4.5.

5.1.4 POST-STRAIGHTENING CYCLE GRINDING – SEPTEMBER 2003

Part of the scope of the present research project is to identify the effects of cycle grinding on corrected welds. To determine the changes, if any, of weld geometry caused by cycle grinding operations, Measurement #3 and #4 were taken immediately before and after cycle grinding activities completed in late September 2003.

As discussed in Section 3.4 and illustrated in Figure 5.1, only one kilometre in each *Division* was exposed to cycle grinding. Therefore, the mean of weld dips and peaks in individual kilometre portions of each *Division* were calculated and summarised in Table 5.3; negative values represent improvements whilst positive values represent deterioration.

From the data in Table 5.3, it can be observed that cycle grinding had a negligible effect on peaks, whilst it seemed to produce a minor worsening in dips.

The slightly negative effect of cycle grinding on dipped welds can be attributed to the configuration of the grinding machines, particularly of the grinding stone block. As described in Section 2.6.3, the grinding blocks tend to follow the longitudinal profile of the rail whilst grinding. All grinding machines have a time delay function inbuilt into the systems that attempts to prevent this from occurring; however, the data included in Table 5.3 suggests that the grinding stones are still removing too much rail head at dipped welds locations and not enough at peaked welds.

Table 5.3 Means of Welds Cycle Ground

***Division 1* - 580-582**		23 Sept 2003 (pre grinding) Measurement #3	28 Sept 2003 (post grinding) Measurement #4
581-582km	Cycle Ground – Dips	-0.255mm	-0.247mm
581-582km	Cycle Ground – Peaks	0.158mm	0.153mm

***Division 2* - 582-584**		23 Sept 2003 Measurement #3	28 Sept 2003 Measurement #4
581-582km	Cycle Ground – Dips	-0.187mm	-0.290mm
581-582km	Cycle Ground – Peaks	0.186mm	0.147mm

***Division 3* -584-586**		23 Sept 2003 Measurement #3	28 Sept 2003 Measurement #4
585-586km	Cycle Ground – Dips	-0.397mm	-0.490mm
585-586km	Cycle Ground – Peaks	0.275mm	0.232mm

These results can also be clearly viewed in Tables 5.1 and 5.2. The variances in means of dips pre and post cycle grinding are slightly greater than the statistical standard error calculated earlier (refer to Section 4.5). This suggests that grinding negatively affected dipped welds, even marginally, is detrimental. On the other hand, the variances in means calculated for peaks are much smaller than the calculated error and therefore can be neglected.

As detailed in Section 2.6.3, the principal aim of cycle grinding is to remove continuous rail defects, minor rail surface defects and establish an effective contact band between wheels and rail by profiling the rail head; removal of poor welds has always been a secondary benefit of this maintenance activity.

The minimal improvements achieved by cycle grinding operations for the rectification of poor welds in track cannot justify using this maintenance activity to remove or alleviate misaligned welds. As a result, grinding schedules are not required to be completed for the removal of misaligned welds hence reducing maintenance cost allocated to such activity.

5.1.5 POST-CYCLE GRINDING TRAFFIC – SEPTEMBER 2003/MARCH 2004

Following the cycle grinding operations, normal traffic tasks resumed operating over the six kilometre test section up until March 2004, in accordance to plan (refer to Figure 5.1). During this time frame, no additional maintenance activities were completed in the area. The total Million Gross Tonnage (Mgt) over the test section between August and September 2003 was estimated to be 0.56Mgt and from late September 2003 until late March 2004 was estimated to be 3.37 Mgt.

The overall quality of dipped weld misalignments was expected to show a noticeable deterioration between late September 2003 and late March 2004 during which normal full traffic was operating. Surprisedly, means of dipped welds calculated for *Divisions 2* and *3* actually showed a small improvement in weld geometry whilst *Division 1* indicated a minor deterioration, as shown in Figure 5.2 (a). These improvements, however, are less than the statistical standard error (refer to Section 4.5) and therefore need confirmation by longer term investigation.

On the other hand, it was anticipated that the misalignments of peaked welds would reduce under the constant loading of rollingstock. As indicated in Figure 5.2 (b) the mean of peaked welds misalignment increased over time.

From Tables 5.1 and 5.2, the variances in means of weld misalignments calculated on a kilometre basis indicates that the effect of all maintenance activities completed on dipped welds helped to maintain the improvements even after 7 months of traffic. Similarly, the mean of peaks in *Divisions 1* and *2* remained almost unaltered giving very small variances. Surprisingly *Division 3* showed a sizeable increase in peaks. To determine if this apparent effect of traffic on the peaks present in *Division 3* was statistically significant, a student t-test was completed using the means of Measurements #4 and #5. The null hypothesis assumed that the means of the two samples were identical.

As indicated in Appendix E, the two-tiled P value resulted in a much smaller value than the 5% confidence of the means being equal. The difference is considered extremely statistically significant meaning that there is a 95% confidence that the null hypothesis can be rejected and the means of the two samples are different.

This implies that traffic indeed affected the weld geometries; however, further investigation on the reasoning for increasing the peaks severity should be undertaken in future projects.

Overall the straightening operations completed in August 2003 had a large positive effect on the geometry of welds by removing the dips and maintaining the new profiles under traffic conditions.

5.2 25%ILE WELD GROUPS

The discussion above looked at simple means of all welds as they were at the time of each Measurement. This approach does not allow study of the effect of straightening, grinding, tamping, etc on individual welds’ performance. In an attempt to extract this information, welds located in *Divisions 2* were sorted into four groups of roughly equal numbers of welds of differing degree of misalignment, the four groups hereafter being called 25%ile groupings.

