THE INTEGRATION OF RAILWAY CONDITION MONITORING TECHNOLOGIES TO ESTABLISH CONTINUOUS TRACK ASSET MANAGEMENT IMPROVEMENT

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SUMMARY

THE INTEGRATION OF RAILWAY CONDITION MONITORING TECHNOLOGIES TO ESTABLISH CONTINUOUS TRACK ASSET MANAGEMENT IMPROVEMENT

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The view of the author presented in this dissertation is that the integration of modern railway technologies and information technology systems establishes effective maintenance management and ensures continuous asset management improvement. In conjunction with the integration of different technologies is the requirement to implement these technologies and strategies in a systematic process according to a prioritised order of value adding, to improve the required service objectives (Mitchell *et al.*, 2007; Woodhouse, 2001).

The dissertation describes the planning of maintenance activities on railway assets. It involves various aspects through the asset management life cycle from asset inventory and condition data acquisitioning methods and the utilization of maintenance history to assist in the work identification, planning and work execution of maintenance activities. The challenge in the railways includes a large geographic area resulting in challenges to minimize maintenance visits and resulting costs. It further provides details on the integration and efficient utilisation of information and presents the value it adds to ensure maintenance effectiveness.

The study focuses on methods for data collection and a systematic process for decision-making analysis with the ultimate aim of producing an effective maintenance plan (specifically for mechanised tamping) based on all available infrastructure management data including operational requirements. Lastly the

effect of condition-based maintenance is illustrated, demonstrating that this strategy increases maintenance effectiveness (doing the right things), resulting in a decrease in maintenance cost and an increase in capacity.

This dissertation is dedicated to the past and future.

My parents Klasie and Zenobia

&

My beautiful daughters Jeán-Nika & Marchelle and my unborn son

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CHAPTER 1
INTRODUCTION

1 Introduction

1.1 Background

The challenge to sustain railways is driven by the ability to optimise the utilization of the asset base. It demands the establishment of a continuous asset improvement process and program that requires maintenance personnel to continuously improve their understanding of the infrastructure's performance and the relevance of the configuration to this performance. A successful asset management process incorporates these elements and results in the optimisation of the infrastructure life cycle by extending useful life while minimising the operational interference thereby increasing capacity.

Key to the asset life cycle optimisation is a decision support system for analysing maintenance requirements enabling effective management of the widely distributed asset base over the hundreds to thousands of kilometres railway network. It is known that the full potential of the existing railway capacity is not completely utilised. Therefore, the industry has to consider other approaches to create additional capacity and ensure better utilisation of available capacity. The integration and efficient utilisation of information is a major contributor to ensure maintenance effectiveness (Ebersöhn and Ruppert 1998).

Over the past 15 years, the Chair in Railway Engineering at the University of Pretoria, Transnet Freight Rail and Amtrak collaborated in various infrastructure maintenance projects. During the course of these projects, the need to develop philosophies of Railway Infrastructure Asset Life Cycle Management became apparent, specifically the need to optimise maintenance effectiveness to minimize maintenance cost while increasing asset reliability and availability that will provide an increase in asset capacity.

Typical railways measure track maintenance cost as a US dollar (or specific country currency) per kilometre or mile. It should be noted that it is difficult to measure/calculate an industry standard as these costs are influenced by multiple factors including operational speed, axle loads, substructure conditions, tonnage per annum (capacity), accessibility and network complexity & configuration. For example the cost to maintain the right-of-way in a metropolitan area such as New York City in the USA, will be totally different than maintaining the right-of-way in a rural area such as Cato Ridge in KwaZulu Natal South Africa. Noting the influences on determining the cost to maintain a section of railway line, it is however important to realise the values to maintain the railway's right of way to appreciate the reason behind conducting this research. According to Wenty (2005) the costs to maintain high capacity railway tracks (more than 100 MGT) per annum can amount to between US$ 38,750 to US$ 313,400 per mile, depending on the subgrade condition varying from standard good subgrade to extremely poor subgrade. These values indicate the importance of maintenance to enable sustainability of the railways.

The view of the author presented in this dissertation is that the correct integration of modern railway technologies and information technology systems could establish effective maintenance management practices and ensure continuous asset management improvement. In conjunction with the integration of different technologies, it is a requirement to implement these technologies and strategies in a systematic process, prioritised according to the relative value adding, to improve the required service objectives (Mitchell *et al.*, 2007; Woodhouse, 2001).

1.2 Objectives of the dissertation

The main objectives of the study are:

- Indicate an understanding of asset and maintenance management principles.
- Compare different types of maintenance strategies/tactics.
- Indicate a detailed understanding of the railway maintenance management business, focusing on track tamping as a key maintenance activity.
- Develop a maintenance decision-making model/process for effective tamping.
- Utilise and integrate technology to optimise maintenance effectiveness.
- Determine increase of maintenance effectiveness for tamping requirements through condition based and condition performance based analysis.
- Calculate the reduction in maintenance cost due to maintenance effectiveness.
- Calculate the increasing in asset availability/capacity due to improve maintenance effectiveness analysis.
- Introduce a continuous improvement philosophy.

1.3 Scope

The essence of the study is to demonstrate the influence that the correct integration of modern railway technologies and information technology systems has on effective maintenance management and that it ensures continuous asset management improvement. This study deals with the development of a maintenance management decision-making model/process to optimise track maintenance management. The integration of railway technologies such as condition measurement vehicles' data and the use of information technology such as the Infrastructure Asset Maintenance Management (IAMM) system will form the basis for the development of an optimised maintenance tamping model and decision-making process.

The limitations involved in conducting the dissertation are:

- The maintenance management analysis model focuses on track tamping only.
- Condition based values were obtained from references and not calculated.
- The study excludes the details for the development of the maintenance management data model.
- The study introduces the continuous improvement methodology.

1.4 Methodology

The dissertation was undertaken in three phases.

a) A literature study on;
    - Asset management
    - Maintenance management
    - Maintenance management processes
    - Computerised asset and maintenance management systems
    - Introduction to railway terminology and component functions
    - Introduction of typical rehabilitation and renewal activities in railways

b) The development of a maintenance decision-making process and analysis model to optimise mechanised track tamping. This phase also include the collection of data and integration of different railway technologies.

c) Extending current information technology (IAMM system) with the development of a tamping analysis model to optimise tamping maintenance requirements. The results of the optimisation through integration of technologies and the analysis model developed are also presented in Appendix A.

1.5 Organisation of the dissertation

The report consists of the following chapters and appendices:

- Chapter 1 serves as an introduction to the dissertation.
- Chapter 2 contains the technical introduction based on a literature study.
- Chapter 3 defines the maintenance decision-making process, data collection methods, technology integration and the analysis methods utilised.
- Chapter 4 describes the analysis undertaken.
- Chapter 5 contains the conclusions and recommendations of the dissertation.
- Chapter 6 provides a list of references.
- Appendix A contains the detailed results from the analysis performed.
- Appendix B provides the details of the maintenance plan developed from the analysis results.

CHAPTER 2
LITERATURE STUDY

2 Introduction

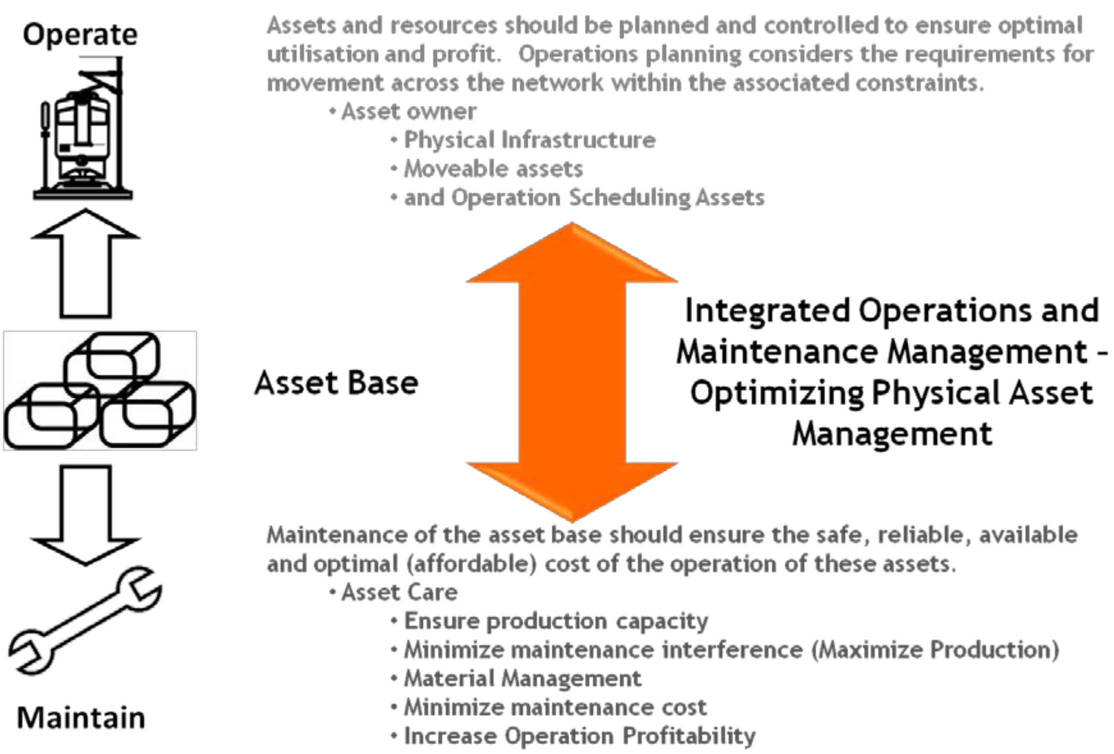
In chapter one, an overview of the dissertation and its contents were provided, and a basic understanding of the importance of the topic was conferred. This included a brief introduction to the broader issues relating to railway maintenance and asset management, and discussion of the aims, objectives and scope of the dissertation.

In this chapter, a literature study is provided, reviewing a combination of asset management principles, maintenance management fundamentals and strategies, technology enablers and railway terminology. In particular, the literature review describes how the planning of maintenance activities on railway assets involves various aspects, ranging from asset condition and utilisation to maintenance history. The assets that require frequent maintenance due to high loads are located over a large geographic area, resulting in challenges to minimise maintenance visits and resulting costs. Maintenance activities also interrupt the service and reduce the availability of the asset and associated income from the service. Although maintenance cost should be minimised, the safety aspect remains critical and minimum service levels should be maintained to ensure business capacity.

The author considers that a detailed review of the available literature is essential to provide a meaningful understanding of the topics in subsequent chapters, and to facilitate the research itself.

2.1 Asset Centric Business Model

The author favours an Asset Centric approach, whereby operations and maintenance are integrated elements of a system and need to be managed as such. Illustrated in Figure 2-1 below is a high-level presentation of an Asset Centric business model, developed by the author and fully compliant with the railway environment.



Assets and resources should be planned and controlled to ensure optimal utilisation and profit. Operations planning considers the requirements for movement across the network within the associated constraints.

- Asset owner
  - Physical Infrastructure
  - Moveable assets
  - and Operation Scheduling Assets

Maintenance of the asset base should ensure the safe, reliable, available and optimal (affordable) cost of the operation of these assets.

- Asset Care
  - Ensure production capacity
  - Minimize maintenance interference (Maximize Production)
  - Material Management
  - Minimize maintenance cost
  - Increase Operation Profitability

Figure 2-1: Asset Centric Business Model

From the model it is evident that the author believes that the traditional historic approach of “silo” functional activity-centred organisations within the business is not effective and that businesses should have a paradigm shift in their way of thinking. This viewpoint is supported by many leading experts in the field of asset management and will be discussed in sections to follow.

2.2 Asset and Maintenance Management

In this section, the author will distinguish between asset management and maintenance management. On a high-level, asset management can be defined as the holistic approach within the entire business to improve its goal, in other words to add value. Maintenance management is defined as one of many components within the asset management approach.

2.2.1 What is asset management?

According to Mitchell *et al.* (2007), Physical Asset Management has a single objective and that is to increase the value and return delivered by the physical assets. It is then argued that Physical Asset Optimisation is a program that is a business initiative, focusing on and determined by opportunities to create value in different areas. These opportunities can include areas such as the reduction of costs and the improvement of availability/capacity. From this should arise an appreciation of why it is required and advocated that this approach requires a close partnership, *a synergy*, between production/operations (the asset owner) and maintenance/engineering (the asset caretaker).

Mitchell *et al.* (2007) stated that the starting point of asset optimisation is to realise that the business is at an initial state, though it has a specific goal to achieve. It is from this initial/current state that the business should build on to achieve greater effectiveness. Woodhouse (2001) defined asset management as a group of tools, processes, methods and disciplines that is utilised to optimise the physical asset's service life cycle. Peterson (2007) also described asset management as a process for asset care decision making.

Some areas identified to improve the required service objectives for asset management optimisation (Mitchell *et al.*, 2007; Peterson, 2007; Woodhouse, 2001) are listed below:

- Improve production availability;
- Increase production;
- Reduce operating cost;
- Increase asset effectiveness;
- Increase reliability and quality;
- Flexible and reliable processes;
- Improve efficiency.

From the above Mitchell *et al.* (2007) discussed value opportunities generated by asset management optimisation. A list of some of the value opportunities is presented and discussed below:

- Production, utilisation and effectiveness improvement:
    - This improvement means meeting delivery commitments at less cost or delivering more at the same cost.
    - Increase stability and reliability
        - Stable, reliable assets ensure a stable and reliable service. Minimise uncertainty as this will have an impact on cost.
- Reduce spending:
    - When reducing costs, this should be sustainable and therefore approached from an asset lifetime perspective, and not from the traditional budgeted business costs.
    - Reducing cost can be achieved by:
        - Reducing failures - ensure the cause of the failures is understood and that the correct action is taken to reduce these failures;
        - Increasing effectiveness - being results orientated;
            - This is to perform the correct tasks (doing the right things) efficiently;
        - Recognising the consequences of failures and operating variation;

        - Improving maintenance and reliability;
        - Increasing skill levels as equipment and systems complexity increase.
- Improve capital effectiveness:
    - Capital reduction has the same influence as reductions in operational costs, i.e. reducing the number of spare parts kept in stores.

These considerations all support the viewpoint of the author that *asset management is a process of continuous improvement*. This process will ensure that asset centric businesses apply and implement a business initiative process to optimise the asset with a single tangible result in mind, and that this result is to maximise the value and return delivered by the physical assets. Peterson (2007) defined a process of implementation to achieve asset optimisation in 5 phases, depicted in Figure 2-2 below. These phases consist of:

- Planned maintenance;
- Preventative maintenance;
- Organisational excellence;
- Engineered reliability and
- Operational excellence.

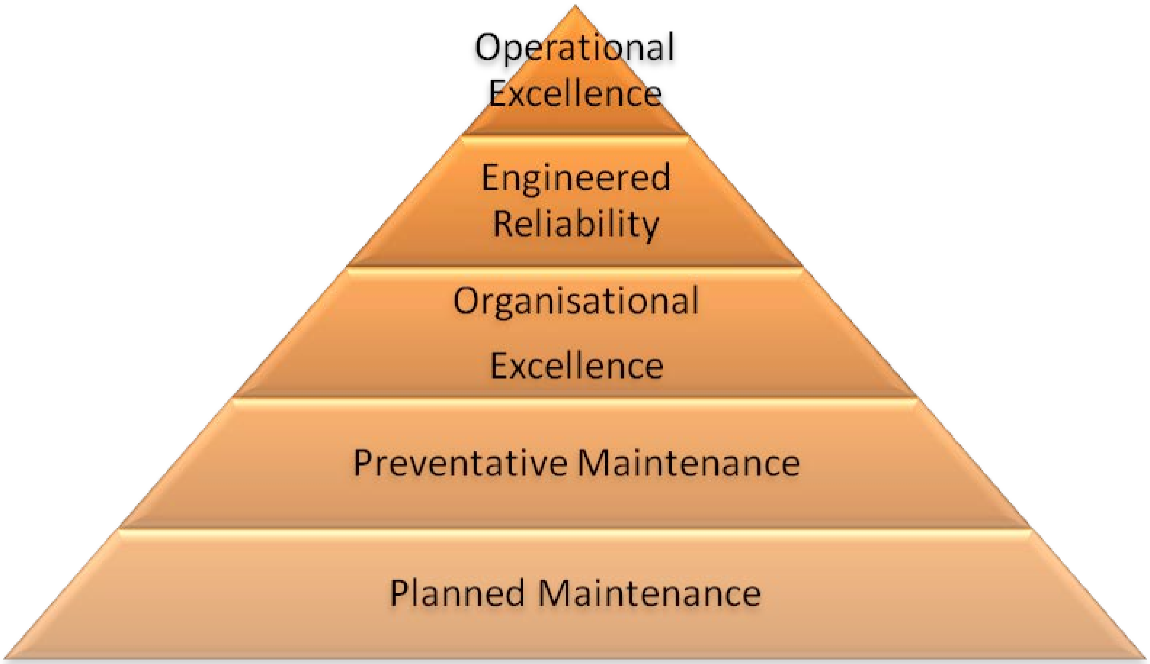


Figure 2-2: Continuous Improvement Phases - Asset Healthcare Triangle (from Peterson, 2007)

The details of the activities, tools, processes, procedures, strategies and disciplines are listed below for information purposes only and will not be discussed in detail as this falls outside the scope of this dissertation.

- Phase 1: Planned maintenance:
    - Work identification and prioritisation;
    - Planning and scheduling;
    - Work execution and review;
    - Turnaround management;
    - Computerised maintenance management system;
    - Routine based maintenance.
- Phase 2: Preventative maintenance:
    - Condition based maintenance;
    - Craft skills enhancement;
    - Equipment history;
    - Failure analysis;
    - Asset strategies;
    - Asset integrity.
- Phase 3: Organisational excellence:
    - Craft flexibility;
    - Engineering/maintenance and operations synergy;
    - External benchmarking;
    - Operational Performance Measures.
- Phase 4: Engineered reliability;
    - Reliability centred maintenance;
    - Vendor reliability;
    - Life cycle analysis;
    - Standardisation.
- Phase 5: Operational excellence:
    - Strategic Asset Management.

2.2.2 What is maintenance management?

Maintenance can be defined as the care, correction and servicing of assets and their components by people. Such intervention would be for ensuring the satisfactory operations of the assets and components before physical or functional failure, or before major defects develop, that will influence operations effectiveness. In short, maintenance can be termed **asset care.** It ensures the availability and capacity required by assets to deliver either a product or a service, depending on the business objective (Mitchell *et al*, 2007).

According to Mitchell *et al. (*2007) and Peterson (2007), the benefits of asset care within the asset optimisation process include but are not limited to:

- Reducing incidents;
- Increasing utilisation;
- Improving quality;
- Maximising effectiveness;
- Reducing and minimising failures;
- Reducing operating and maintenance costs;
- Reducing spares parts;
- Setting operational and maintenance goals.

From this it is clear that if maintenance/engineering partner synergistically with operations, this will add value to the operational profits. Maintenance should therefore become a core management responsibility within the asset centric business, and continuous participation of maintenance in the business decision-making and production process is not negotiable. The involvement of maintenance in these decisions assists in asset lifecycle optimisation by addressing problems such as:

- Availability of the assets and there components,
- Capacity problems due to operational bottlenecks;
- The continuous business concern, namely increased maintenance costs.

Mitchell *et al.* (2007) explained (see Figure 2-3) how service interruption can influence and maximise asset effectiveness, indicating the value of a partnership between maintenance and operations. The shaded areas above the breakeven line represent the requirements to achieve the objective of making a profit, whilst the shaded areas below the breakeven line represent areas where there are interruptions within the operational objectives that realise a loss within the business.

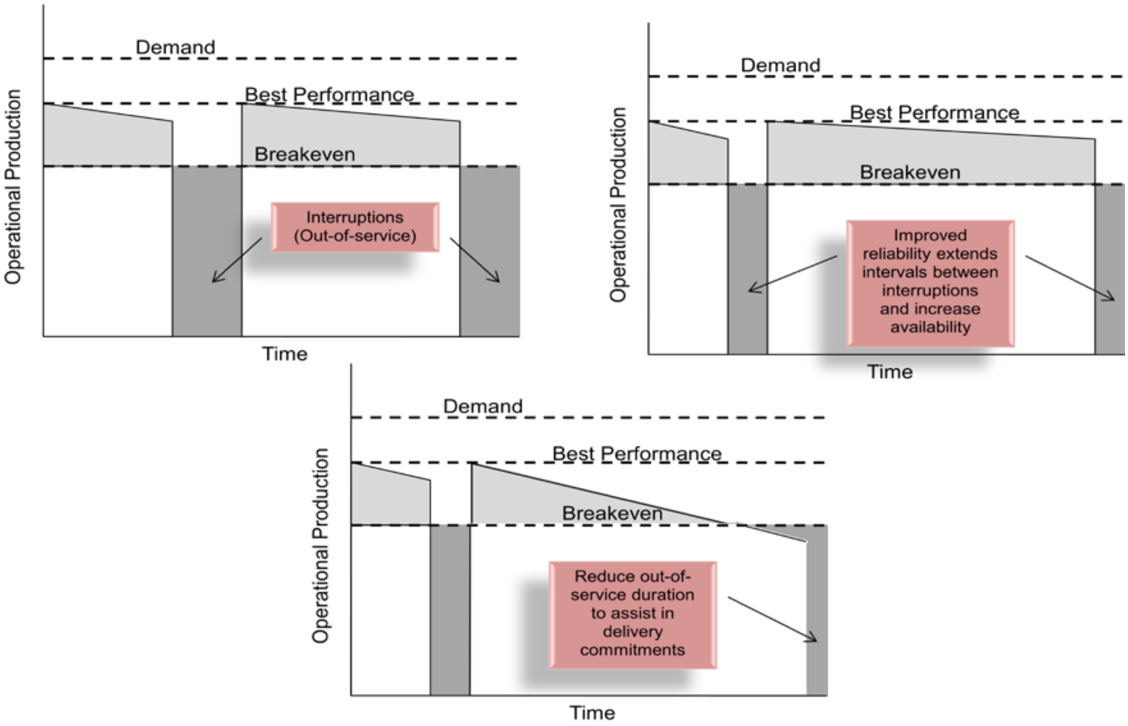


Figure 2-3: Intervention effecting Asset Effectiveness (from Mitchell *et al.*, 2007)

The focus of the dissertation will now shift to maintenance management. The objective is to determine how maintenance management can add value to the asset management optimisation process. This will be determined by analysing methods and processes within the maintenance and/or engineering environment to increase operational availability, capacity and the reduction of maintenance cost. In the author’s opinion, these are the areas where the most value can be added promptly.

2.3 Maintenance Management Life Cycle

Infrastructure deteriorates under operational loads and various environmental conditions, requiring maintenance to ensure its availability for the required operations at an operational standard (Ebersöhn and Ruppert, 1998).

As part of the decision making process, the infrastructure maintenance manager should select between the following maintenance options in order to provide assets of a required operational standard, that are affordable and based on different maintenance strategies:

- Rehabilitation: This action is required to keep/restore the facility to a serviceable condition or status (e.g. re-profiling the rail, re-aligning the track or painting a steel bridge). These actions are typically considered to be operating expenses.
- Renewal: This is the replacement of the structure or its components. It is replaced with comparable new structures or components when condition and reliability improvements are

required (e.g. replacing a worn out 48kg rail with a new 48kg rail or re-surfacing a road). These are typically considered to be capital expenses.

- Upgrade: To reconstruct equipment, components or facilities to improve or enhance its physical functionality. This is implemented when enhanced performance and reliability are required (e.g. replacing the track structure with stronger sleepers and heavier rail or improving the substructure to carry heavier loads). These are typically considered to be capital expenses.

To illustrate the maintenance management life cycle, a hypothetical example of infrastructure assets' deterioration trends are shown in Figure 2-4. The graphs illustrate the effects of various maintenance activities regarding asset performance. These are represented by changes in the asset's roughness (an indication of condition) over its life cycle, with respect to the traffic volume which can transposed into time.

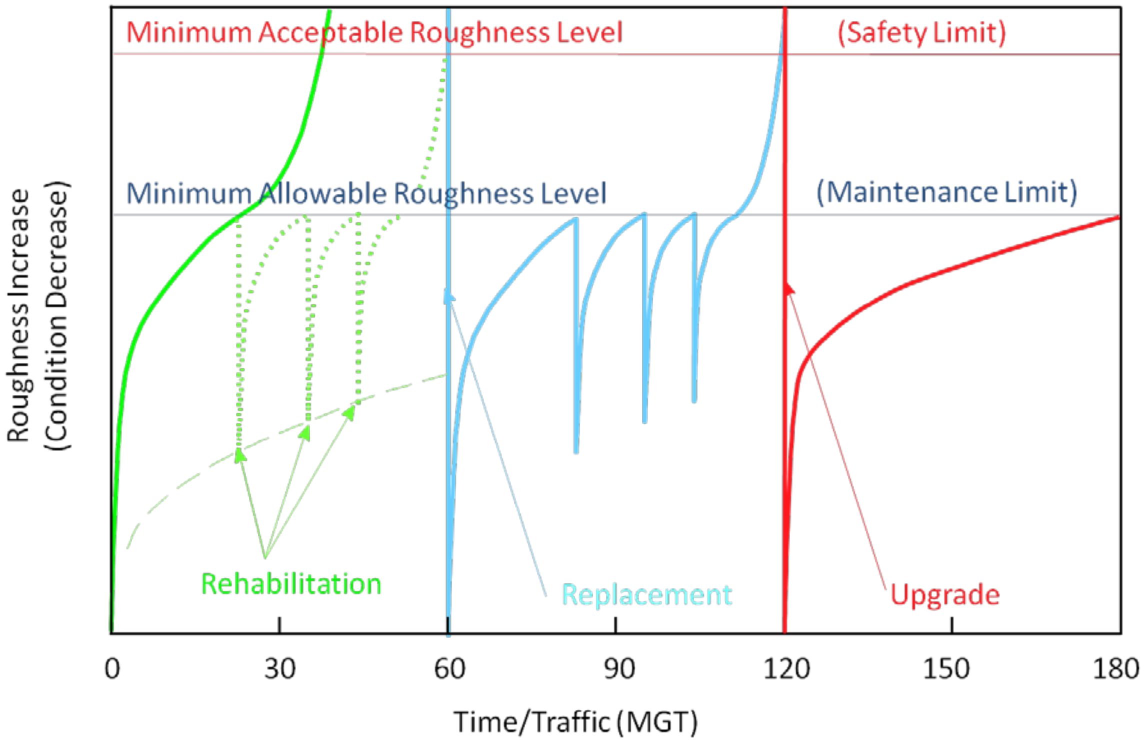


Figure 2-4: Hypothetical Infrastructure Asset Deterioration Rates with and without Maintenance (from Ebersöhn and Ruppert, 1998)

2.4 Maintenance Process

According to Mitchell *et al.* (2007), leaders within the Asset Centric business consider maintenance as an integral part of the operations and business process generating and adding value to the business. The importance of a well-defined and documented maintenance process to assist in the delivery of the business objective, must be fully recognised. Dunn (1997) categorised the maintenance management decision-making process into six phases as follows:

1. Work identification;
2. Work planning;
3. Work scheduling;
4. Work execution;
5. Recording work history; and
6. Analysis.

At the end of the sixth phase, there is a feedback loop where the decision-making process starts at Phase 1 to identify the new maintenance requirements. This process relates to the familiar management philosophy, *Theory of Constraints* (Goldratt, 2004). This proposes that at any given point in time, at least one constraint limits the system's performance. As the process repeats over time, the constraint may change, although the same constraint may also reappear over time.

The author also categorized this step, as the platform, where the opportunity arises to improve the existing and/or current methods and strategies, to ensure continuous improvement.

Ebersöhn and Ruppert (1998), as well as Woodhouse (2001), include these phases in their maintenance cycle. At first it seems somewhat different, but the principles of maintenance management clarify when analysing these maintenance process models. This confirms the fundamentals of the maintenance management process. The basic maintenance process, as adopted from Dunn (1997), is presented in Figure 2-5 below.

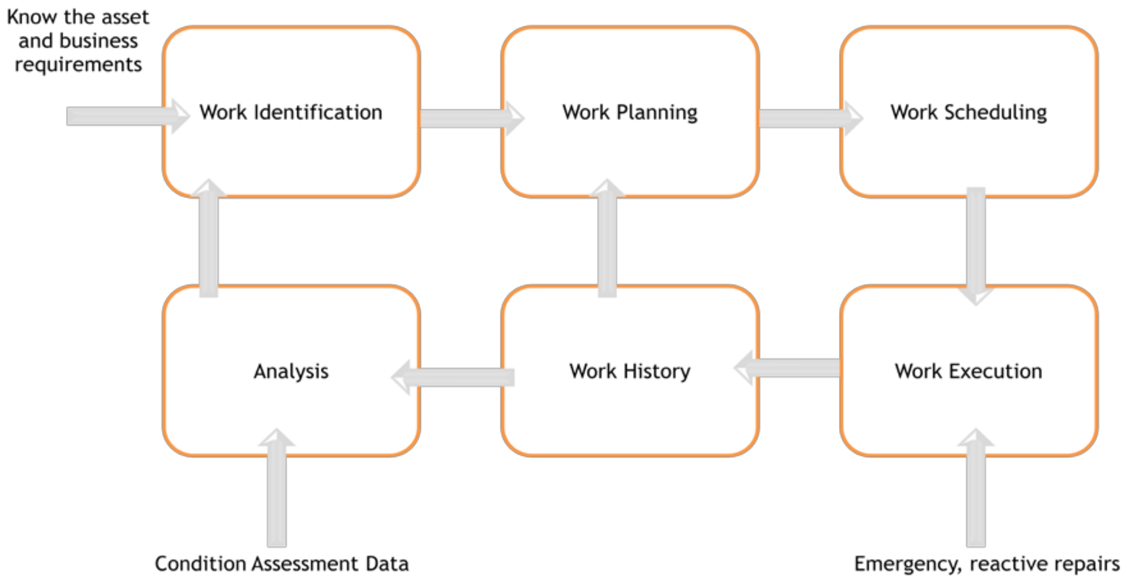


Figure 2-5: The Basic Maintenance Process (from Dunn, 1997)

2.5 Maintenance Strategies

Within maintenance, asset management optimisation requires a mix of maintenance strategies to minimise maintenance interference and failures. Typical well known maintenance strategies used for asset optimisation include:

- Corrective maintenance;
- Planned/Routine Maintenance;
- Condition based maintenance.

The Industry has recognised that there is an advantage in moving from reactive, corrective maintenance to condition based maintenance. Advantages of this include:

- Increased effectiveness;
- A decrease in maintenance cost.

This shift of maintenance strategies is confirmed in Figure 2-6 below (Mitchell *et al.*, 2007).

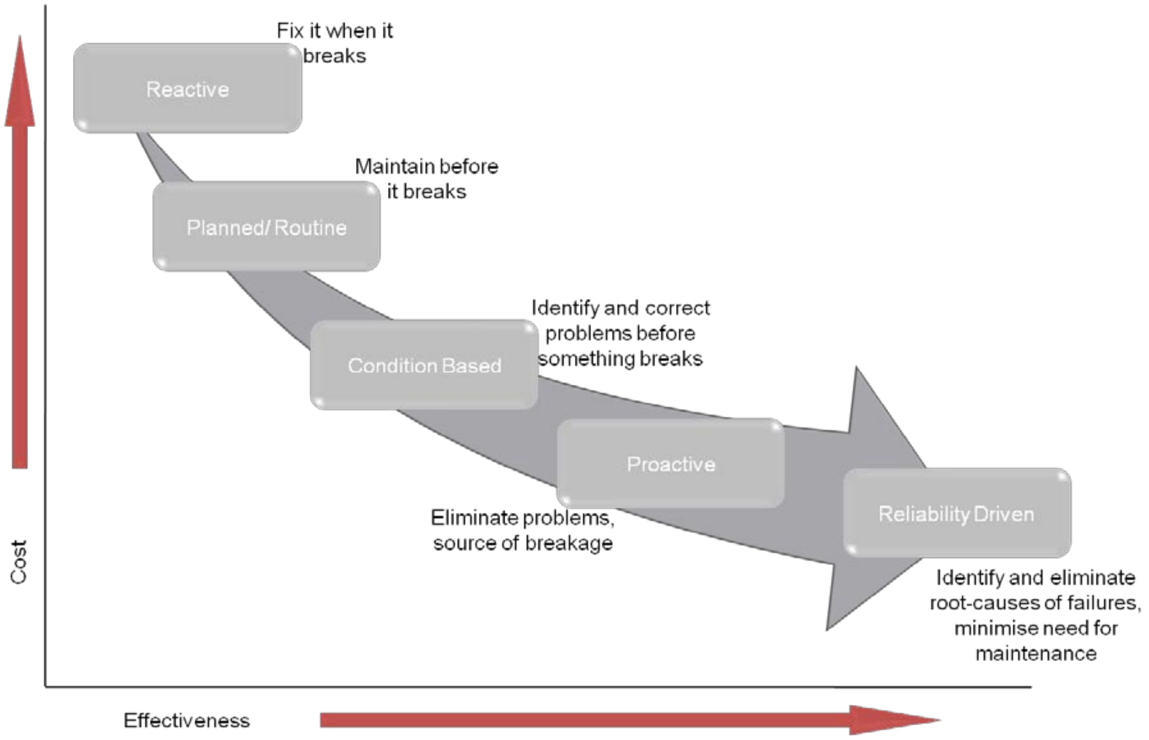


Figure 2-6: Cost advantages of maintenance types (from Mitchell *et al.*, 2007)

For this dissertation the scope is limited to reactive, planned or routine and condition based maintenance. This is discussed in more detail in the following sections.

2.5.1 Corrective Maintenance

“Fix it when it breaks!” would be the layman’s term for corrective maintenance. As defined and described by Mitchell *et al.* (2007), corrective maintenance covers problems usually identified by production and/or operations. In the railway industry examples include:

- Derailments;
- Theft;
- Rail breaks;
- Earthwork slips;
- Wash-away of substructure components.

This maintenance tactic is by far the most costly and must be minimised to increase effectiveness and decrease operational cost. Corrective maintenance has a direct relationship with uncertainty. It is therefore apparent that an organisation utilising a corrective maintenance tactic with a high number of occurrences, will have a high uncertainty value. This will influence the reliability of operations and service delivery. This paradigm will have a direct impact on the operational profits. It should be noted that corrective maintenance often leads to downtime in production, thus limiting the available capacity to deliver the required service.

2.5.2 Preventive Maintenance

The author considers that preventive maintenance includes routine based as well as condition based maintenance, and this is the assumption for this dissertation. This, however, differs from one organisation to the next.

Preventive maintenance can be defined as a tactic that is applied to mitigate failure. In contrast with corrective maintenance, preventive maintenance assists in reducing long downtimes. This ensures capacity availability, decreasing uncertainty and thus ensuring an increase in reliability and service delivery.

Routine Based Maintenance

Routine based maintenance is activities performed on a time based interval. The time based interval can be either calendar based or operating time based. It should be noted that in some cases, performing routine based maintenance might be maintenance activities performed unnecessary as it will not improve asset reliability. This translates into over maintained assets, increasing the operational cost and therefore impacting the operational profits. This is confirmed by Mitchell *et al.* (2007), who stated that only up to 20% of failures are time base related in the maintenance industry. Therefore 80% of routine based maintenance is ineffective to prevent failures. He further comments that in some cases routine based maintenance can introduce failures.

This is consistent with Selig and Waters (1994) with regards to railway ballast maintenance utilising a tamping machine. It is explained that the tamping action breaks down the ballast and introduces some additional functional failures of the ballast properties. This includes:

- Ballast bed loosening, resulting in further settlement with additional traffic;
- Initial reduction in vertical and horizontal resistance;
- Increasing the degree of settlement as the ballast deteriorates.