The cumulative percentage graph in Figure 5.3(a) shows the distribution of welds at the time of Measurement #1, and was used for this purpose. The following limits for the resulting groups of corrected welds in *Division 2* were therefore established to be as follows, as illustrated by the dotted red lines on Figure 5.3(a):

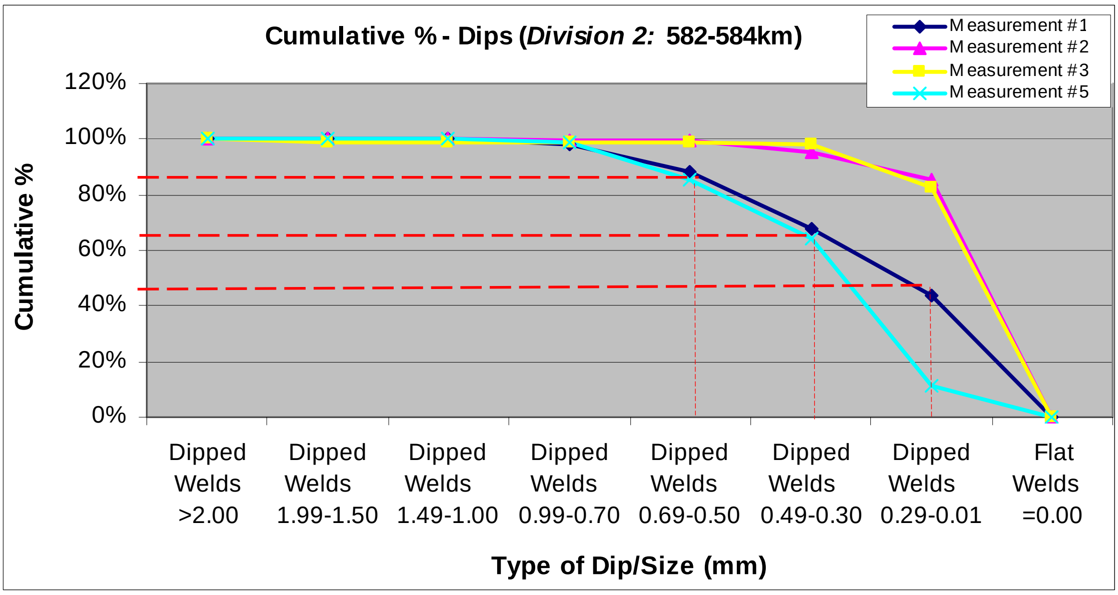
- all corrected dipped welds that were smaller than 0.3mm at the time of Measurement #1 – Group 1 (note that the limit of 0.3mm is based on the dip calculated for a 1m straightedge; whether a weld was to be corrected or not was based on the 1.5m straightedge centre reading – this is why there were some dipped welds <0.3mm which were corrected);
- all corrected dipped welds smaller than 0.42mm but greater or equal to 0.3mm – Group 2;
- all corrected dipped welds smaller than 0.61mm but greater or equal to 0.42mm – Group 3;
- all corrected dipped welds greater than 0.61mm – Group 4.

Two additional groups included the corrected peaks and the not-corrected dips (i.e. those with a vertical misalignment smaller than 0.3mm on a 1.5m straightedge reference - refer to Section 3.4).

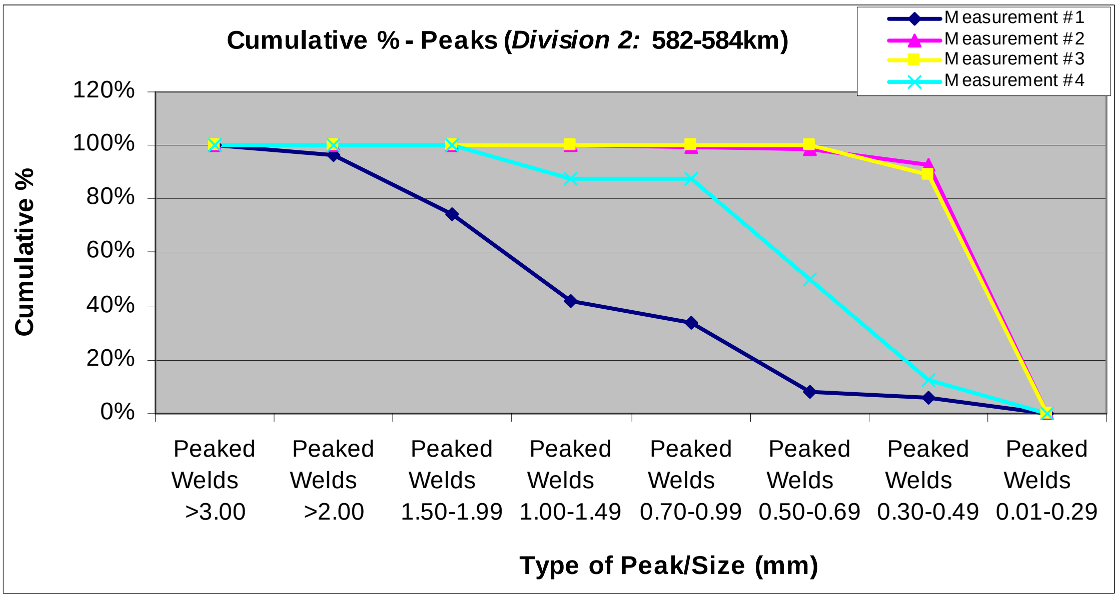
The welds falling into each of the above 6 groups were then tracked individually through the various Measurements. The mean misalignments in mm of all welds in each group were then plotted against time and are presented in Figure 5.4. Each coloured line represents the history of one unique group of welds.

Straightening activities proved to have a very significant effect on all groups of welds; in fact, corrections of poor weld misalignments proved to reduce the means of all groups of welds to a common value close to zero. However, Figure 5.4 does not represent the distribution of corrected weld within each of the 25%ile groups, only the means.

Figure 5.5 illustrates the distributions of all corrected welds combined, within *Division 2*. Each array of single colour columns represents a given set of recorded Measurements (as described in Section 3.4) divided into five ranges of weld misalignment, with the median of each of those ranges (-1.2mm, -0.8mm, etc) shown on the horizontal axis.