Condition Based Maintenance

Reviewing routine based maintenance, it is apparent that some assets are over maintained due to ineffective maintenance activities. The over maintenance of assets necessitated the development of condition based maintenance. Condition based maintenance can be defined as the objective to maintain the correct asset/equipment at the right time, therefore being effective. As maintenance effectiveness increases, reliability increases and therefore production increases, resulting in a decrease in the overall maintenance cost.

According to Mitchell *et al.* (2007) condition based maintenance can assist in the following instances:

- Warn the maintenance function of problems that might occur in time to minimise failures;
- Minimise disruptions, thereby increasing asset and component utilisation and life;
- Reduce maintenance cost due to effectiveness;
- Allow the elimination of unnecessary routine maintenance, thereby reducing maintenance costs;
- Increase the probability that assets and components will operate to their optimum lifetime;
- Reduce requirements for stocked spare parts/inventory;
- Increase awareness of the assets' and components' condition;
- Form the core of effective asset lifetime management;
- Provide essential information for continuous improvement, work and logistics planning.

He argues that condition based maintenance however, does NOT assist in the following instances:

- Eliminate defects and problems;
- Stop assets from deteriorating;
- Eliminate all routine based maintenance, for example lubrication inspections;
- Effectively warn the maintenance function of failures due to fatigue;
- Warn the maintenance function of electronic failures;

- Reduce personnel or produce a major decrease in lifetime maintenance costs without a commitment to improve reliability by eliminating defects and reoccurring problems.

2.6 Computerised Asset and Maintenance Management Systems

The author believes that it is essential to implement a proper maintenance management system by integrating different technologies to support decision makers in improving the management of existing infrastructure. This concurs with Mitchell *et al.* (2007) who advocate technology as a prime enabler for asset management optimisation. The management system is obtained by integrating aspects such as control, management and monitoring technologies in an interoperable structure that needs to be accurate and accessible. Accessibility is another key requirement for ensuring the effectiveness of those requiring specific information for decision-making in the maintenance function.

Dunn (1997) argued that the importance of a successful maintenance management implementation ties up with the selection of the asset and maintenance software. He considered it essential that the software supports the maintenance management processes, and that people do not change the way they work just because they are told to. It therefore requires involving key maintenance personnel to assist in defining the processes as this will ensure approval and support of the system at all levels.

2.6.1 Maintenance Management System Components

As previously mentioned, Dunn (1997) considered it essential that the software supports the maintenance management processes. Understanding the processes is but one requirement in order to understand the system components' requirements. In conjunction with this, is the question "What data are required to add value to the decision makers?" This adds to the rationale (Drucker, 2006), that information must lead managers to ask the right questions. They should not be saturated with an overflow of information, but primarily need to know what information they require to make decisions.

The following elements are identified as primary requirements within a maintenance management system, to assist in asset management optimisation (Woodhouse, 2001):

- An asset register;
- Work order scheduling;
- Condition assessment and monitoring;
- Performance and maintenance history data.

Some other important elements required for an integrated asset management system include:

- Resource management;
- Safety, risk and environmental management;

- Project management;
- Financial management;
- Key Performance Measurement Reports, including measuring efficiency, effectiveness and quality assurance.

From a railway infrastructure management perspective, Ebersöhn and Ruppert (1998) group the Asset Maintenance Management System into the following elements:

- Location of the infrastructure assets;
- Condition measurements of the assets;
- Traffic characteristics of trains operating over the line;
- Records of work input to keep the line operational.

From the above it is apparent that the basis of any asset management system is the asset register. Obtaining a complete record of all assets, their properties and location is the first step in establishing an asset management system. This provides the ability to relate all assets and their locations to information such as condition and work history.

2.6.2 Railway Assets and their Location

The geographic location of all physical infrastructure assets should be the basis of the referencing system used for an infrastructure asset maintenance management system (Ebersöhn and Ruppert, 1998).

This is the first most important step in setting up an asset register for a maintenance management system. In general, all railroads have track charts (schematic diagrams) or line books representing all infrastructure assets along the railway line in a linear manner. The schematic diagrams are based on a linear referencing system, where all assets are referenced to km/mile posts, followed by a distance measurement from these referencing points in metres/feet (Ebersöhn and Ruppert, 1998).

Generally these sets of as-built engineering drawings are kept up-to-date by the infrastructure/engineering department. In the experience of the author, working closely with Transnet Freight Rail (a South African state-controlled rail transport company), Amtrak (The National Railroad Passenger Corporation in the United States) and other international railways, it became apparent that, due to downsizing and outsourcing, the updating of these plans and schematic diagrams were often neglected and that different departments were collecting and maintaining the same data. This led to discrepancies and missing data, as well as incorrect asset locations, resulting in unreliable data (Van der Westhuizen and Ebersöhn, 2003). The view is supported by Esveld (2001) and he explains that railways extend over large areas and distances and therefore surveying these networks and collecting data are not simple tasks.

Technology is therefore needed to assist in collecting asset and asset location data, faster and more accurately than the old method of walking along the track with a measuring wheel. From Esveld (2001) as well as Ebersöhn and Ruppert (1998), the following technologies have been identified to assist with fast and accurate data collection:

- Ortho-photo technology;
- Light Detecting and Ranging (LiDAR) and video integrated with GPS;
- Video surveying (Videography) integrated with GPS.

All of these systems can be used to identify and extract objects geographically and record any required attributes. Assets identified as objects within these technologies can be defined as polygons, polylines or points, depending on the asset type. Examples of the technologies are presented in Figure 2-7 (Ortho-photo), Figure 2-8 (LiDAR) and Figure 2-9 (Videography).

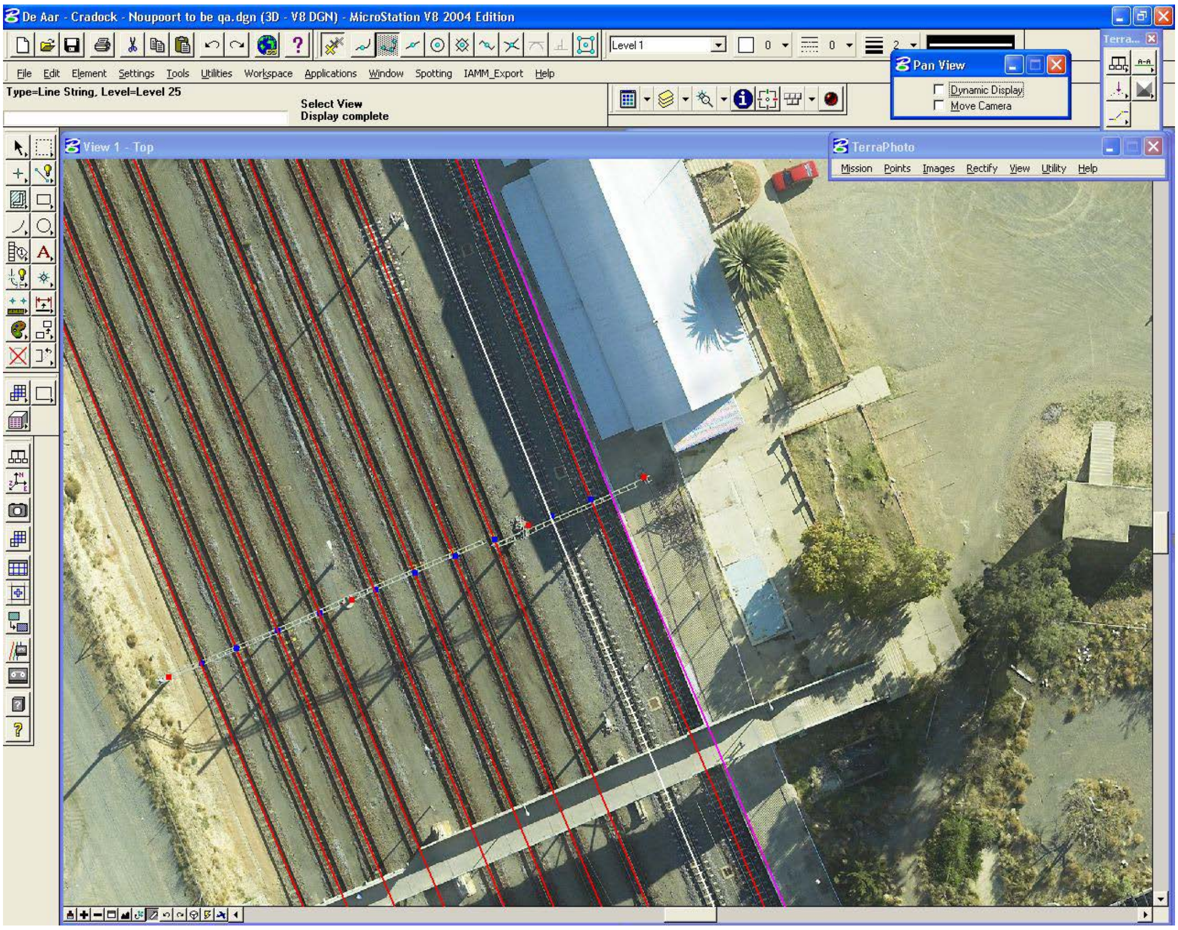

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Figure 2-7: Ortho-photo showing track centre line (red poly-line), platform (purple poly-line) and Overhead Track Equipment Support (Mast pole) (red points) objects

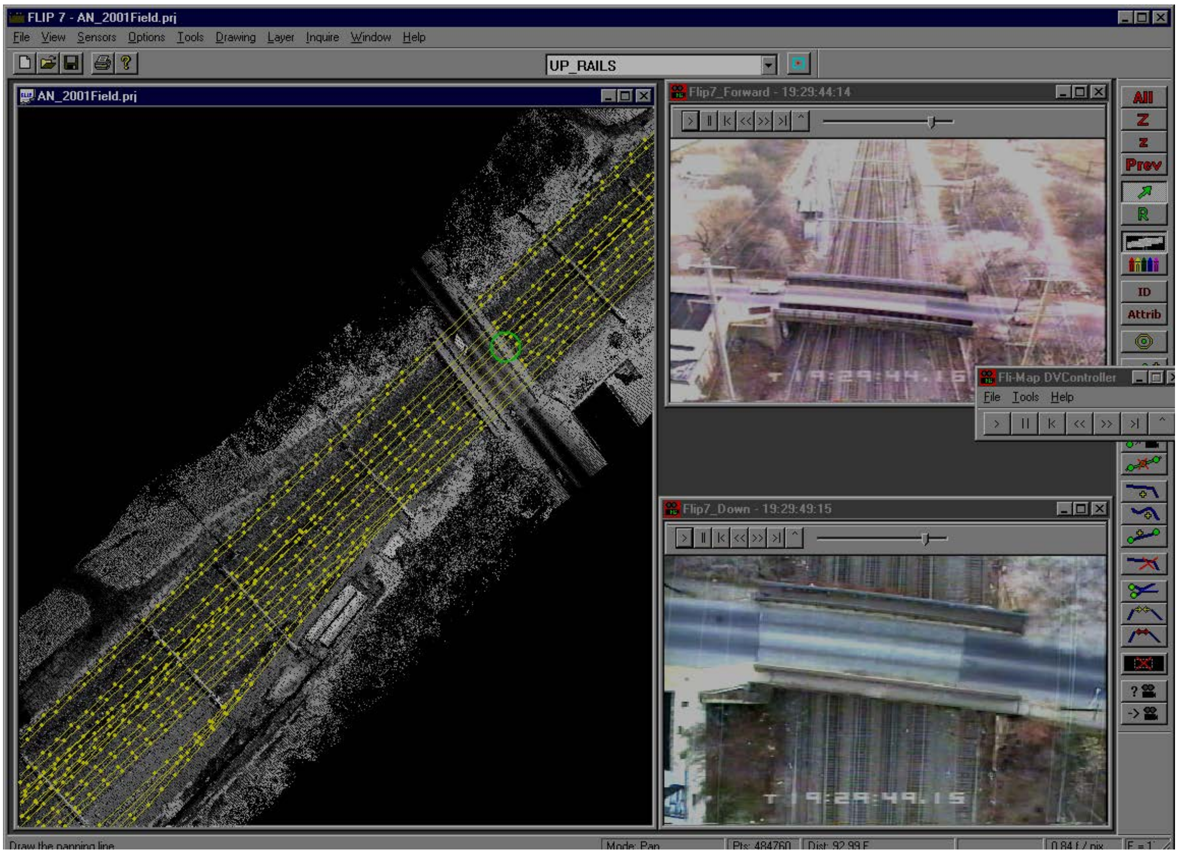
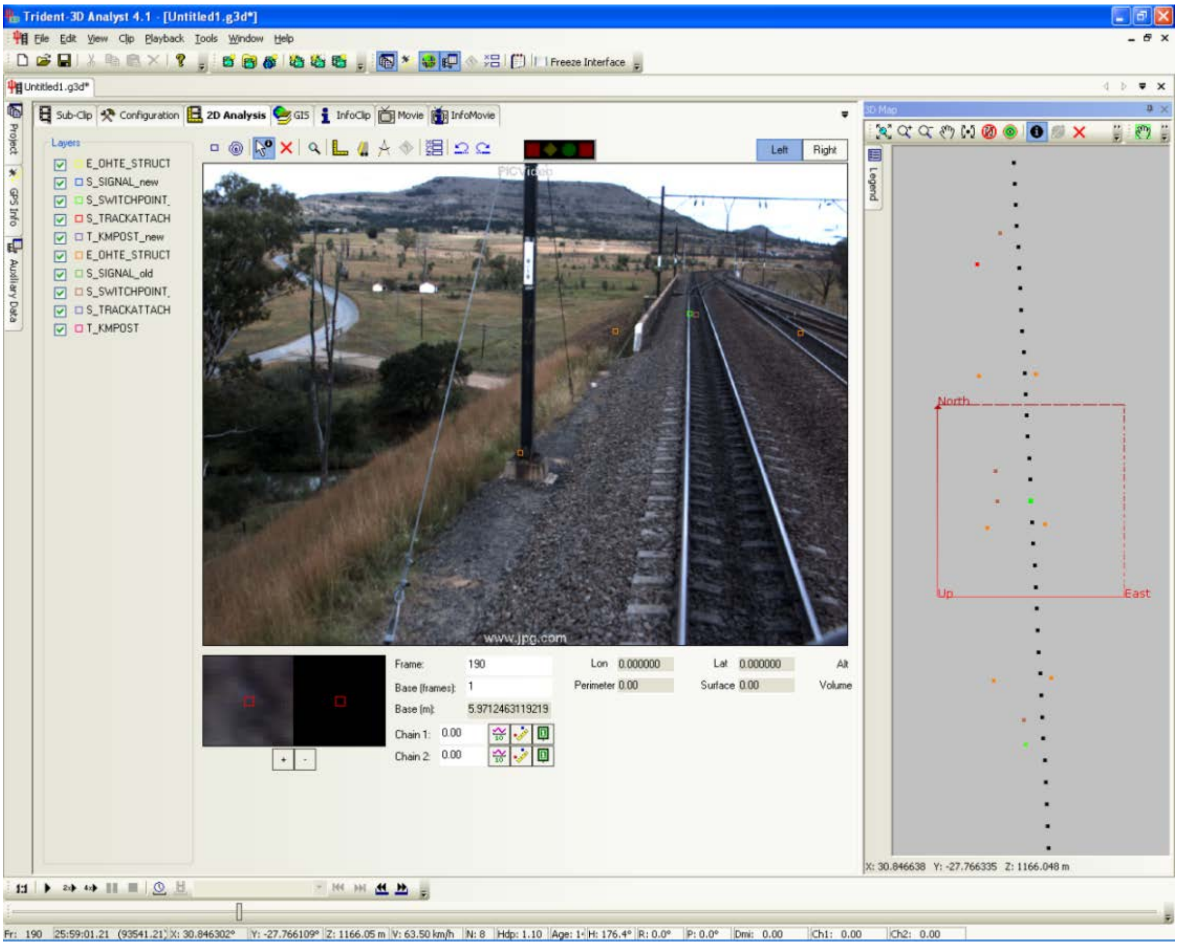


Figure 2-8: Plan view of laser scans showing track centre line objects (yellow dotted poly-line)



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Base (frames): 1
Base (m): 5.9712463119219
Chain 1: 0.00
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Lon 0.000000
Lat 0.000000
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Perimeter 0.00
Surface 0.00
Volume

X: 30.846638 Y: -27.766335 Z: 1166.048 m

Fr: 190 | 25:59:01.21 (93541.21) | X: 30.846302° | Y: -27.766109° | Z: 1166.05 m | V: 63.50 km/h | N: 8 | Hdp: 1.10 | Age: 1 | H: 176.4° | R: 0.0° | P: 0.0° | Dmi: 0.00 | Ch1: 0.00 | Ch2: 0.00

Figure 2-9: Videography showing Overhead Track Equipment Support (Mast pole) (orange points) objects

2.6.3 Railway Maintenance Management System Functionality

According to Ebersöhn and Ruppert (1998), a railway maintenance management system should have the following elements and functionality to enable decision-making:

- The maintenance management database;
- Graphic visualisation tools;
- Various track performance trend analysis applications;
- What-if analysis applications;
- Budgeting tools.

Using the geographically referenced data and their defined properties/attributes, the data need to be imported into the database to set up the physical asset register. The system should allow for the incorporation of condition monitoring and assessment data to relate the condition data with the assets in the database. The maintenance management system requires the functionality to create an electronic track chart (schematic diagram) from this database, presenting the data in a linear graphical manner. Figure 2-10 illustrates a typical track layout schematic example of a section of track, shown both in the geographic and track chart format (from Ebersöhn and Ruppert, 1998).