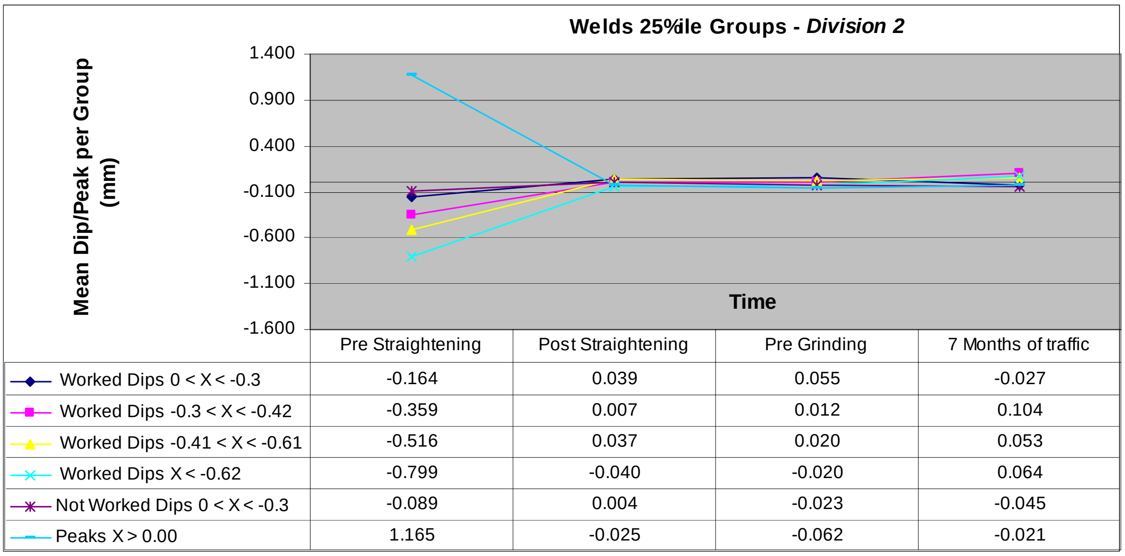


(a) Dips



(b) Peaks

Figure 5.3 *Division 2* Cumulative Percentages of Welds (a) Dips (b) Peaks



	Pre Straightening	Post Straightening	Pre Grinding	7 Months of traffic
◆ Worked Dips 0 < X < -0.3	-0.164	0.039	0.055	-0.027
■ Worked Dips -0.3 < X < -0.42	-0.359	0.007	0.012	0.104
▲ Worked Dips -0.41 < X < -0.61	-0.516	0.037	0.020	0.053
× Worked Dips X < -0.62	-0.799	-0.040	-0.020	0.064
✳ Not Worked Dips 0 < X < -0.3	-0.089	0.004	-0.023	-0.045
− Peaks X > 0.00	1.165	-0.025	-0.062	-0.021

Figure 5.4 Means (mm) of Misalignments in Each 25%ile Group – *Division 2*

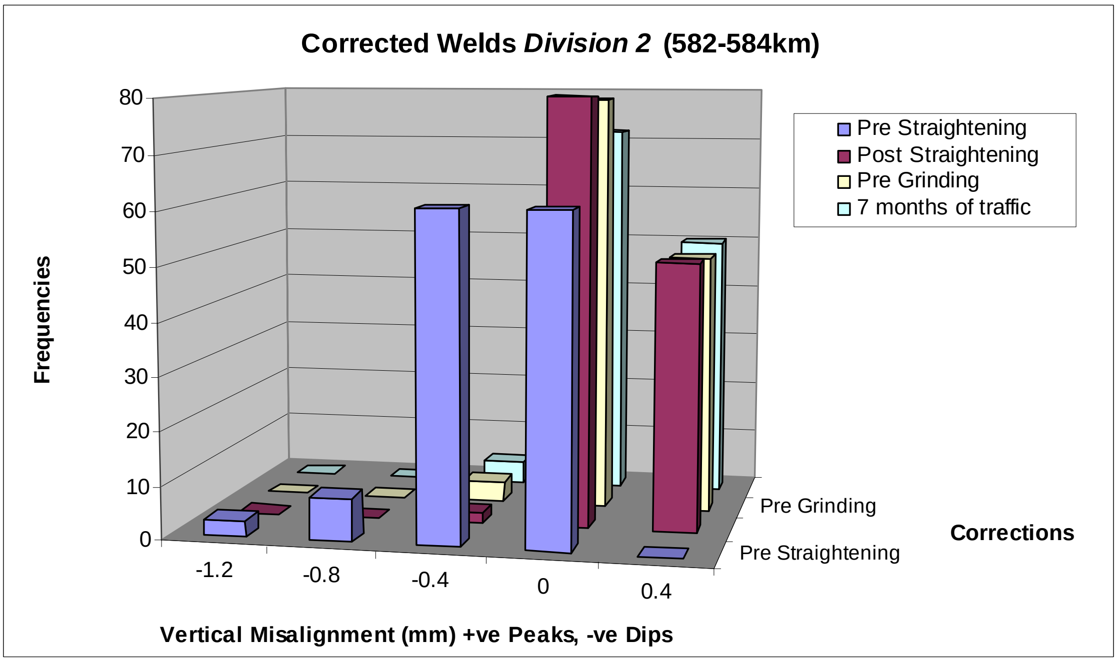


Figure 5.5 Weld Misalignments Distributions – *Division 2*

It is obvious from Figure 5.5 that straightening operations pushed the weld misalignments distributions towards the positive (peaked) side of the graph. This implies that straightening works removed all of the severe and many of the small dips present in track and created more peaks. The tamping works undertaken following straightening but before the cycle grinding appears, yet again, to have little or no effect on the state of the track. Additionally, cycle grinding appears to have very little effect on peaks and dips post straightening; this is shown by the similarity in distributions between Pre grinding and 7 Months of Traffic.

A comparison between corrected and not corrected welds was undertaken to confirm the effectiveness of each maintenance intervention completed in *Division 2*. Figures 5.6 and 5.7 represent the cumulative percentages of corrected and not corrected welds, respectively, present in *Division 2* following each maintenance work.

The means of all the corrected welds post-straightening in Figure 5.7 are all around zero, confirming the results shown in Figure 5.4. However, Figure 5.7 shows that the distributions of welds post-straightening were little affected by tamping or cycle grinding, and remained approximately between ±0.3mm.

Referring back to Figure 5.4, two of the six 25%ile groups were analysed separately; see Figures 5.8 and 5.9 where the distributions of welds within Groups 1 and 4 illustrate changes in weld misalignments after each maintenance intervention. Each coloured line represents the cumulative percentage of the welds misalignments at specific Measurements recordings.

Again, it is possible to see that no matter the severity of the weld misalignment, straightening operations managed to improve the weld geometry to a common level, which averages between ±0.3mm. Additional maintenance activities, such as cycle tamping post straightening and cycle grinding, and traffic loads are confirmed to have little influence on the means or distributions of corrected welds at all.