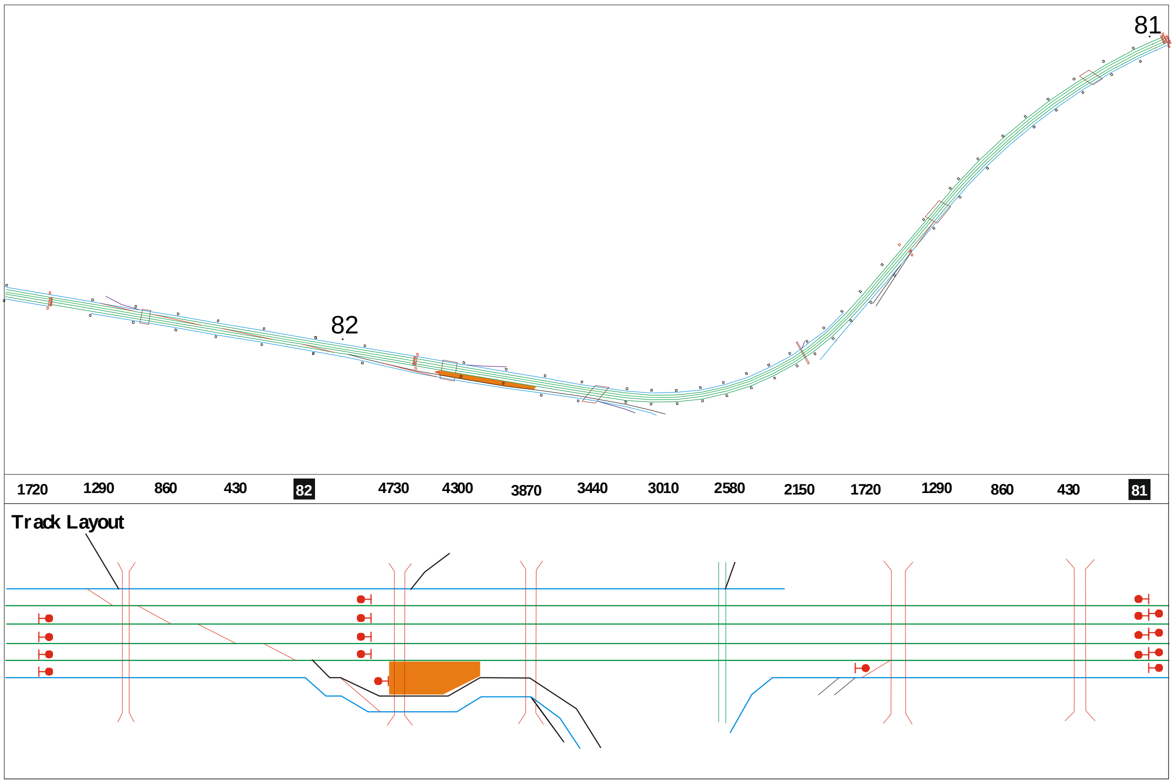


Figure 2-10: Geographic Layout and Track Chart Plot

The management system should then enable the decision maker to analyse information, assisting in the identification of required maintenance areas, based on condition measurements that need to form the basis for triggering work requests in a work management system. This will be the first step in adding value to the asset management optimisation process. Transnet Freight Rail developed an Infrastructure Maintenance Management (IAMM) system over the past 10 years. The IAMM system is an electronic asset register that integrates railway assets, condition data and work history information in an integrated and related graphical manner (see Figure 2-11). The IAMM system will be utilised as the basis for this dissertation.

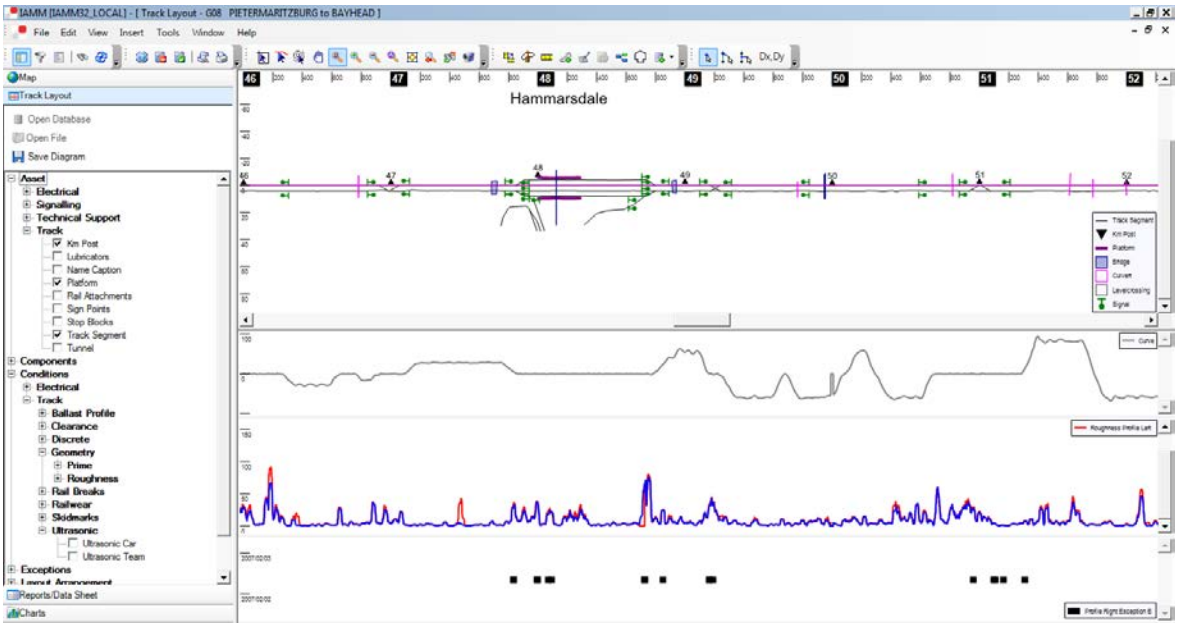


Figure 2-11: Infrastructure Asset Maintenance Management (IAMM) System

2.7 Railway Terminology

This section focuses on railway terminology, presents the fundamentals of permanent way components, and facilitates a high-level understanding of these components' functions. It forms the basis of the decision-making analysis to ensure effective maintenance, assisting the business in optimising the management of its assets. This section summarises the basics of rail track components as given by Selig and Waters (1994).

2.7.1 Track Structure Terminology

Figure 2-12 (below) shows the main components of a ballasted track. It is grouped into two main categories:

- Superstructure;
- Substructure.

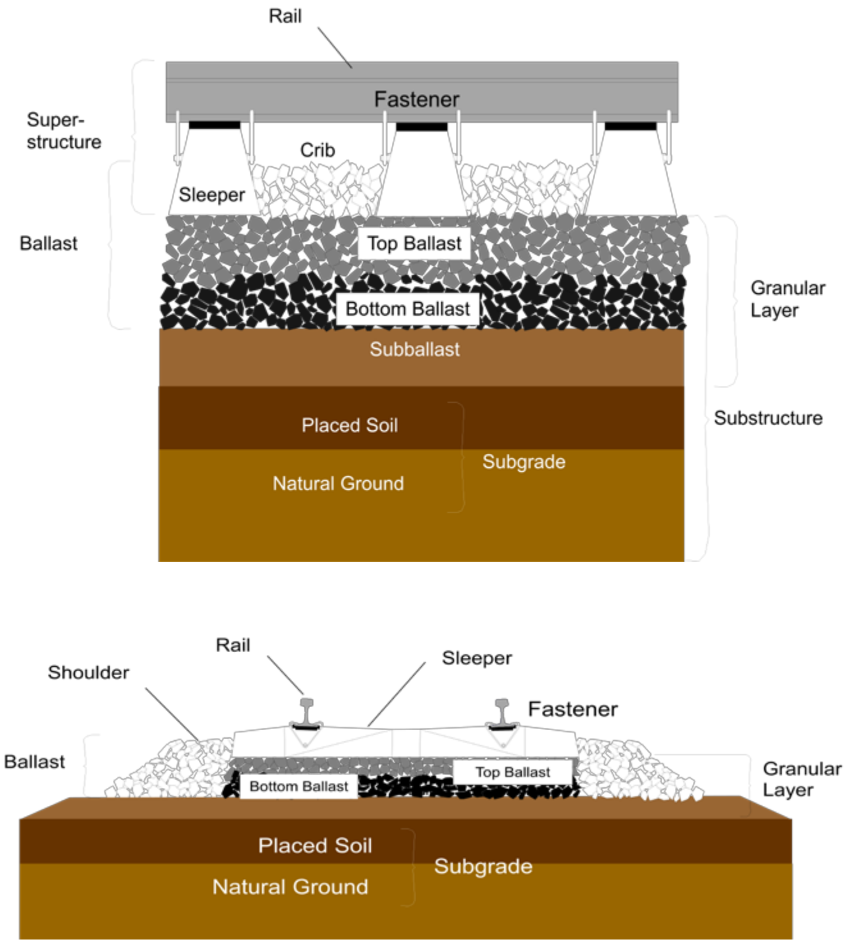


Figure 2-12: Track Component Terminology (from Selig and Waters, 1994)

The superstructure consists of the components:

- Rails;
- Fastening system;
- Sleepers.

The substructure consists of:

- Ballast;
- Subballast;
- Subgrade.

The sections to follow will provide detailed descriptions of the functions of some of these components, these being the components of significance within the scope of this dissertation. These include:

- Track geometry;
- Load distribution;
- Superstructure components;
- Substructure.

2.7.2 Track Geometry Terminology

Track geometry refers to the location each rail resides in, in space. Track in the longitudinal direction is composed of various track characteristics such as straight or tangent sections, horizontal curves (transition and circular curves), and vertical circular curves.

In practice, deviations are measured to determine the condition of the track geometry. These deviations contribute to the *roughness* of the track that describes the ride-quality of the right-of-way. Roughness occurs for a large diversity of reasons and requires root-cause analysis to determine the reason for these irregularities. In general these deviations occur due to:

- Variation of the substructure construction and therefore its stiffness;
- Overloading of the track structure compared to the design load;
- Localised weak spots in track structure;
- Track discontinuities such as block joints, level crossings and turnouts.

The projection of the track geometry onto various planes (see Figure 2-13), enables track geometry parameters to be specified. These parameters can be measured and used to determine the condition of a track, highlighting areas with irregularities and requiring maintenance input.

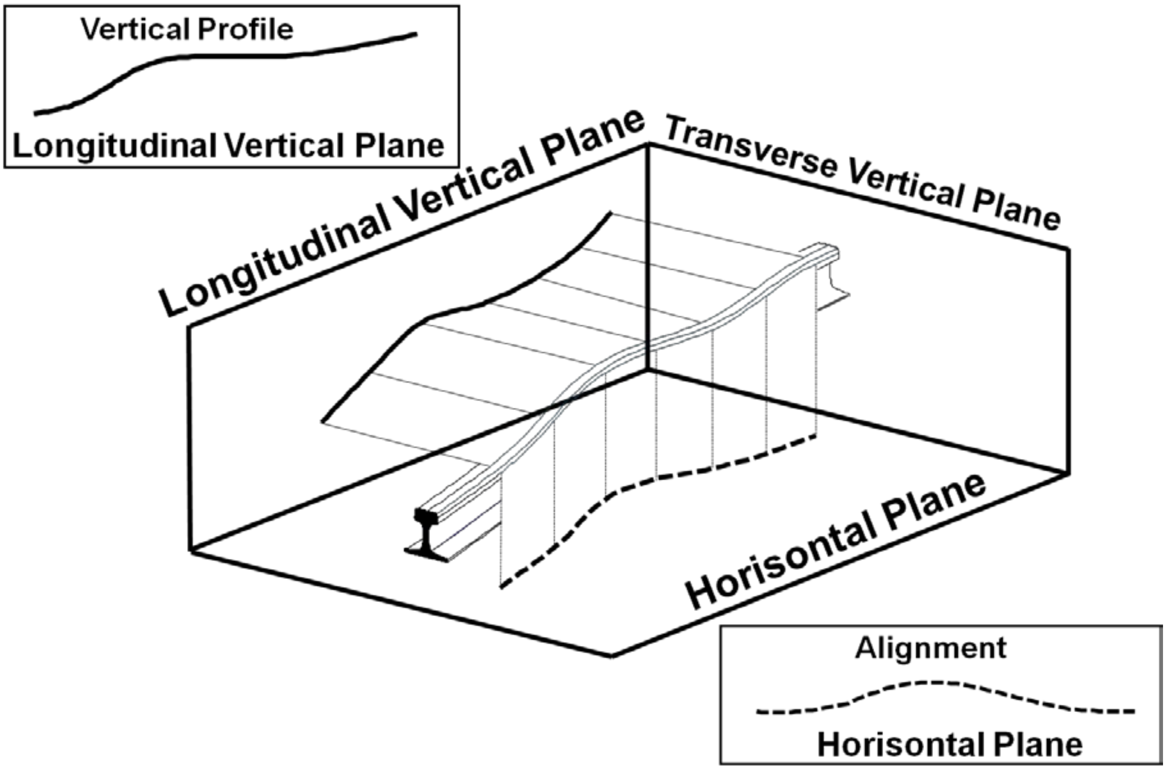


Figure 2-13: Horizontal and Vertical Track Planes

Track geometry parameters are grouped as follows:

- Parameters in the horizontal plane;
- Parameters in the longitudinal vertical plane;
- Parameters in the transverse vertical plane;
- Parameters in the track plane (located 15 mm below the top of both rails along the track centre line)

Track Geometry in the Horizontal Plane

In Figure 2-13 the horizontal plane represents the track geometry parameter "alignment". Alignment represents a rail with a line along the rail gauge side, 15 mm below the top of the rail. The design alignment of a track is measured in terms of the absolute geometrical location of the track in the horizontal plane.

The deviations from the design alignment are measured using either a non-contact or a contact geometry measuring system. In general, a mid-chord measurement is used in the rail industry to determine the deviations from the design alignment. A chord is a straight line between two points of the alignment. The mid-chord measurement is the horizontal projected distance between the mid-point on the chord and the point on the alignment, perpendicular to the chord. These measurements can also be referred to as versine.

Longitudinal Vertical Track Geometry

The longitudinal vertical track geometry is called "vertical profile" or “top”. Vertical profile is the projection of each rail onto the longitudinal vertical plane, as indicated in Figure 2-13. The line along the top of the rail is used for the projection.

The design longitudinal profile is measured in terms of the absolute elevation of each geometrical location of the longitudinal profile. These geometrical locations define the absolute vertical space curve.

The deviations from the design alignment are also determined using a mid-chord measurement. The chord measurement is the vertical projected distance between the mid-point on the chord and the point on the longitudinal profile, perpendicular to the chord. These measurements will be referred to as the profile.

Track Geometry in the Transverse Vertical Plane

The transverse vertical plane describes two parameters that need to be managed by maintenance managers. The parameters superelevation and twist are indicated in Figure 2-14.

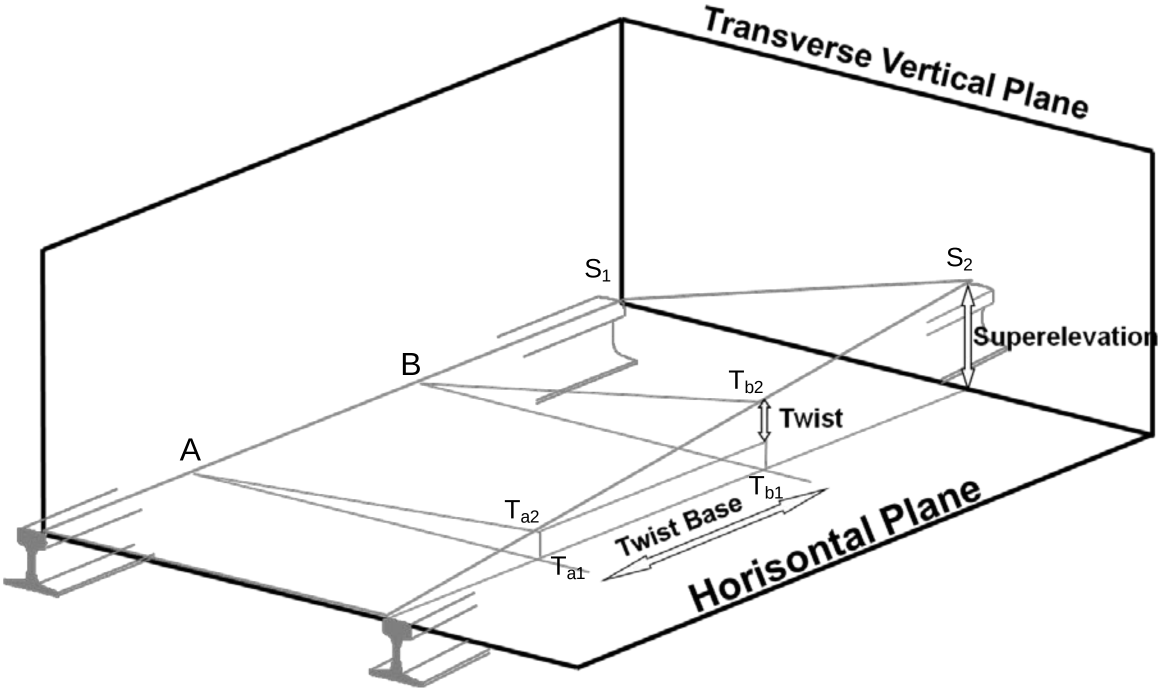


Figure 2-14: Transverse Vertical Plane

Superelevation is the difference in elevation between a point on one rail (S_1) and elevation of a point on the other rail (S_2) measured along a line perpendicular to the track centre line as indicated in Figure 2-14.

Twist is the difference in elevation of two points, one on either rail (T_{a1} and T_{a2} at position A and T_{b1} and T_{b2} at position B) a fixed distance apart along the length of the track as indicated in Figure 2-14. The distance between the two points (A and B) is referred to as the twist base.

Track Geometry in the Track Plane

Gauge is used to describe track geometry in the track plane, as indicated in Figure 2-15. Gauge is the distance measured normal to the track axis, between the inside of the rail heads, which are 15 mm below the top of the rail surface.