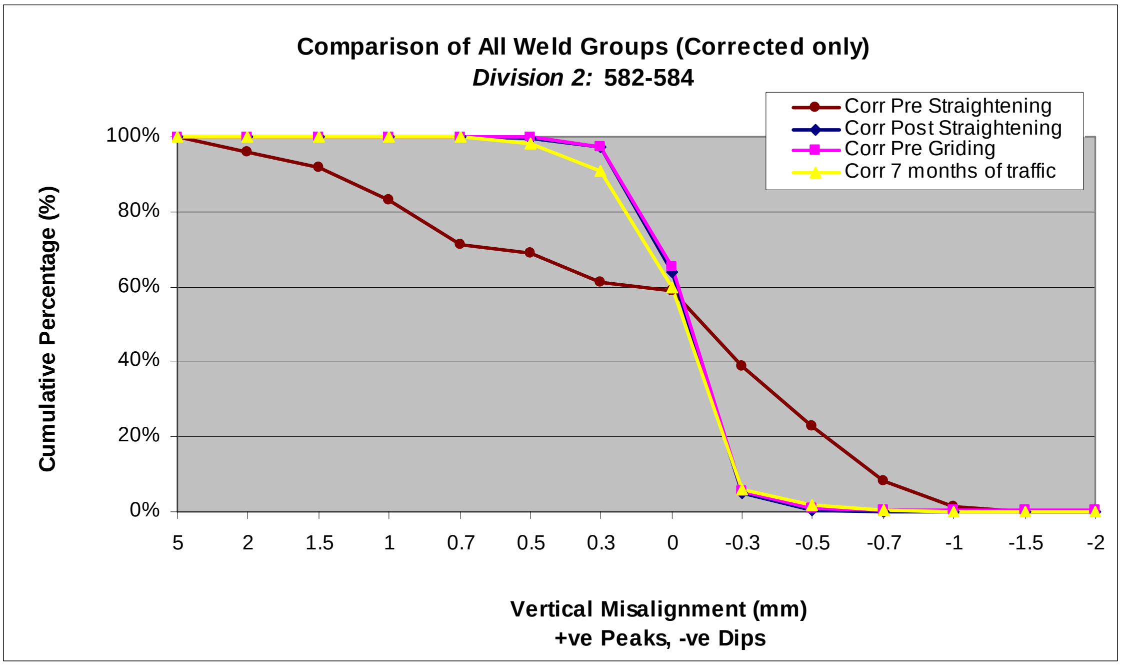


Figure 5.6 Comparison of all Corrected Welds in *Division 2*

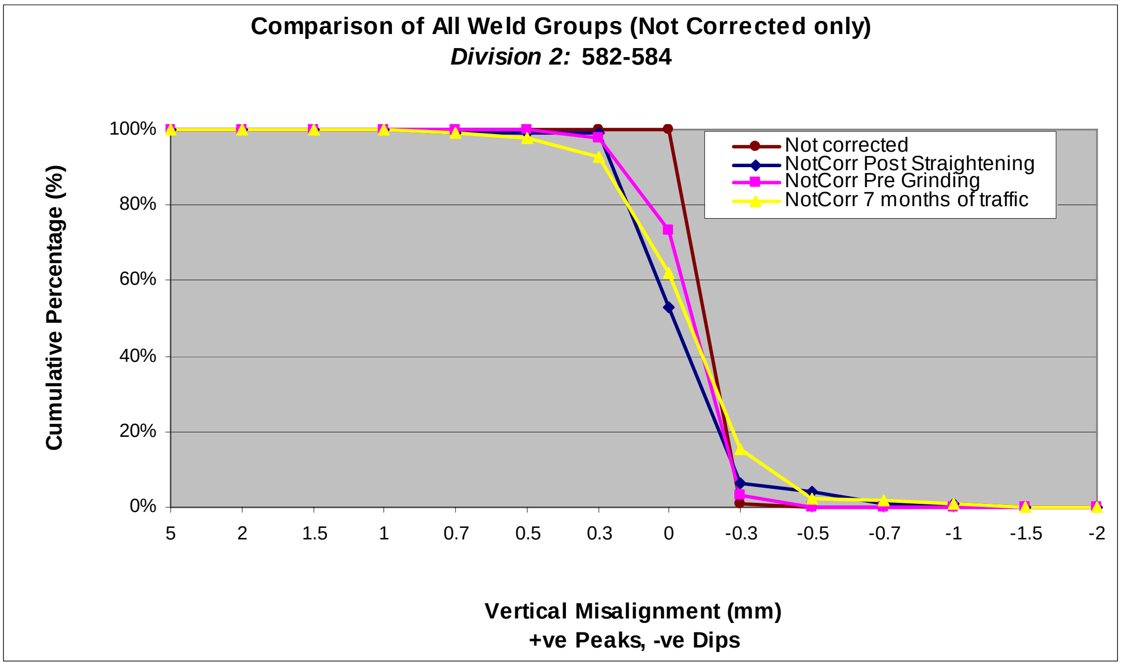


Figure 5.7 Comparison of all Not Corrected Welds in *Division 2*

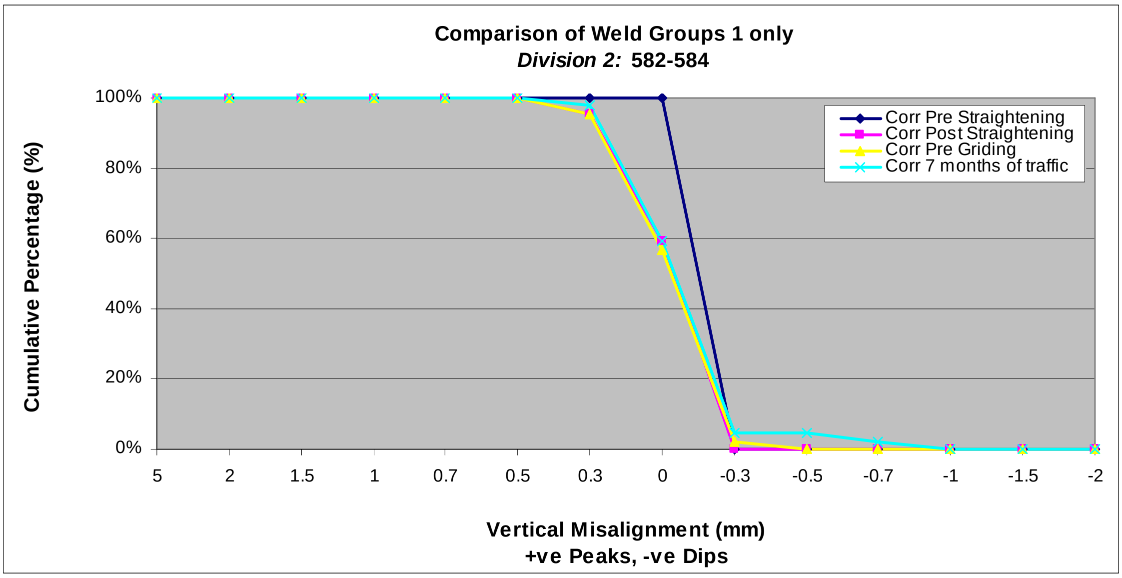


Figure 5.8 Comparisons of Welds – Group 1 only

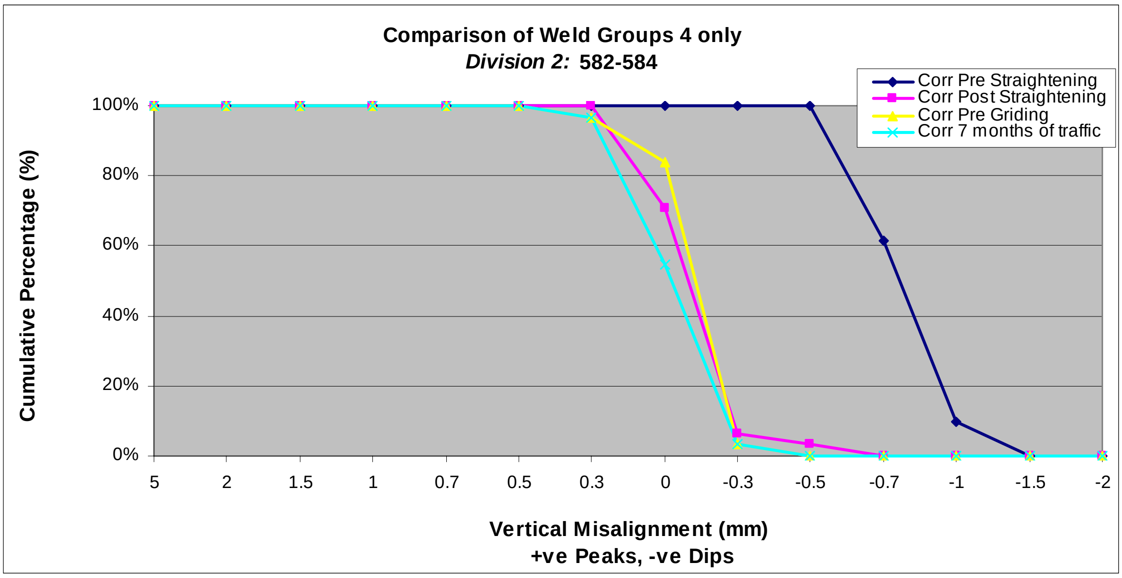


Figure 5.9 Comparisons of Welds – Group 4 only

6.0 CONCLUSIONS & RECOMMENDATIONS

In making commercial decisions in railways, there are often obvious benefits to be gained by operating trains at higher speeds and greater axle loads. It is important then to maintain the track at the highest practical quality and lowest reasonable safety risk at the same time.

The track is exposed to a variety of forces, both vertical and lateral. The ones that are of most concern to the performance and longevity of all track components are the vertical dynamic impacts caused by existing track irregularities, poorly maintained welds, rail wear patterns (i.e. corrugation) and rollingstock defects. Removal of track and wheel defects is essential to minimise the high dynamic forces that otherwise would be induced in all the track components.

6.1 CONCLUSIONS

Only in relatively recent years has the importance of dipped/peaked welds on track degradation been realised. The straightness of the welds is important to prevent high dynamic force increments and particularly to reduce defect growth, noise propagation and poor vehicle ride. Limited research has been undertaken on the effects of misaligned welds on the components of the track.

Scheduled maintenance activities such as cycle tamping and rail grinding, temporarily improve the longitudinal alignment of weld. However, when the track is re-opened to traffic, the weld geometry appears to return close to its original state.

Following an internal investigation conducted by QR on the state’s entire rail network, it was identified that the Mt Isa Line (MIL) required a better rail defect management, particularly of misaligned welds, in order to improve the overall quality and extend the life of the track structure. A 6km test region was selected on the MIL and sub-divided into three 2km Divisions. Each Division was exposed to a number of maintenance operations (i.e. cycle tamping, weld straightening and cycle grinding); the data was analysed and number of conclusions drawn, which are listed as follows:

a) The effect of cycle tamping operations was clearly identified following the analysis of the collected data from the six kilometre test region. It was clear from the comparison of the mean misalignments of peaked and dipped welds present in the three *Divisions* that cycle tamping affected the geometry of the welds. Cycle tamping, without any other intervention, was shown to have a significant positive effect on the geometry of dipped welds. On the other hand, the peaked welds were adversely affected by cycle tamping. However, when cycle tamping occurred after straightening operations, it appeared to not have a sizeable effect on the weld geometry.

   Improvements in the general track top alignment were also observed following cycle tamping operations, when analysing data from the Track Recording Car (refer to section 3.1.2). The rate of deterioration in the parameter known as track top, following cycle tamping, demonstrated the short term effect of cycle tamping improvements on track top values.

b) Cycle grinding of the test section proved to have little effect on the removal of either peaks or dips. In fact, due to the configuration of rail grinding machines, grinding operations produced a slight worsening of dips and a minimal improvement in peaks misalignments.

c) Weld straightening operations were undertaken on two of the three *Divisions* and each of the corrected *Divisions* was exposed to a different level of correction. A number of key findings were achieved following a detailed analysis of the data and subsequent comparison of the results of each *Division* to each other, as follows:

   - No additional benefit, in terms of overall misalignment of weld, was achieved when straightening operations targeted all dips compared to dips equal or greater than 0.3mm.
   - Following 7 months of traffic, the geometry of the corrected welds appeared to remain unchanged. The variance between the weld geometries following approximately 3.9 Mgt of traffic was within the tolerances of the statistical error in measurements on the test section, and therefore negligible.

d) The distribution of weld misalignments, following straightening operations, was moved from being mostly dips to being mostly peaks. It is a railway preferred option to have peaked welds than dipped welds in track. The data analysis also demonstrated that straightening operations were able to reduce the weld misalignment to a common level, between the limits of +0.3mm, no matter the original severity of the weld.

e) Additionally, from the Track Recording Car data, it was demonstrated that straightening operations may have contributed in maintaining more prolonged long term improvements in track top geometry. In fact, the degradation rate of the track top condition for the six kilometre test section was sizeably reduced following straightening operations in 2003/04 when compared to the results in 2002/03.