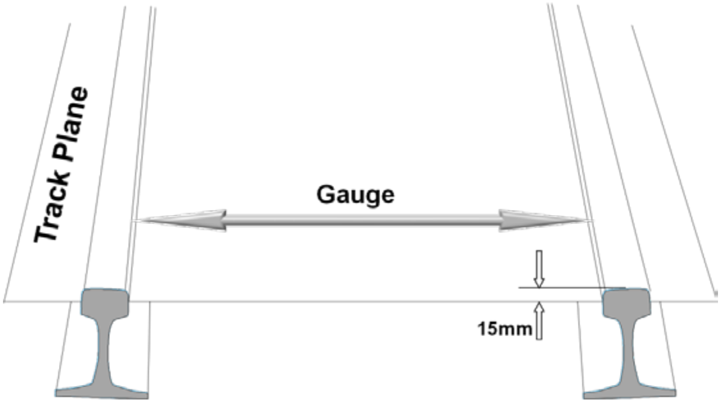


Figure 2-15: Gauge in the Track Plane

2.7.3 Vertical Load Distribution

The principal purpose of the superstructure and substructure is to transfer the wheel load from the Wheel/Rail interface through to the subgrade as indicated in Figure 2-16. The superstructure works as a continuous beam, supported on an elastic foundation - the substructure. This beam distributes the high vertical loads into the track structure.

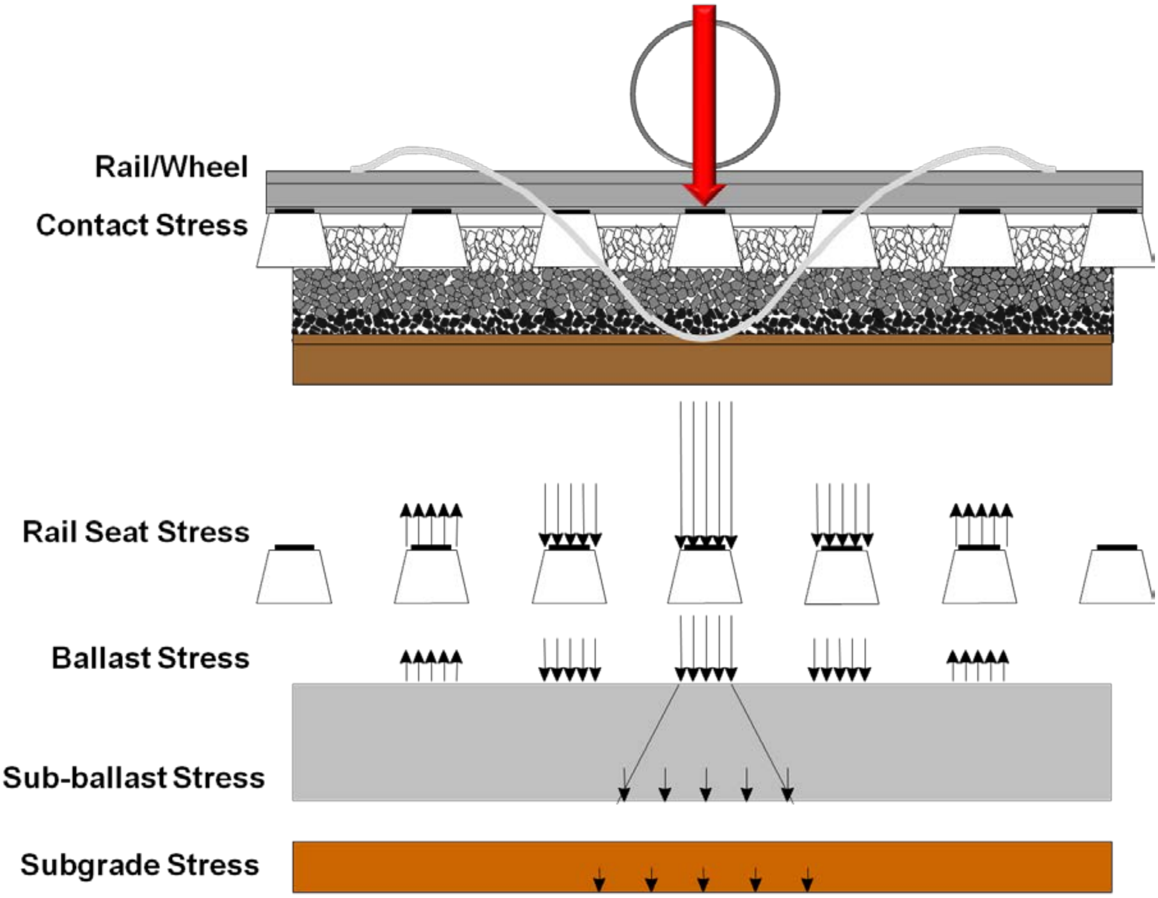


Figure 2-16: Vertical Load Distribution (from Selig and Waters, 1994)

2.7.4 Superstructure Components

This section will focus on the functions of the superstructure components.

Rails

Rails are the longitudinal steel members that distribute the point load from the wheel to the rail through to the subgrade. The rails' functions and characteristics are summarised as follows:

1. Contact surface between the wheel and rail. The rails should have the correct profile to guide the wheel evenly and continuously to limit the wear and fatigue rate to a minimum. See Figure 2-17 (below), indicating a generic form of wheel/rail interaction.
2. Rails must have sufficient stiffness to serve as beams that transfer the wheels' point load to the spaced sleeper supports without excessive deflection.
3. Rails also serve as electrical conductors for the signal circuit and also can serve as the earth line for the electric locomotive power circuit.

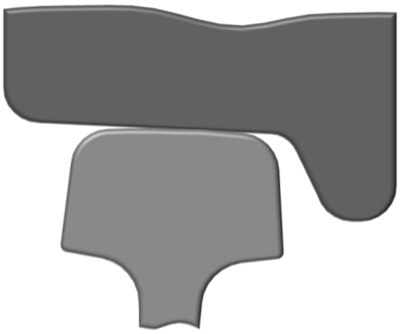


Figure 2-17: Traditional Form of Wheel and Rail Contact

As technology developed over the years, two measurement systems have greatly impacted the railway industry, thus assisting in rail management. The measurement systems are:

- A rail flaw detection measurement system utilising ultrasonic wave measurements, assisting in identifying fatigue areas developed in the rail;
- The rail profile measurement system utilising infrared laser technology, assisting in measuring the actual rail profile. These actual measurements are compared to the profile of a new rail from where the wear at specific positions is then calculated.

Three points (parameters) in the rail cross-sectional profile are measured to determine the wear that occurred on the rail at a specific linear location along the track (see Figure 2-18). These measurements assist in determining the remaining rail-life at a specific location. The three parameters measured are:

- Crown wear;
- Gauge wear;
- Side wear.

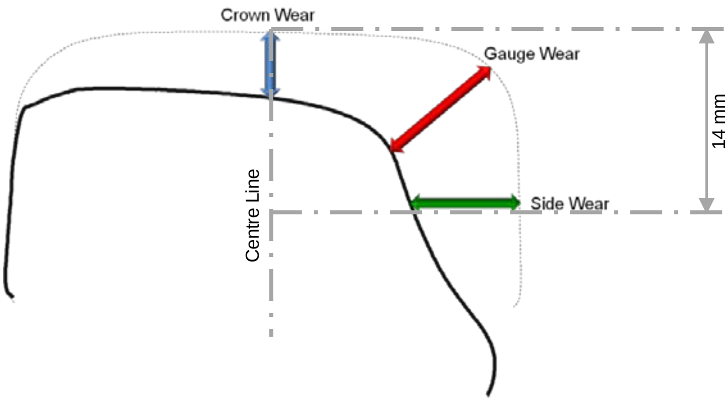


Figure 2-18: Rail Cross-Sectional profile

Fastening System

The connections between the sleeper and the rails have many variations that usually depend on the track design approach followed. The purpose of the fastening system is to retain the rails against the sleepers and resist vertical, lateral, longitudinal, and overturning movements of the rail. The force systems causing these movements are from the wheels and from temperature change in the rails.

Wooden sleepers require steel plates under the rail to distribute the rail force over the wood surface. This provides suitable bearing pressure for the wood and protects the wood from mechanical wear. In addition these plates:

1. Assist the fasteners in restraining lateral rail movement through friction;
2. Provide a canted surface to help develop proper wheel/rail contact.

The size of the sleeper plate is an important factor in sleeper performance. If the sleeper plate size is inadequate for the rail loading, the resulting pressure may exceed the wood fibre compressive strength, and thus cause accelerated plate cutting and premature deterioration of the sleeper.

Concrete sleepers have spring fasteners that provide vertical, longitudinal as well as lateral restraint. The fastener is insulated electrically from the sleeper or the rail to minimize signal circuit current leakage. Pads are placed between the rail seat and the concrete sleeper surface to fulfil the following functions:

1. Provide resiliency for the rail/sleeper system;
2. Provide damping of wheel induced vibrations;
3. Prevent rail/sleeper contact attrition;
4. Provide electrical insulation.

Sleeper

Sleepers are laterally spaced cross ties, supporting and holding the rails. This open structure of rail and evenly spaced sleeper panel was developed to facilitate maintenance, but still structurally provides a stable roadway.

Sleepers have several important functions:
1. Receive the load from the rail and distribute it over the supporting ballast at an acceptable ballast pressure level.
2. Hold the fastening system to maintain the proper track gauge.
3. Concrete sleepers provide a inclination to the rails to help develop proper rail/wheel contact.
4. Restrain the lateral, longitudinal and vertical rail movement by anchoring the superstructure in the ballast.

Concrete sleepers generally have a more secure fastening system than wood sleepers and are also heavier. Concrete is potentially more durable than wood. This combination of factors means that better rail restraint is provided with concrete sleepers. However, concrete sleepers are more difficult to handle than wood sleepers and require pads to provide sufficient resiliency.

2.7.5 Substructure

Ballast

Ballast is the crushed, granular material placed as the top layer of the substructure. Traditionally the following material characteristics were considered to ensure good ballast performance:

- angular;
- crushed hard stones and rocks;
- uniformly graded;
- free of dust and dirt;
- not prone to cementing action.

However, according to Selig and Waters (1994), no universal agreement exists concerning the proper specifications for the ballast material index characteristics. It is rather availability and economic importance that are the primary criteria for the selection of ballast material.

Ballast performs many functions. The primary functions are:

1. Resist vertical, lateral and longitudinal forces applied to the sleepers to keep the track in its required position;
2. Provide resiliency and energy absorption for the track;
3. Provide large voids for storage of fouling material in the ballast;
4. Facilitate maintenance surfacing and lining operations (to adjust track geometry) by the ability to rearrange ballast particles with tamping;
5. Provide immediate drainage of water falling onto the track;
6. Reduce pressures from the sleeper bearing area to acceptable stress levels for the underlying material

Secondary functions are:

7. Alleviate frost problems by providing an insulating layer;
8. Inhibit vegetation growth by providing a cover layer not suitable for vegetation growth;
9. Absorb airborne noise;
10. Provide electrical resistance between rails;
11. Facilitate rehabilitation or renewal of track.

As shown in Figure 2-12 the ballast layer is subdivided into four zones:

1. Crib - material between the sleepers;
2. Shoulder - material beyond the sleeper ends;
3. Top ballast - upper portion of supporting ballast layer, that is disturbed by tamping;
4. Bottom ballast - lower portion of supporting ballast layer, that is not disturbed by tamping and which generally is the more fouled portion.

The functions of the ballast vary among the four zones as suggested in Table 2-1.

Table 2-1: Functions of Ballast by Zone

No.	Function	Crib	Shoulder	Top	Bottom
1(a)	Vertical resistance			✓	✓
1(b)	Lateral resistance	✓	✓	✓	
1(c)	Longitudinal resistance	✓		✓	
2	Resiliency			✓	✓
3	Void storage		✓	✓	✓
4	Rehabilitation/Maintenance	✓		✓	✓
5	Drainage	✓	✓	✓	✓
6	Stress reduction			✓	✓
7	Frost	✓	✓	✓	✓
8	Vegetation	✓	✓		
9	Noise reduction	✓	✓		
10	Electrical resistance	✓		✓	
11	Renewal	✓	✓	✓	✓

Subballast

Subballast is the layer between the ballast and the subgrade. It forms the transitional layer between the ballast and the formation (Esveld, 2001).

As with ballast, subballast fulfils the following functions:

1. Reduces the traffic-induced stress at the bottom of the ballast layer to a tolerable level for the top of the subgrade;
2. Extends the subgrade frost protection.

In fulfilling these functions, the subballast reduces the otherwise required greater thickness of the more expensive ballast material. However, the subballast has additional primary functions not serviced by the ballast layer. These functions are:

3. Prevent interpenetration of the subgrade and ballast;
4. Prevent upward migration of fine material coming from the subgrade;
5. Prevent subgrade erosion by ballast, which in the presence of water leads to slurry formation, and consequently prevents this source of pumping;

6. Shed water, i.e. intercept water coming from the ballast and direct it away from the subgrade to ditches at the sides of the track;
7. Permit drainage of water that might be flowing upward from the subgrade.

Subgrade

The subgrade is the base the track structure is constructed upon. As indicated in Figure 2-12 the subgrade will possibly be divided into two categories, namely:

1. Natural ground (formation);
2. Placed soil (fill).

Existing ground should be used with minimal disturbance. Often some of the formation must be removed to construct the track at its required elevation, and in other cases placed fill needs to be utilised to raise the natural ground level to the required elevation for the track structure. In some cases, at specific locations, it may be required to replace the available top portion of unsuitable *in-situ* ground with placed fill.

The subgrade’s primary function is to provide a stable foundation for the subballast and ballast layers.

Drainage

Figure 2-19 represents a simplistic configuration of the drainage system, ensuring good track performance. Although not part of the track structure components, the drainage system contributes vastly to the properties of the substructure that influence track geometry performance, and therefore the author believes it is important to consider the drainage system and its functions within the total track structure system.

The major functions of the drainage system are:

1. Intercepting subsurface water entering the area of the track substructure;
2. Intercepting surface water approaching the track structure from the sides;
3. Removing water draining out of the ballast and subballast.

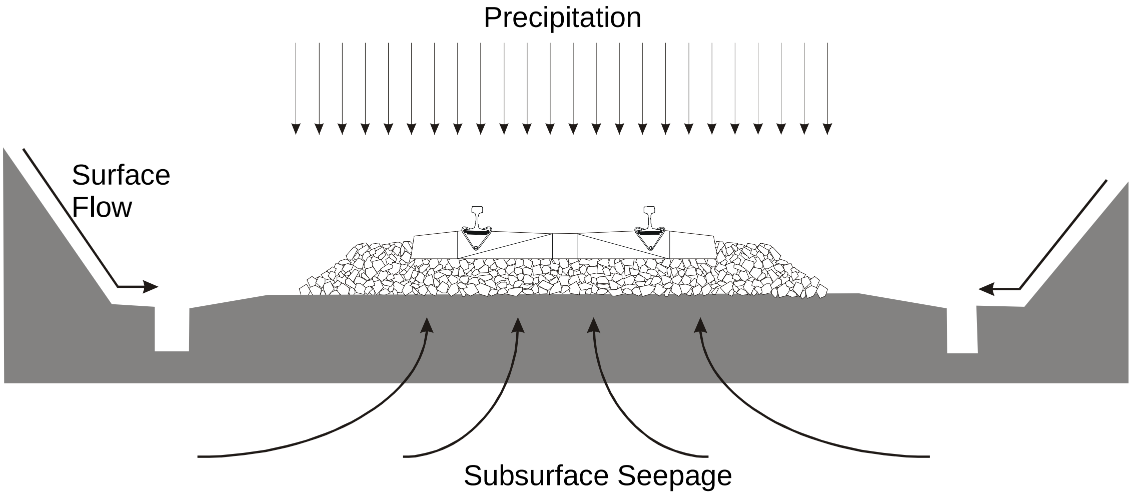


Figure 2-19: Typical Drainage System Indicating Sources of Water

Drainage is fundamental to the condition of the substructure, it is often the factor causing problems and is a basic requirement for a good maintained track. According to Selig, E.T. and Cantrell D.D (2001), drainage of railway track is recognized as a fundamental, yet often neglected aspect of track design in the railway industry, it knowingly influences the performance of track condition and track maintenance requirements. It is further made clear that the drainage system must include means of handling water flowing over the ground surface (surface flow) towards the track, shedding or draining water falling onto the track through precipitation, and controlling water from the subgrade (subsurface seepage).

Selig, E.T. and Cantrell D.D (2001) continuous to clarify that achieving proper drainage is not simply a matter of digging cross drains and letting water out of the track. If not managed, longitudinal drains result in discontinuities that can increase the roughness of the track (increase of condition deterioration). Further it's advised that drainage is a complex system and factors that should be considered include: ballast fouling condition, subballast gradation, slope of subgrade surface, ditch/drainage or longitudinal slope and rainfall characteristics. Lastly it would be desirable to have the subballast shed the water draining down from the ballast to keep the water from the subgrade.

2.8 Typical Rehabilitation and Renewal Activities

The principal function of engineering / maintenance in the railway business is to ensure an effective and optimised maintenance strategy. Engineering performs the role of asset caretaker, ensuring asset capacity. In many instances, maintenance / engineering is perceived as a major expense in a business, and is therefore traditionally the primary location to reduce the budget to affect the operational profitability.

The author is of the opinion that "managing" operational profitability by means of reducing the maintenance budget is only a short-term solution, and does not have a sustainable impact on the business in the long term. He therefore supports the viewpoint of Peterson (2000) that describes asset management as a process through which decisions about the use and care of the organisation's assets are consistently made and executed.

Figure 2-20 (below) illustrates high-level maintenance tactics used to optimise the maintenance input for railway track assets. This being to maximise operational availability and capacity, with knowledge of the business requirements.