In conclusion, dipped/peaked welds are a hazard to railway network. The change in angle between the entry and exit slope into and out of the misaligned weld causes large dynamic forces. Reduction of the degree of dip/peak (i.e. the change of angle) is an important operation to be adopted in maintenance activities to extend the life of track assets by reducing impact forces. It is important to take every possible step to ensure the total removal of such irregularities to increase the service life of track components, to reduce any safety risk and improve the ride comfort for the future services.

6.2 RECOMMENDATIONS

Railway systems can earn more money from their track if they can carry heavier and/or faster trains on it. The challenge to the track engineer is to match this by showing where the track can properly carry much higher axle loads without expensive upgrades, and to predict accurately when and where there is an unavoidable need to spend money on maintenance or upgrading.

The results gained from the present project are the first “stepping-stone” to understand the effects of straightening and grinding of welds on the overall quality of the track. It is important to continue to monitor the six kilometre test region on the MIL to quantify the long-term benefits of straightening operations versus tamping or grinding works on the geometry of welds.

Welds not corrected in *Division 2* should be monitored in the future to identify their dynamic effect on the overall deterioration of the track structure. Furthermore, the increase in magnitude of peak misalignments in *Division 3* should be investigated.

The following issues need investigation in future studies:

- Identification of the most effective intervention level for dipped welds to be straightened; that is, can the limit below which welds are not straightened be raised to 0.4mm, 0.5mm or more.
- A cost-benefit analysis on straightening operations versus quality of track.

7.0 REFERENCE

Baggott, M. G., Mau F. (1988). "Steel Sleeper Application and Viability", Rail Research Papers 2 32-35 1988, BHP, Melbourne, Australia.

Bogdaniuk, B., Massel A., Radomski R. (2003). "Increasing rail life by forecasting fatigue failure." NDT & E International 36 n 3 131-134 April 2003, Poland.

Budai, G., Huisman, D. Dekker, R. (2004). "Scheduling Preventive Railway Maintenance Activities" Econometric Institute Report EI 2004-41, Erasmus University Rotterdam, Netherlands.

Clark, R. A. (1984). "Slip-stick vibrations may hold the key to corrugation puzzle", Railway Gazette International 140 n 7 531-533 Jul 1984, Reed Business Publishing, Sutton, Great Britain.

Cope, G. H. (1993). "British Railway Track - Design, Construction and Maintenance", 1993, The Permanent Way Institution, UK.

Daves, W., Fischer F. D. (2002). "Modelling of the plastification near the rough surface of a rail by the wheel-rail contact." Wear **253**(1-2): 241-246, Institute of Mechanics, Montanuniversitat Leoben, Austria.

Esveld, C. (2001). "Modern Railway Track", The Netherlands, Delft Univeristy of Technology, MRT Productions.

Frederick, C. O. (1978). "The effect of wheel and rail irregularities on the track", Heavy Haul Railways Conference, Session 204, Paper G.2. 14 pp 1978, Institution of Engineers, Australia & Australian Institute of Mining & Metallurgy., Barton, Australia.

Grassie, S. L. (1992). "Dynamic models of the track and their uses", FRA / ERRI Conference, TU Delft 24-26 June 19 pp Jun 1992, Kluwer Academic Publishers, Dordrecht, The Netherlands.

Grassie, S. L. (1996). "Models of railway track and vehicle/track interaction at high frequencies: Results of benchmark test." Vehicle System Dynamics **25**(Suppl): 243-262, Swets Zeitlinger Publisher, Lisse, Netherlands.

Grassie, S. L., Gregory R. W., (1982). The dynamic response of railway track to high frequency vertical excitation, Journal Mechanical Engineering Science 24 n 2 77-90 1982, Institute Mechanical Engineers.

Grassie, S. L., Gregory R. W., (1982). "The Dynamic Response of Railway Track to High Frequency Longitudinal Excitation." Journal of Mechanical Engineering Science **24**(2): 97-102, Institute Mechanical Engineers.

Grassie, S. L., Kalousek J. (1993). "Rail corrugation: characteristics, causes and treatments", Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit 207 n 1 57-69 1993, Mechanical Engineering Publications Limited, London and Birmingham, USA.

Holm (1978). "Track Structure - Optimisation of Design", Heavy Haul Railways Conference (ISBN 0 909421 02), Session 414, Paper B.5. 1978, Institution of Engineers, Australia & Australian Institute of Mining & Metallurgy., Barton, Australia.

Jenkins, H. H., Stephenson J. E., Clayton E.A., Morland G.W and Lyon D. (1974). "The effect of track and vehicle parameters on wheel/rail vertical dynamic forces", Railway Engineering Journal, Volume 3, Issue 1 2-16 Jan 1974, Institute Mechanical Engineers, Great Britain.

Kalousek, J. (1989). "Keeping heavy haul track corrugation-free", Railway Gazette International 145 n 8 545-547 Aug 1989, Reed Business Publishing, Sutton, Great Britain.

Knothe, K., Grassie S. L. (1993). "Modelling of Railway Track and Vehicle/Track Interaction at High Frequencies" Vehicle System Dynamics 22, pp 209-262 International Journal of Vehicle Mechanics and Mobility, Lisse, Germany

Lim, N.-H., Park N.-H., Kang Y.J. (2003). "Stability of continuous welded rail track." Computers & Structures **81**(22-23): 2219-2236, Pergaman-Elsevier Science, England.

Marich, S., Stewart P., Epp K.G. (1994). "Optimisation of rail grinding at BHP Iron Ore", Tenth International Rail Track Conference on Coming of Age, Australian Rail Track Past, Present and Future 1994, Railway Track Association, Brisbane, Australia.

Martin, M. (2003). "The function of ballast", Shared Services Group, QR, Brisbane, Australia.

McMichael, P.L. (1990). "RASTIC and SUPERLEV smooth the rail", British Rail Research, UK.

Mutton, P. J., Alvarez E. F. (2003). "Failure modes in Alumino-thermic rail welds undr high axle load conditions." Engineering Failure Analysis, Australia.

Mutton, P. J., Jeffs T. (1992). "Towards Improving the Performance of Rail Welds", Ninth International Rail Track Conference on Permanent Ways and Effective Means 9 pp 1992, Rail Track Association Australia, Perth, Australia.

Mutton, P. J., Moller R. H. (1994). "Improved aluminothermic rail welding technology", Tenth International Rail Track Conference on Coming of Age, Australian Rail Track Past, Present and Future 1994, Railway Track Association Australia, c/- PO Box 6068, BLACKTOWN NSW 2148, Brisbane, Australia.

O'Rourke, M. D., Waddington E. B. H. P. C. L. (1981). "Track Conditions and Standards", Transactions of The Institution of Engineers, Australia: Mechanical Engineering. v ME 6, n 3.

QR (1997) "Track Recording Car Manual", Infrastructure Services Group, QR, Brisbane, Australia.

QR (1998a). "Long Pitch Corrugation", Shared Services Group, QR, Brisbane, Australia.

QR (1998b). "P2 Forces, Shared Services Group", QR, Brisbane, Australia.

QR (2000). "Thermit Weld", Shared Services Group, QR, Brisbane, Australia.

QR (2001a). "Module Civil Engineering Track Standards Version 2 - Module: Rail", Shared Services Group, QR, Brisbane, Australia.

QR (2001b). "Mt Isa Line Information Pack", Network Access, QR, Brisbane, Australia.

QR (2001c). "Mt Isa Line Weld Straightening Contract", Network Access, QR, Brisbane, Australia.

QR (2001d). "Rail Grinding Machine", Mt Isa Line, Infrastructure Services Group, QR, Brisbane, Australia.

RIC (2003). "Field Weld Standards", Rail Infrastructure Corporation, Civil Engineering Standard, Version 2, November 2001, Australia.

Ryan, M. (2000). "The function of sleepers and fastenings", Shared Services Group, QR, Brisbane, Australia.

Shelley, S. J., Williams M. D. (1990). "Future Track Maintenance Strategies at Australian National", Conference papers for the Eighth International Rail Track Conference on Resources for Courses on Track for 2000 1990, Rail Track Association Australia, Sydney, Australia.

Shelley, S. J. (2002), "Track Recording Car Data Evaluation", Network Access, QR, Brisbane, Australia.

Shenton, J. (1978). "Deformation of railway ballast under repeated loading conditions", reprinted from Railroad Track Mechanics and Technology, pp.405-425. 405-426 1978, Pergaman Press, New York, USA.

Steffens, D. (2004). Dynamic analysis of track and assessment of its capacity with particular reference to concrete sleepers, Master of Engineering thesis, Queensland University of Technology, Brisbane, Australia.

Turner, M. (2003). "Rail Grinding", Infrastructure Services Group, QR, Brisbane, Australia.

UIC, (1979). "Rail Defects", Leaflet 712: Rail, 4th Edition, January 2002.

Zarembski, A. M. (1991). "Forecasting of track component lives and its use in track maintenance planning", Preprints of International Heavy Haul Workshop on Maintenance of Way and Train Operations, Balancing the conflicts, pp.38-44. 1991, International Heavy Haul Association, Vancouver, Canada.

Zarembski, A. M. (1997). "Intelligent use of rail grinding". Railway Gazette International. **153:** 95-97, American Railway Engineering Association, USA.

Zhai, W., Cai Z. (1997). "Dynamic interaction between a lumped mass vehicle and a discretely supported continuous fail track." Computers and Structures **63**(5): 987-997, June 1997, Ontario, Canada.

Zhai, W., Sun X. (1994). "Detailed model for investigating vertical interaction between railway vehicle and track", Proceedings of the 13th IAVSD Symposium on the Dynamics of Vehicles on Roads and on Tracks. Source: Vehicle System Dynamics v 23 n Suppl p 603-615 1994, Southwest Jiaotong Univ, Sichuan, China, Sichuan, China.

Zhai, W. M., Cai C. B., Wang Q.C, Lu Z.W., Wu X.S. (2001). "Dynamic effects of vehicles on tracks in the case of rising train speeds". Proceedings of the Institution of Mechanical Engineers. Part F, Journal of Rail and Rapid Transit **215:** 125, Professional Engineering Publishing, Republic of China.

8.0 APPENDICIES

APPENDIX A – RAIL DEFECTS CLASSIFICATION

Table A Coding used in International Union of Railways (UIC) Classification of Rail Defects (UIC 1979)

This table is not available online.
Please consult the hardcopy thesis
available from the QUT Library

APPENDIX B – CORRUGATION MECHANISMS

The rail is initially uncorrugated, but the profile has components of roughness, and inevitably, some irregularities are larger than others. This 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, thereby modifying the initial profile. The rail surface deformation, the structure reaction to the dynamic loading and the wear phenomenon are also called *damage mechanism* as shown in **Figure A**. Provided sufficient traffic passes over the site at a similar speed, the wavelength at which the dynamic load varies is similar from one train to another, and corresponds to the specific wavelength-fixing mechanism as schematically illustrated in **Figure A**. The same irregularities excite each train, and the damage caused by one train tends to exacerbate vibration of subsequent trains, leading to further damage at a specific wavelength (Grassie and Kalousek 1993).

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

Figure A Components of a General Corrugation Mechanism (Grassie and Kalousek 1993)

Grassie and Kalousek (1993) reviewed over 40 references and published a paper which summarised the work that was undertaken to understand the causes and characteristics of corrugated rail. Based on their experience, corrugation could be classified into six groups which have different wavelength-fixing and damage-mechanisms. These are summarised in Table A.