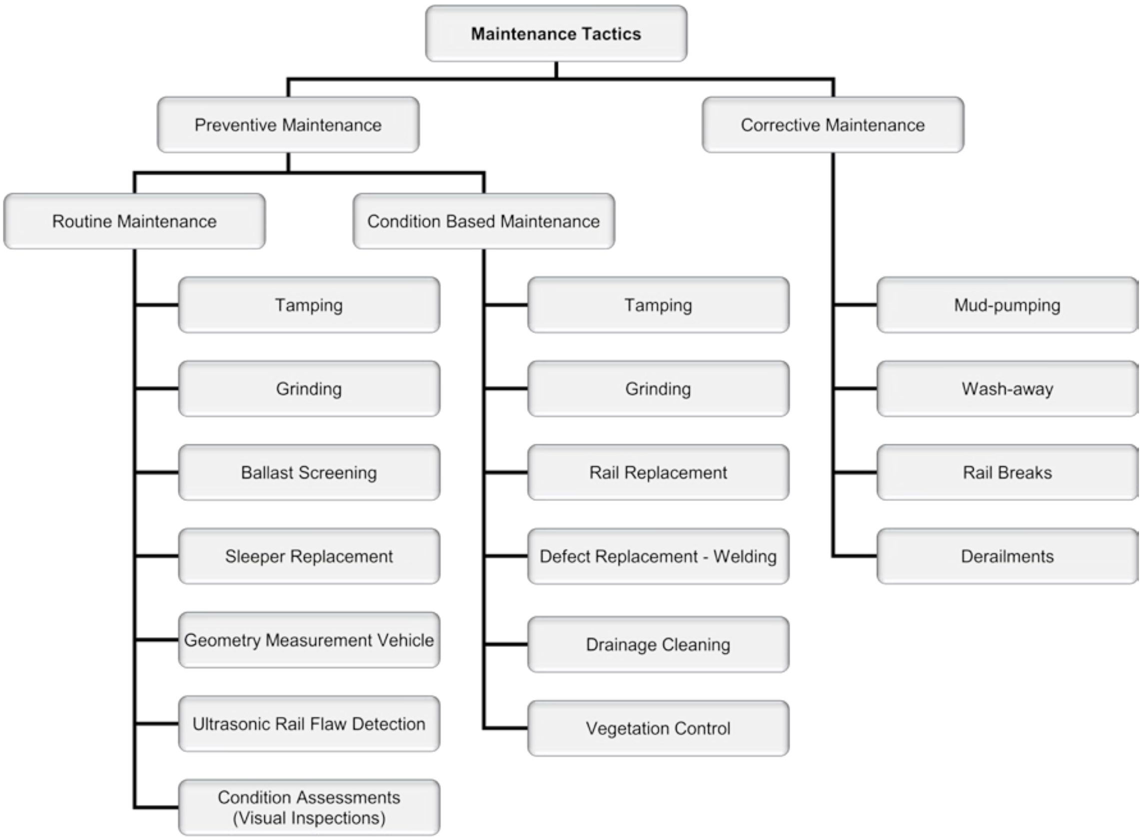


Figure 2-20: High-level Track Maintenance Tactics

For the purposes of this dissertation, the author only offers an in depth discussion on the production tamping maintenance activity in the section to follow.

2.8.1 Ballast Tamping

Tamping lifts and aligns the track to a desired geometric level to mitigate geometry irregularities and deviations caused to the track, due to repeated traffic loading. Tamping is considered the most effective maintenance activity for correcting these geometry deficiencies. Tamping consists of two basic actions as indicated in Figure 2-21, namely the down-feed action and the squeezing action. It should be noted that care must be taken when ballasted track is tamped, as it will introduce some additional functional failures of the ballast properties that include (according to Selig and Waters 1994):

- Ballast breakdown that adds to increased fouling;
- Ballast bed loosening;
- Initial reduction in resistance;
- Loosening of the ballast resulting in further settlement with additional traffic;
- Degree of settlement increase as ballast deteriorates

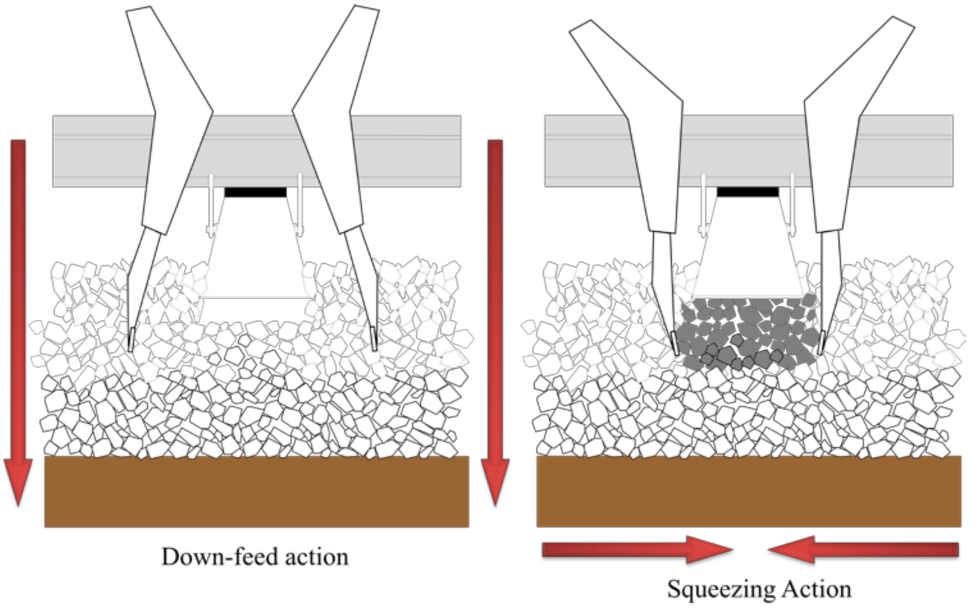


Figure 2-21: Tamping Action

Understanding tamping improves the vertical and alignment geometry parameters, it is clear, utilising condition monitoring techniques, vertical profile and horizontal alignment parameters are the primary condition indicators to identify areas that can be improved through the tamping activity. Understanding the layout configuration (i.e. whether in a tangent track section or a curve) also performs a function in how to identify the requirements and needs consideration in the tamping activity process.

Further to the above is should be understand that tamping is a science in its own right. Although it is explained above that tamping is the action to improve geometry irregularities, specific to vertical profile and horizontal alignment, tamping should also be seen as a system of activities. The tamping system consists typically of two or three separate machines that work as a unit. The first set/grouping of machines is the tamping (levelling and aligning) machine in conjunction with a ballast regulator. After this activity the railway imposes a speed restriction/slow order due to initial settlements taking place, related to vertical stability of the track. According to Wenty (2011) the first few trains cause a first irregular settlement of the track - laying the seed for the development of further track faults. He further argues that in current times, more attention is being paid to the positive effect on the vertical stability of the track geometry. From Lichtberger (2002), it is apparent that the value of introducing a dynamic track stabilizer, following the ballast regulator, result in an extension of the maintenance cycles, increasing the asset life cycle by approximately 30%. The dynamic track stabilizer effects a uniform initial settlement restricting further settlement, resulting in durable track geometry. Wenty (2011) indicates that the initial settlement achieved by the dynamic track stabilizer, is equal to approx. 700 000 to 800 000 load tons. Therefore allowing railways not imposing speed restrictions and allow for normal train operations directly after the maintenance activity. The combination of a tamping (levelling and aligning) machine, ballast regulator in conjunction with a dynamic track stabilizer is generally referred to as Mechanized Track Maintenance Train MDZ (Esveld, 2001). Further it is presented that maintenance for short wavelengths (20 to 30 m) are automatically smoothed during the tamping activity through an inherent measuring system, while correcting longer wavelengths required absolute external control data. This is data is obtained through other technology systems such as specialised track geometry survey machines for example the EMSAT recording car using laser reference chord before the maintenance activity.

Lastly author realise the high demand in maintenance productivity, the value it adds to the holistic business objective in the current railway operation. Therefore it is acknowledged that maintenance production machines and technology innovation over the years played a major part in the improvement of maintenance activity in the railway. This is confirmed by Wenty (2011) where it is presented that since the 1950's tamping technology development firstly into a two sleeper machine after which development of two and three and four sleeper tamping machines in continuous action mode increased the tamping speed to more than 2600 m/hr. This result in the ability to increase operational capacity due to the decrease in maintenance time required for occupying the right-of-way.

2.9 Conclusion

This chapter provided a fundamental review of the literature pertinent to the topic of the dissertation. Issues relating to maintenance and asset management in the railway industry, and relevant maintenance strategies and computerised management systems were reviewed in detail. The chapter also reviewed railway terminology, thus presenting the fundamentals of permanent way components and facilitating a high-level understanding of these components' functions. The literature review concluded with a discussion of rehabilitation and renewal strategies, with particular reference to tamping.

The literature review sets the scene for Chapter three, where the reader will need to understand the need for a maintenance management model and understand issues relating to data collection and analysis in the study area - a section of railway line between Pietermaritzburg and Durban (South Africa).

CHAPTER 3
ANALYSIS MODEL

3 Introduction

In the previous chapter, the literature review dealt with issues relating to maintenance and asset management, relevant maintenance strategies, computerised management systems and pertinent railway terminology. The literature review concluded with a discussion of rehabilitation and renewal strategies, with particular reference to tamping in the railway industry.

According to Ebersöhn and Ruppert (1998) it is known that the full potential of the existing railway capacity is often not realised. Therefore, the industry needs to consider other approaches for better utilisation of available capacity. The integration and efficient utilisation of information will be a major contributor to ensure maintenance effectiveness.

In this chapter the need for an effective analysis model is discussed, using a 100 km section of line between Durban and Pietermaritzburg (KwaZulu-Natal, South Africa) as the study focus. The chapter discusses methods for data collection and analysis in the study area, with the ultimate aim of producing an effective maintenance plan (specifically for tamping) based on all available data and the operational requirements for the section of line in question.

The effect of condition-based and condition performance maintenance is illustrated, demonstrating how this maintenance strategy increases maintenance effectiveness (doing the right things), resulting in a decrease in maintenance cost. With this in mind it is apparent that with an increase in maintenance effectiveness, less time will be spent maintaining assets. This will increase the availability of assets, adding value to the business through increased available capacity. Availability translates into the opportunity to increase production capability. This corroborates the asset management optimisation philosophy of Mitchell *et al.* (2007) - maximising return on investment.

3.1 Background

Over the last decade, the Chair in Railway Engineering at the University of Pretoria (South Africa), Transnet Freight Rail (a South African state-controlled rail transport company) and Amtrak (The National Railroad Passenger Corporation in the United States), all collaborated in various infrastructure maintenance projects. During the course of these projects, the need to develop philosophies of Railway Infrastructure Asset Life Cycle Management became apparent. During this period the author commenced his postgraduate studies while at the time working for Transnet Freight Rail. Transnet Freight Rail seconded the author to the Chair in Railway Engineering at the University of Pretoria to form part of the research team developing these philosophies.

3.2 Objective

The model defined in this section has the following objectives:

- Integrating operational requirements within the maintenance optimisation process to assist in asset optimisation;
- Demonstrating that utilising condition based maintenance results in a sound scientific maintenance management approach;
- Demonstrating that condition based tamping has a vast impact on maintenance management effectiveness;
- Demonstrating that condition based tamping has a vast impact on asset management optimisation;
- Demonstrating that a systematic maintenance management process can reduce maintenance cost;
- Demonstrating that the next step in the process is to move from condition based maintenance to a continuous improvement maintenance strategy.

The scope of the above only relates to geometry condition improvements that will influence tamping maintenance activities.

3.3 Conceptual Effective Maintenance Management Model

From the literature study, the following linear asset maintenance management process is derived and presented in Figure 3-1. The process consists of:

- Electronic asset register (Asset Configuration) and Infrastructure Management Data (data collection that includes asset conditions, operational data such as capacity utilised and financial data);
- Analysing condition data;
- Plan and schedule maintenance activities according to analysis;
- Work execution;
- Performance measurement.

A continuous feedback loop is present to enable the decision maker to go to the previous step in the process at any time during the management process.

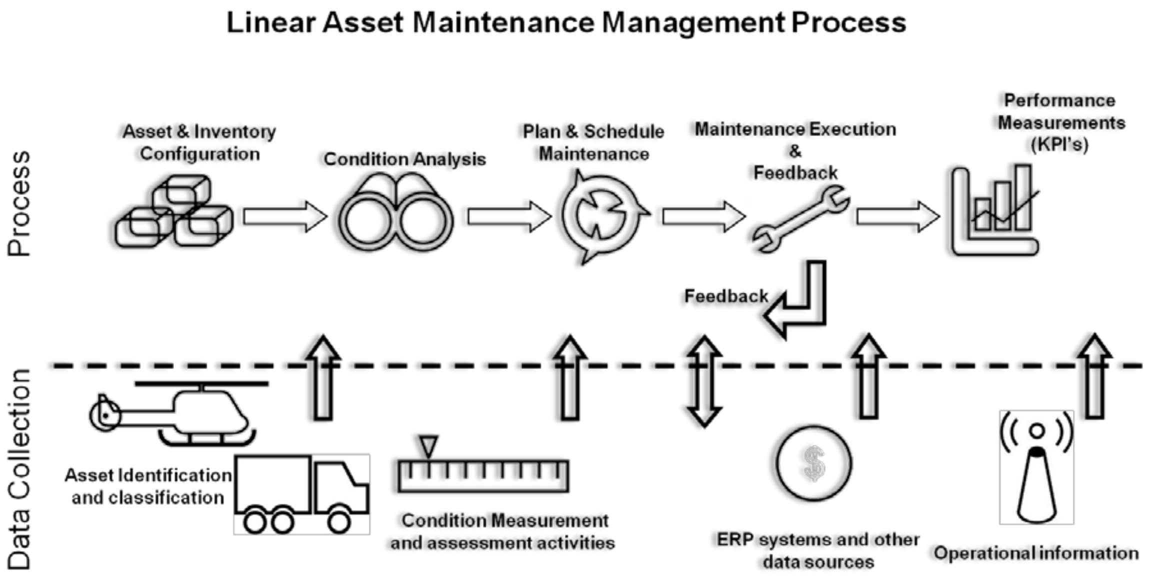


Figure 3-1: Linear Asset Maintenance Management Process

From this, a model was developed to assist in the optimisation/continuous improvement of an effective maintenance management process. This model will be discussed in detail in this section. It is presented in Figure 3-2 and consists of the following steps:

- Setting up a maintenance management database consisting of:
  - An Asset Register (Asset Configuration);
  - Infrastructure Management Data
    - Condition based assessment data:
      - Automated Condition Assessment ;
      - Visual Condition Assessment.
    - Operational Data
      - Utilisation
    - Work History
      - Work Activities
- Developing or acquiring a maintenance management system that fully integrates into the maintenance management process;
- Utilising the data and system to assist in the analysis phase;
- The analysis process consists of:
  - Understanding Operational input requirements:
    - Know the operational needs;
    - Understand the asset base and its configuration;

        - Understand the assets' functions and purpose;
        - Understand asset deterioration;
        - Know the maintenance strategies for different assets.
    - Condition/Performance Analysis:
        - Define the maintenance input parameters where required;
        - From the above, utilise parameters to analyse the current condition status.
    - Identifying maintenance needs:
        - Utilising results, identify maintenance needs;
        - If required, make changes to parameters according to engineering knowledge.
    - Setting up a preliminary maintenance plan (Plan and schedule):
        - Quantify work load;
        - Determine resource requirements;
        - Develop a preliminary budget.
    - Setting up a maintenance/work plan (Final plan and schedule):
        - Integrate other maintenance functions and preliminary maintenance plans;
        - Optimise the maintenance plan accordingly;
        - Setting up a budget.
    - Executing maintenance;
    - Measuring performance;
    - Implementing Continuous Improvement.

Note, in this dissertation analysis will be limited to condition analysis specifically related to tamping.

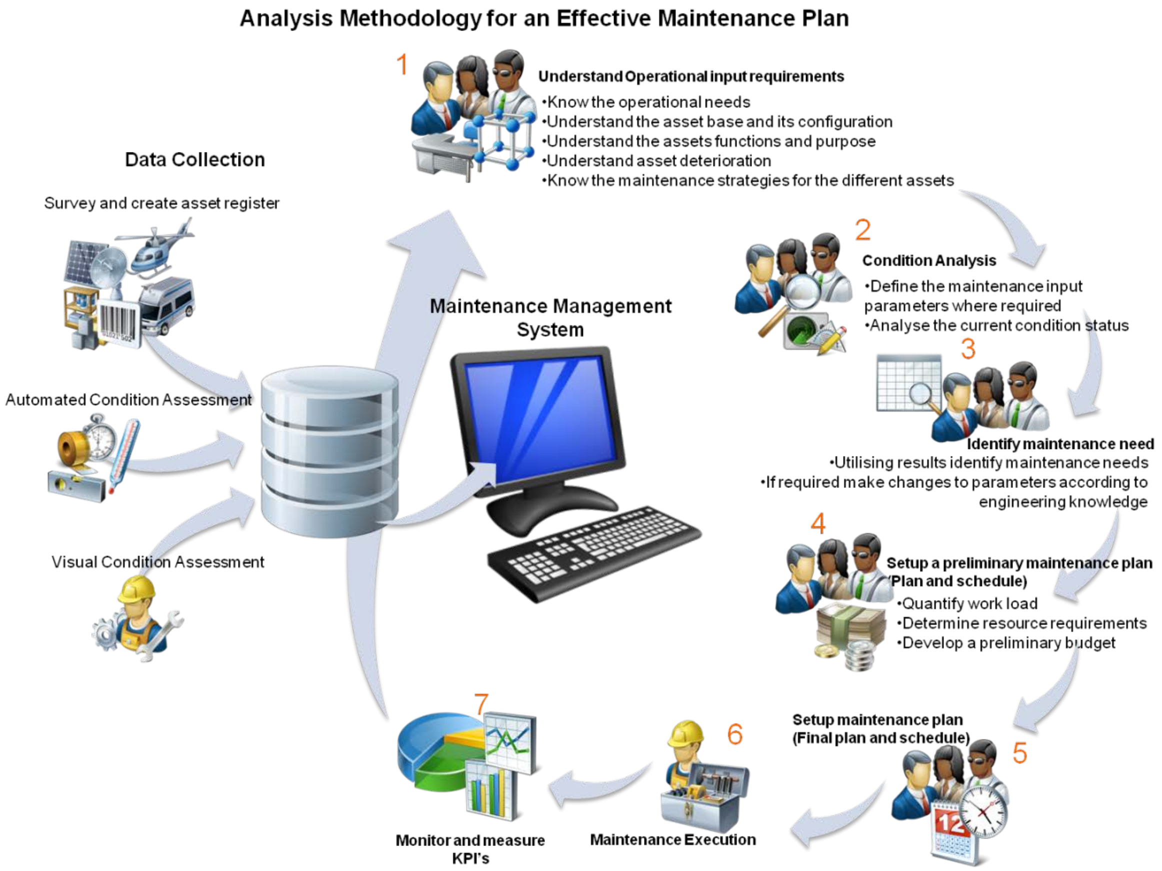


Figure 3-2: Maintenance Management Model for Effective Maintenance Planning

3.4 Data Collection

In this section, the process utilised to collect data is discussed. It presents the methods and technology utilised to gather data from the field.

3.4.1 Asset Register

Asset register data were obtained from Transnet Freight Rail for the section of line between Pietermaritzburg and Durban (South Africa). The line is approximately 100 km long and is utilised in this dissertation. This line is a double line, but only the number one line was analysed. The line is normally used for the transport of general freight from Johannesburg to Durban for export purposes and for moving goods from Durban's port to Johannesburg. The specific section between Pietermaritzburg and Durban is partially located in a mountainous area, resulting in the presence of multiple tunnels and sharp curves, influencing the operational capabilities on this section.

Transnet Freight Rail initially collected an asset register for the Natal Main line in 1998. The survey was conducted utilising Light Detection and Ranging (LiDAR) and GPS technology, recording the right-of-way at speeds up to 60 km/h. The points cloud (laser data) resulting from this survey provided a density of approximately 10 to 15 points per m^2. A software tool called Flip 7 was utilised to extract the data into a geographical format. It consists of polygon, polyline and point objects, geographically referenced to an accuracy of 10 cm. As part of the data extraction, a process was developed enabling an accurate and repetitive data extraction result.

Listed below in Table 3-1 are all the principle railway assets required in the asset register. All these layers formed part of the extraction process to populate the asset register.

Table 3-1: Principle Railway Asset Layers

Layer	Layer Properties
Switch Points	Location and Attributes
Signal Support	Location and Attributes
Bridge	Location and Attributes
Culvert	Location and Attributes
Drain	Location and Attributes
Km Post	Location and Attributes
Level crossing	Location and Attributes
Platform	Location and Attributes
Track Segment	Location and Attributes
Signal	Location and Attributes
Tunnel	Location and Attributes
OHTE Mast pole	Location and Attributes
Run-away Derailers	Location and Attributes
Track Attachment	Location and Attributes
Stop Blocks	Location and Attributes
Wayside Readers and Equipment	Location and Attributes

Data extraction process

Discussed in the section below is the process of data extraction. As mentioned in the literature, objects are defined as points, polylines (lines), or polygons. A process for each object type is discussed by means of a practical example.

Point layer – Signals and signal support

Point layers are defined as layers containing single points that each represents an object. Typical point layers include signals, switch-points, mast poles and signal support objects. It is proposed to identify the location of a point object in terms of its function. For example, identify the signal object on the signal light while identifying a signal support object at its foundation.

In Figure 3.3 below, the actual points captured and recorded in the asset register are illustrated. This example is for demonstration purposes only.

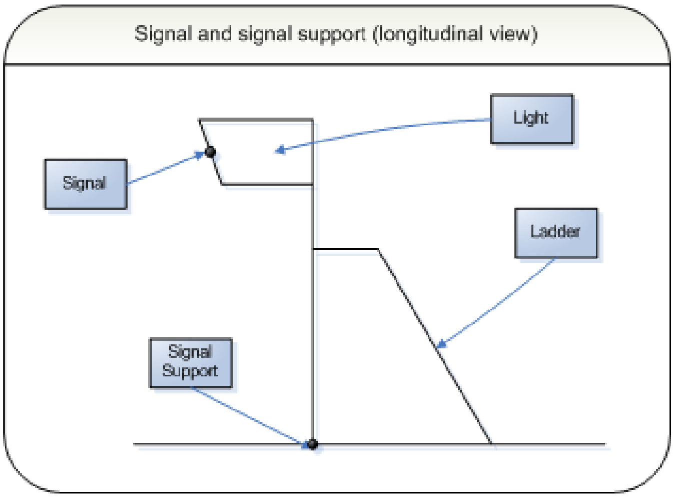


Figure 3-3: Point object identification (Signal and signal support example)

Line layer – Tracks

Polyline (line) layers are defined by vertices that define the location properties of the polyline object. For polyline objects, the data extraction process consists of two phases:

- Phase 1: Identify the polyline points;
- Phase 2: Connect points to form a single polyline object, defined by the identified points that forms the vertices of the polyline.

Phase 1: Identify polyline points

For polylines, polyline points are defined in line with the Overhead Track Support Structures on Electrified lines, or approximately every 50 m on Non-Electrified lines for each polyline. For the track layer, the point in the middle of the two rails in line with the top of the two rails is defined. See Figure 3-4 (below).

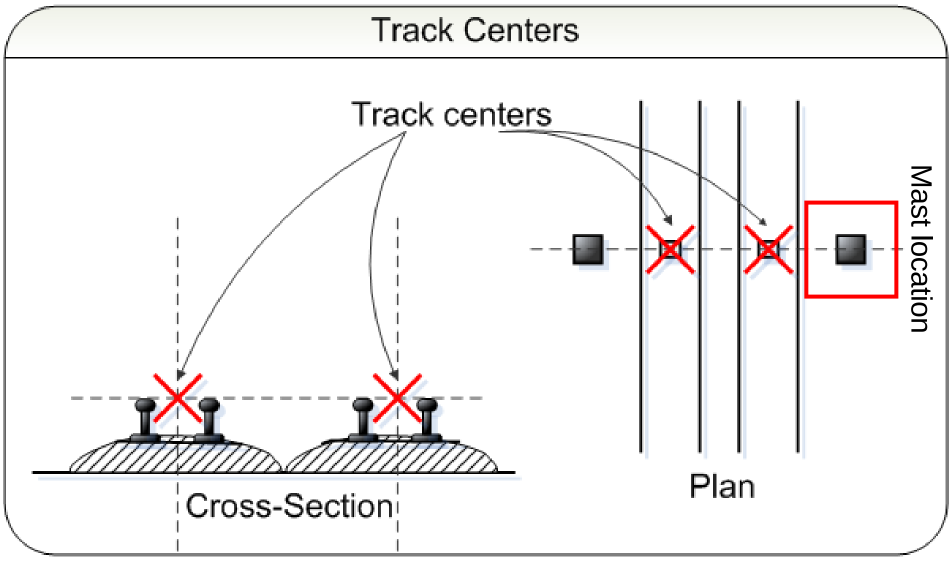


Figure 3-4: Identification of polyline points (Track segment example)

Phase 2: Build polyline connectivity

Each polyline consists of at least two points defining the start and end locations of the polyline object. The polyline object is defined by connecting the identified points, starting from the vertex at the smallest station (linear distance) value, to the highest. Therefore, connectivity should always be in the direction of increasing kilometre values.

Vertices are defined as different types to indicate whether that vertex should be defined as a node. In other words, a start point or an end point. The vertex types in this study are defined as follows:

- M – Kilometre post or Mile post points. A vertex at a Km-post on the polyline will have one “M” point type. This point does not indicate the start or end of a track segment. The point is the zero “+ meter” distance for that kilometre.

- P – Point of switch. Whenever there is a P point, there must be two other P points that indicate the start or end of two other track segments. This means that there are always a total of 3 “P” points at the same location. See Figure 3-5 (below). Note that polyline element numbers are indicated in red, showing that a switch point is located. A polyline’s element numbers stop continuing from the previous vertex number and restart at 1. This also indicates that this position is the location where the connectivity process should stop and be restarted.

- L – Beginning or end of Section. On a section there is only one unique L point, but there can be a similar L point on another section. For example, the end of one section might also be the start of another section. Refer to Figure 3-6 (below).
- B – Stop block. Refer to Figure 3-7 (below).

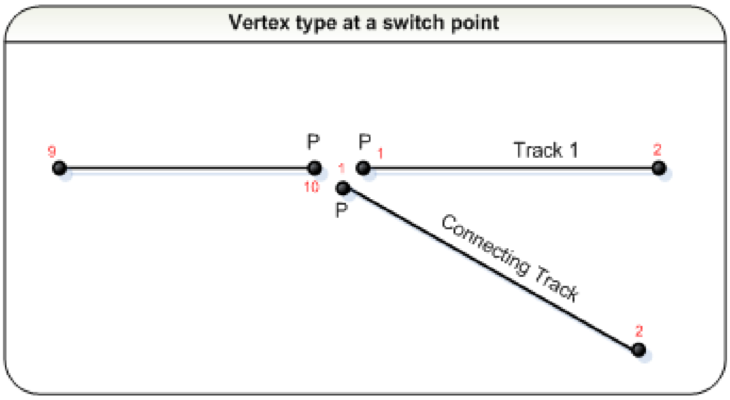


Figure 3-5: Switch point vertices

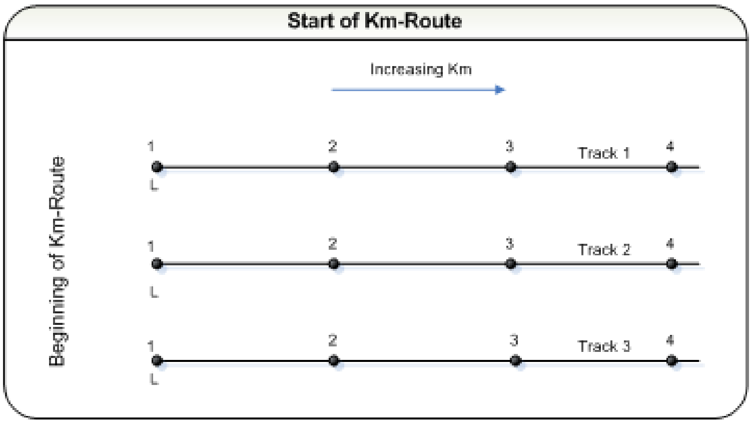


Figure 3-6: Section beginning or ending vertices

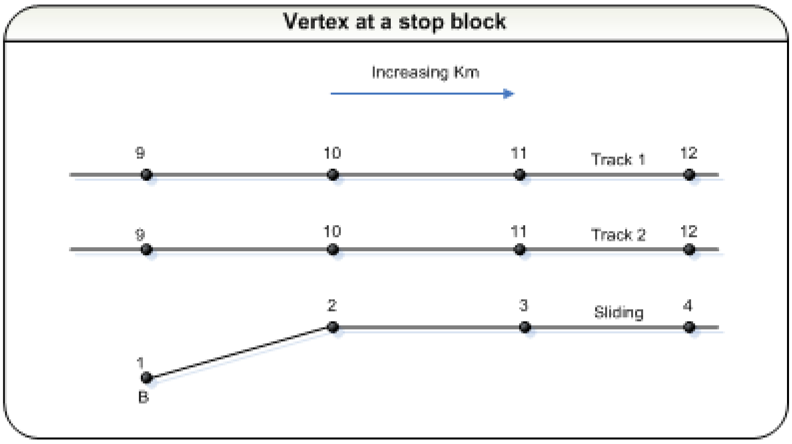


Figure 3-7: Stop block vertex

Connecting polyline points should ensure that there is a continuous increase in polyline element numbers. From the experience of the author, frequently when connecting polyline points to make-up a polyline object, the connectivity process was wrongly executed following the connectivity flow indicated in red (see Figure 3-8, below). Care should be taken during the connecting phase to ensure data integrity.

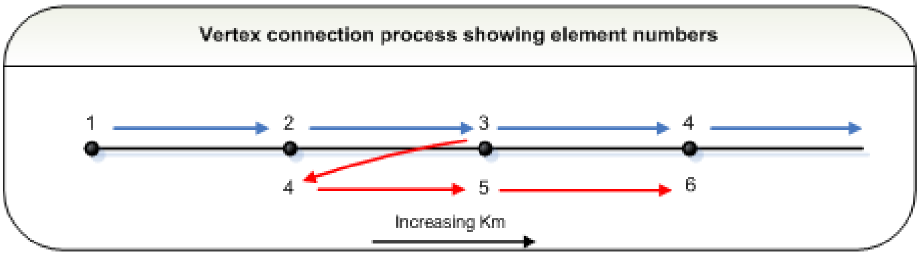


Figure 3-8: Polyline connectivity process (Track example)

Polygon layer – Bridge

Polygon layers are defined by vertices that define the location properties of the polygon object. For polygon objects, the data extraction process consists of two phases:

- Phase 1: Identify the polygon points;
- Phase 2: Connect points to form a single polygon object positional defined by the points (vertices).

Phase 1: Identify polygon points

Points are identified on the four corners of the bridge at the embankments. When the polygon crosses mainlines, two additional points are identified on one of the main lines. See Figure 3-9 (below).

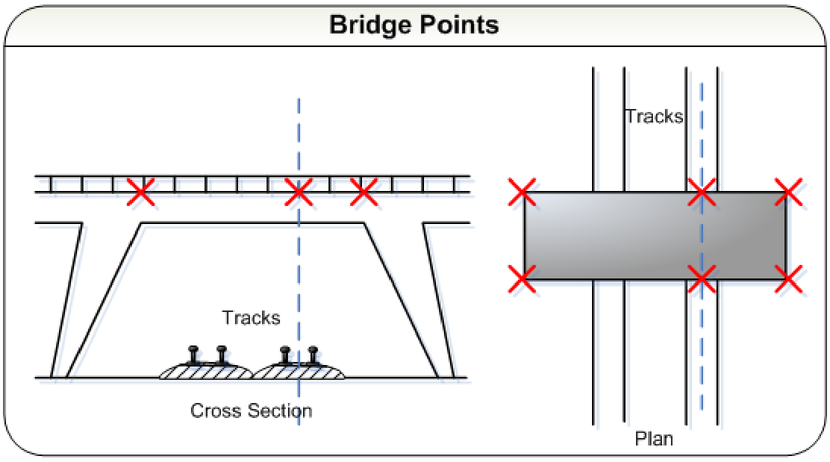


Figure 3-9: Phase 1: Identification of polygon points (Bridge example)

Phase 2: Build polygon connectivity

Each polygon consists of at least four points as discussed above. The polygon object is defined by connecting the identified points, starting from the most north-eastern corner (vertex 1) in a clockwise sequence. The object should be closed, ensuring that a polygon is formed. This is done by ensuring that the first and last vertices in the object have the same location properties. See Figure 3-10 (below), explaining the connecting process.

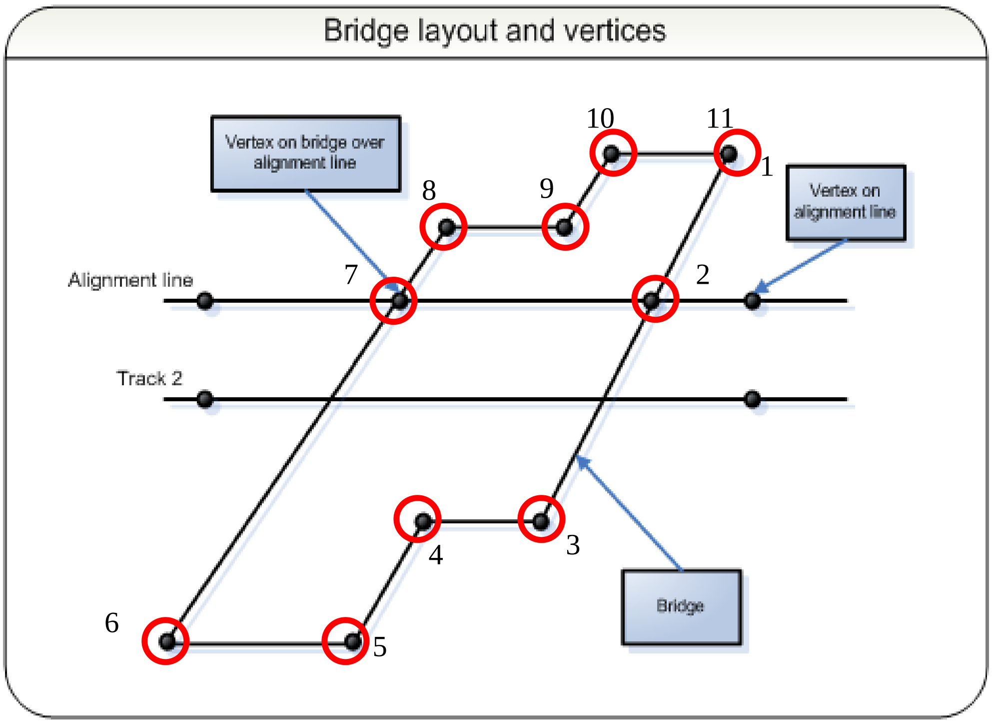
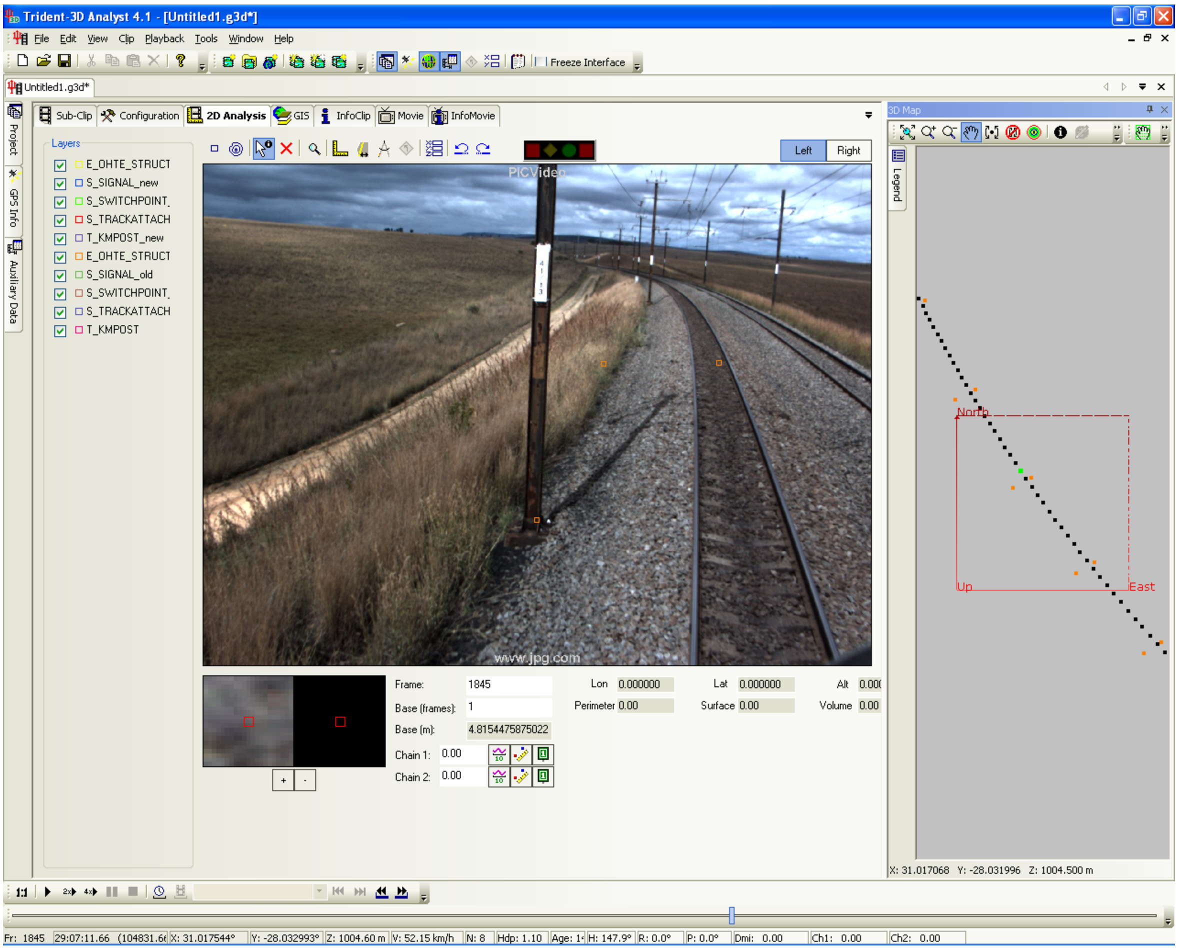