Table B Types and characteristics of corrugation (Grassie and Kalousek 1993)

This table is not available online.
Please consult the hardcopy thesis
available from the QUT Library

APPENDIX C – IMPACT FORCES ON TRACK COMPONENTS

Table C Track Components: Roles, Impact Forces, Effects and Remedies

COMPONENT	ROLES	IMPACTS FORCES	EFFECTS	REMEDIES
Ballast	Provide a firm, even bearing for the sleepers and to distribute the loads imposed by traffic as evenly as possible over the formation; Reduce pressures from the sleeper bearing area to acceptable stress levels for the underlying sub-ballast and subgrade materials Provide a resilient bed or cushion below the sleepers and absorb some of the impact from the passage of trains over the track Prevent lateral movement of the track by filling the cribs or boxes between the sleepers, providing a shoulder at the ends of the sleepers and by friction on the base and sides of the sleepers Prevent longitudinal movement of the track (i.e. rail creep) It is easily worked to enable top and line of track to be adjusted or improved without the formation being disturbed (Martin 2002)	P_2 type dynamic forces High, localised vibrations due to tamping activities	Greater ballast compaction near rail irregularities leading to an overall differential settlement Ballast crushing which will lead to: Loss of track geometry Reduced drainage properties and eventually Pumping of the track	Scheduled tamping Scheduled rail grinding to relieve rail surface irregularities which cause ballast problems Ballast Cleaning to remove finer particles or impurities such as coal dust Undercutting to re-establish a total new ballast bed of higher quality and standard

COMPONENT	ROLES	IMPACTS FORCES	EFFECTS	REMEDIES
Fastening	Vertical and horizontal supports of loads – To absorb the rail forces elastically and transfer them to the sleeper. The vertical clamping force of the rail on the sleeper much be sufficient in all load situation, even in the case of wear, in order to provide the necessary longitudinal resistance to limit the breathing length in CWR rail, to limit gaps in the case of rail fractures and to resist creep To damp vibrations and impacts caused by traffic as much as possible Lateral support of rails – To retain the track gauge and rail inclination within certain tolerances (Ryan 2000)	P_2 type dynamic forces	Amplification of the impact forces will be produced if rail is allowed to vibrate more due to a loosed or broken fastener	Replacement of loosed or broken fastening Scheduled tamping Scheduled rail grinding to relieve rail surface irregularities which cause loosening of fastenings

COMPONENT	ROLES	IMPACTS FORCES	EFFECTS	REMEDIES
Sleeper	To provide support and fixing capabilities for the rail foot and fastenings To sustain rail forces and transfer them uniformly to the ballast To preserve track gauge and rail inclination (Esveld 2001)	P_2 type dynamic forces	Timber sleepers Abrasion of the sleeper causing rapid structural degradation Cutting of the pads into the sleeper caused by high dynamic impacts induces lower services life of timber sleepers Steel sleepers High vibration will lead to less anchorage between the sleeper and the ballast due to the crushing of the ballast stones. This will lead to a reduction in vertical resistance to load impacts Concrete sleepers On poor formation, pumping may occur due to the reduced elastic properties of concrete sleepers Dynamic loads and ballast stresses can be as much as 25% higher than timber sleepers allowing greater vibrations and therefore greater crushing of the ballast stones Near dipped welds sleepers may be found “walking” along the rail or “skewing” relative to each other	Removal of defective or broken sleepers Scheduled tamping to restore good top-and-line which will reduce the impact forces onto the rail Scheduled rail grinding to relieve rail surface irregularities which will then reduce the impact loads

APPENDIX D – DATA CONVERSION

The X axis represents the distance along the 1.5m straight edge having origin at point (a), see **Figure 4.6**). The Y axis corresponds to the vertical misalignment measured from the 1.5m straight edge. Using "similar triangle" rules the Y co-ordinates for point A and C were calculated, giving:

$$A_y : \left(\frac{250}{375}\right) R_{right} \text{ and } C_y : \left(\frac{250}{375}\right) R_{left}$$

The Y co-ordinate for point **B** corresponds to the centre reading R_{centre} taken with the 1.5m straight edge, $B_y : (R_{centre})$. Therefore, the co-ordinates for point **A**, **B** and **C** are as follows:

$$A : \left(250; \frac{250}{375} R_{left}\right) \qquad B : (750; R_{centre}) \qquad C : \left(1250; \frac{250}{375} R_{right}\right)$$

However, in order to determine the actual reading recordable using a 1m straight edge, the co-ordinates of point **D** must be known, (refer to **Figure 4.11**). The intersection between a hypothetical vertical line originating at point **B** and the 1m straight edge line (heavy brown line in **Figure 4.11**) was called Point **D**. Using "similar triangle" rules it was possible to identify the Y co-ordinates of point **D**, which are:

$$D_y : \left({(C_y + A_y)}/{2} \right)$$

Where:

$$A_y : \left(\frac{250}{375}\right) R_{right}$$

$$C_y : \left(\frac{250}{375}\right) R_{left}$$

This gives:

$$D_y : \left(\frac{250}{375}\left(R_{left} + R_{right}\right)\right)$$

Therefore, the final point D co-ordinates are:

$$D:\left(750;\frac{250}{375}\left(R_{left}+R_{right}\right)\right)$$

The distance between point **B** and **D** correspond to the converted 1m straight edge reading for any given weld (see **Figure 4.11**). Now that the co-ordinates for point **D** are known, the distance **BD** can be easily determined. The distance **BD** simply corresponds to the B_y minus D_y :

$$BD: B_y - D_y$$

Where:

$B_y : \left(R_{centre}\right)$

$D_y : \left(\frac{250}{375}\left(R_{left}+R_{right}\right)\right)$

APPENDIX E – STANDARD ERROR

Table D Regression Statistics

SUMMARY OUTPUT

Regression Statistics	
Multiple R	0.940557
R Square	0.884648
Adjusted R Square	0.882588
Standard Error	0.087018
Observations	58

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	3.25201	3.25201	429.4714	6.14E-28
Residual	56	0.424039	0.007572		
Total	57	3.676049			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*	*Lower 95.0%*	*Upper 95.0%*
Intercept	0.02202	0.011766	1.87145	0.06651	-0.00155	0.045591	-0.00155	0.045591
X Variable 1	0.944664	0.045584	20.72369	6.14E-28	0.853349	1.035979	0.853349	1.035979

APPENDIX F – T-TEST

Table E t-Test results

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	-0.31957	-0.6913
Variance	0.094309	0.052724
Observations	23	23
Pearson Correlation	0.947589	
Hypothesized Mean Difference	0	
df	22	
t Stat	15.40401	
P(T<=t) one-tail	1.44E-13	<<0.05
t Critical one-tail	1.717144	
P(T<=t) two-tail	2.87E-13	<<0.025
t Critical two-tail	2.073875	