Figure 3-10: Phase 2: Connecting polygon points to form a single polygon object (Bridge example)

Updating the asset register (Asset Identification and Verification)

After the asset register was collected from Transnet Freight Rail, the author conducted an asset identification and verification process because of the age of the asset register data in the IAMM system. A videography measurement was conducted on the mainline from Pietermaritzburg to Durban where the video recording data were utilised to identify and update any changes that occurred in the period after the Light Detection and Ranging (LiDAR) and GPS survey was conducted. An example indicating the integration between the videography technology and the IAMM asset register data is illustrated in Figure 3-11 (below). This method assisted in identifying changes that occurred in the asset configuration. Data exported from the IAMM asset register are imported into the videography system, called Trident 3-D Analyst. The data are displayed in a map view in the software. If a change is identified, it can be updated by either deleting objects that have been removed, adding new objects or by moving (shift) objects that have moved.

It should be noted that related Infrastructure Management Data is automatically updated and re-aligned according to asset configuration changes within the IAMM system.



Layers
- ☑ E_OHTE_STRUCT
- ☑ S_SIGNAL_new
- ☑ S_SWITCHPOINT_
- ☑ S_TRACKATTACH
- ☑ T_KMPOST_new
- ☑ E_OHTE_STRUCT
- ☑ S_SIGNAL_old
- ☑ S_SWITCHPOINT_
- ☑ S_TRACKATTACH
- ☑ T_KMPOST

Frame: 1845
Base (frames): 1
Base (m): 4.8154475875022
Chain 1: 0.00
Chain 2: 0.00
Lon 0.000000
Lat 0.000000
Alt 0.00(
Perimeter 0.00
Surface 0.00
Volume 0.00

X: 31.017068 Y: -28.031996 Z: 1004.500 m

Fr: 1845 | 29:07:11.66 (104831.6(| X: 31.017544° | Y: -28.032993° | Z: 1004.60 m | V: 52.15 km/h | N: 8 | Hdp: 1.10 | Age: 1(| H: 147.9° | R: 0.0° | P: 0.0° | Dmi: 0.00 | Ch1: 0.00 | Ch2: 0.00

Figure 3-11: IAMM Asset Register Data integrated with Trident 3-D Analyst

After this process was completed, the asset register was certified as being current with the field observation data and was used in the analysis process.

3.4.2 Condition Data

Condition assessment data (Track Geometry) were obtained from Transnet Freight Rail for the section of line between Pietermaritzburg and Durban. Track geometry assessment data are automated condition assessment data recorded by a contractor utilised by Transnet Freight Rail. As discussed in the literature study, numerous track geometry parameters can be measured to determine the condition of the track, thus revealing the health of the track structure. The track geometry condition assessment vehicle records these parameters at intervals of between 250 mm to 2 m, depending on the parameter measured. A list of parameters obtained from Transnet Freight Rail is as follows:

- Vertical profile left;
- Vertical profile right;
- Horizontal alignment left;
- Horizontal alignment right;

- Super-elevation;
- Twist;
- Gauge;
- Curvature (Indication of the radius);
- Radius;
- Roughness profile left;
- Roughness profile right;
- Roughness alignment left;
- Roughness alignment right;
- Exception B profile left;
- Exception C profile left;
- Exception B profile right;
- Exception C profile right;
- Exception B alignment left;
- Exception C alignment left;
- Exception B alignment right;
- Exception C alignment right.

From Hanreich, Mittermayr and Presle (2002) it is clear that the fundamental geometry parameters is utilised in railways all over the world to monitor the condition of the track. Standard deviation of vertical profile and horizontal alignment as discussed in the literature study forms the basis of the fundamental geometry parameters. Many railways calculate a Track Quality Index (TQI) parameter. From experience and the literature review, it is apparent that no standard exist for TQI, and is often dependent from individual to individual, railway to railway, country to country (region to region) and continent to continent. All these TQI calculations are in some way based on the fundamental standard deviation measurements.

From Veit (2003), the Austrian Federal Railways (ÖBB) evaluates the track condition considering long-term behaviour and deterioration. The track quality index used is presented in equation (1) below:

$$Q(t) = Q_0 * e^{b*t} \tag{1}$$

Where:

Q(t) = Actual Track Quality at Time t

Q_0 = Initial Track Quality after investment (example tamping)
b = rate of deterioration
t = time

Another TQI developed is Track Roughness; it is the sum of squares with variable summation lengths. This condition index was developed by Ebersöhn (1995) and is expressed in equation (2) below:

$$R^2 = \left(\frac{\sum_{i=1}^{n} d_i^2}{n} \right) \tag{2}$$

Where:

- n = number of measurements in the summation length;
- d_i = the mid-chord measurement for profile and alignment and deviation for twist and gauge.

From this equation, it should be noticeable that the Roughness index is a variation measurement of each condition parameter under consideration.

As an example, the mid-chord measurements for a length of track including a good and poor section are plotted in Figure 3-12. The corresponding plotted running roughness was calculated using the mid-chord measurements values and a 50 m calculation length. The beginning and end of the good and poor sections can clearly be identified.

For the purpose of this dissertation, the author decided to utilise the Roughness TQI. It is a easy to understand TQI and is focused on the current condition of the track, allowing to focus on the current maintenance requirements and therefore used

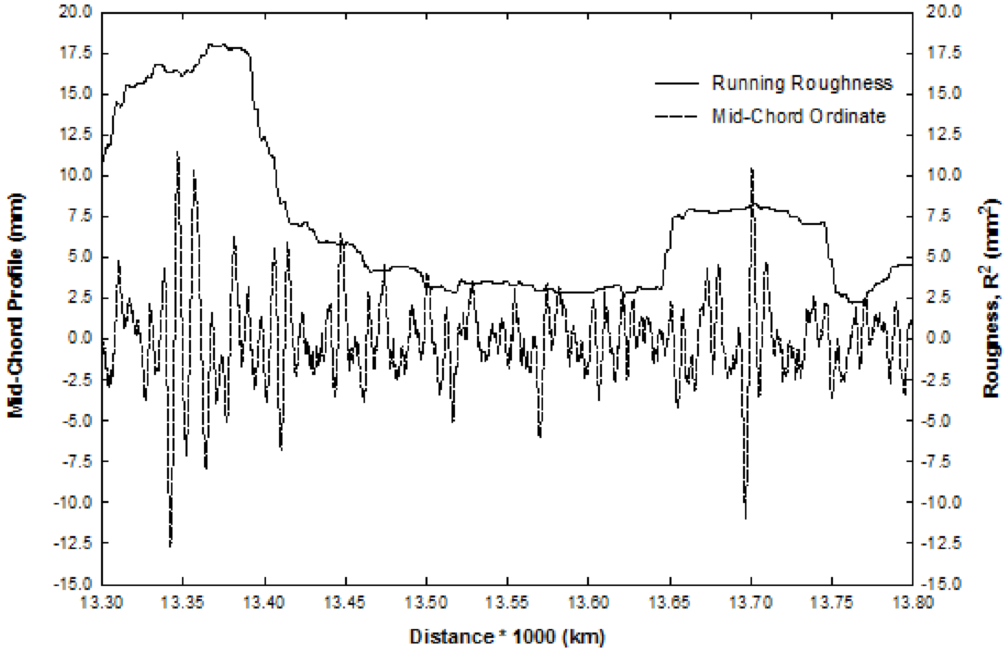


Figure 3-12: Mid-Chord measurement and associated Roughness index plot (from Ebersöhn, 1995)

3.5 Analysis Methodology

In this section, the maintenance management process is discussed to indicate how it is used to produce effective maintenance optimisation. As discussed previously, an effective maintenance management process will add value to the asset management optimisation of the business, and consists of the following steps:

- Understand Operational input requirements;
- Condition Analysis;
- Identify maintenance need;
- Set up/Compile a preliminary maintenance plan (Plan and schedule);
- Set up/Compile maintenance plan (Final plan and schedule);
- Execute maintenance;
- Measure performance.

For this dissertation, the process will be applied in detail for the first 4 steps. The discussion will demonstrate the value of this maintenance management process and how it results in effective maintenance, assisting in the realisation of the objectives discussed at the beginning of this chapter.

3.5.1 Operational requirements

As with any systematic approach, the end result cannot be determined if the problem is viewed in isolation. Asset management optimisation requires an approach where the business objectives are fully understood. This entails determining the requirements needed for synergy between operations and maintenance/engineering, ensuring maximum return on investment.

The process is therefore designed to ask the right questions, enabling the maintenance function to determine the business requirements and objectives. From this information, the maintenance requirements and approach to optimise the asset lifetime, and to ensure availability and reliability required for maximum production/serviceability, are established. The key objectives in the first step of the process are the following:

- Know the operational needs;
- Understand the asset base and its configuration;
- Understand the assets' functions and purpose;
- Understand the assets' deterioration;
- Know the maintenance strategies for the different assets.

Know the operational needs:

This is the first opportunity to build a good partnership between operations and maintenance/engineering. Knowing the operational needs from a maintenance function is fundamental in defining the condition intervention parameters in step 2 of the process. However, it will also indicate to operations the willingness of the asset caretaker to comply and add value to business objectives.
During this study the following operational needs were identified:

- The current demand transported over this section is 18 MGT (million gross tons);
- Future growth indicates that the demand to be transported over this section in future is 63 MGT;
- The mixture of traffic is primarily containers, vehicles and coal, although in the early mornings and late afternoons there are many passenger trains;
- Running 25 trains on line 1 on average per day;
- Average train lengths are approximately 30 trucks;
- Allowable axle loads of 20 metric tons;
- Passenger trains should be able to travel up to speeds of 80 km/h;
- General freight trains should be able to travel up to speeds of 60 km/h.

Understand the asset base and its configuration:

Using the asset register and condition assessment data within the IAMM system allowed the author to fully understand the asset base and its configuration. The details of the asset base and its configuration, specifically related to the track, are presented and discussed below.

Track Information

From the derived information it was determined that the line between Pietermaritzburg and Durban has a route length of 97.4 km. The total length of track for both lines and all stations adds up to an amount of 250.7 km. That translates to a total rail length of 501.4 km.

Earthwork Distribution

The cuts, fills and at grade data were analysed, and a distribution was determined as presented in Figure 3-13 (below).

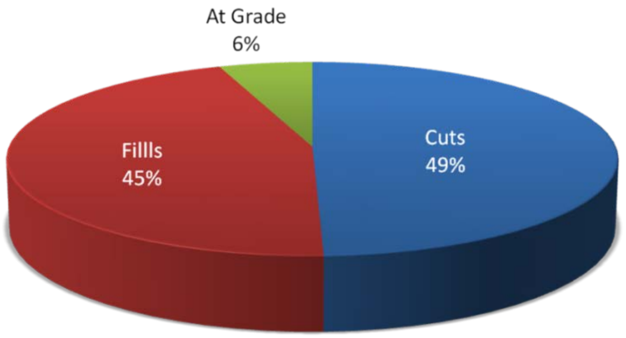


Figure 3-13: Earthworks distribution

From the distribution it is clear that the area is largely undulating, as more than 90% of the line moves through cuts and fills. Understanding the configuration signifies the importance of drainage and vertical profile maintenance activity functions to assure a state of good repair track system supporting train operations.

Drainage distribution

From understanding the earthworks distribution and the environmental configuration of the line, it was decided to analyse the drainage distribution of this section of line. It is apparent that the drainage system will play an important role with the earthworks and environmental configuration at hand.

The drainage distribution is indicated in Figure 3-14 (below).

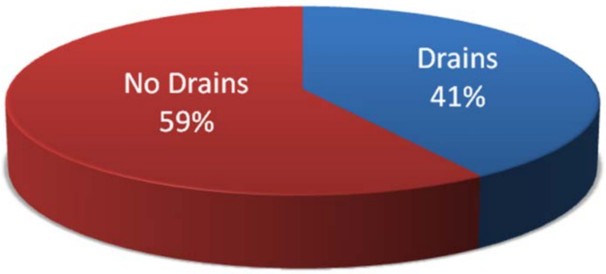


Figure 3-14: Drainage distribution

From the above and by comparing the earthworks distribution with the drainage distribution, it is seen that there are 49% cuts and only 41% drains. A shortage of drains therefore exists on this section of line.

Curve distribution

Utilising the geometry condition measurements, the line’s curvature is seen to be distributed according to the following categories:

- Sharp curves (Radii between 0 and 300 m) – 31%;
- Medium curves (Radii between 300 and 1500 m) – 26%;
- Tangent track – 43%.

These values are determined from the curvature breakdown presented in Figure 3-15 (below).

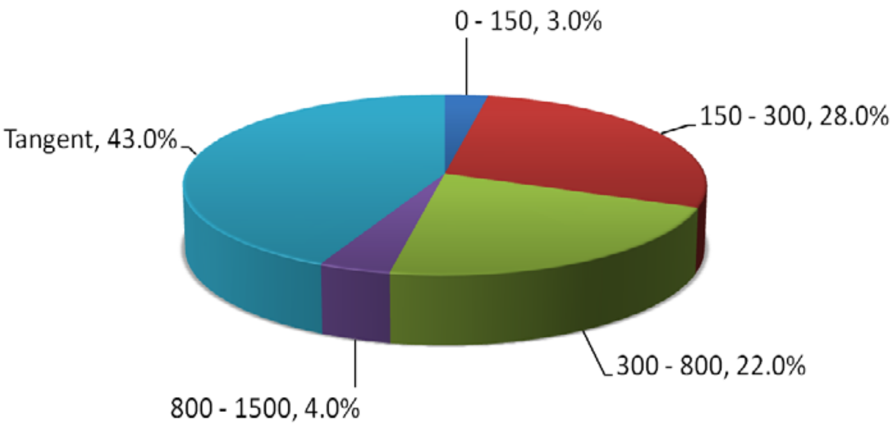


Figure 3-15: Radius breakdown according to predefined radius intervals

This analysis reveals that approximately 60% of the route can be defined as curved track, confirming the observation made during the earthwork analysis. This shows that the line is located in an undulating area. Knowing that the line largely comprises curved track implies that rail wear will be one of the prime maintenance activity functions for prolonging the life of the rails.

Switch point distribution

From the IAMM data, it was determined that approximately 60% of the switch points falls into the 1:12 turnout angle category. All these switches are located on the mainline of the section.

Rail distribution

Lastly, the distribution of the rail types was analysed. It is clear from the analysis that most rails are 57 kg/m rails. The distribution is presented in Figure 3-16 (below).

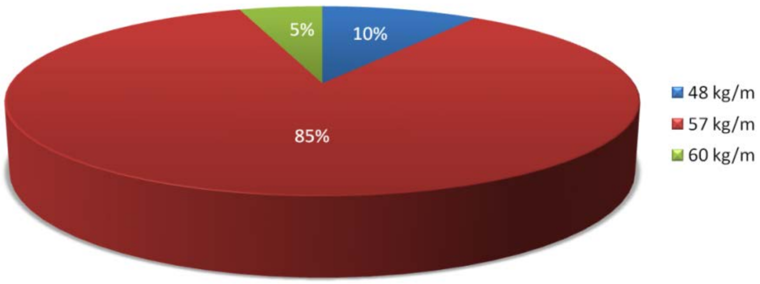


Figure 3-16: Rail distribution on the Pietermaritzburg–Durban section

Based on this information, the section’s asset base and configuration can be summarised as follows:

- Route distance is 97.4 km;
- Approximately half of the line is within cuttings, whilst 45% is on fills;
- Drainage will have a major impact on the condition of the section as half of the route should have drains installed, with analysis showing drains existing on only 41% of the line;
- Almost 60% of the line consists of curved track;
- Switches on the mainline are 1:12 switches;
- Generally rails on this section are 57 kg/m rails.

Before continuing to the next section, the author would like to reiterate that this study is limited to tamping maintenance activity only. Bearing this and the above summarised view in mind, the principal information that will have an influence on the tamping optimisation includes:

- The earthwork distribution;
- The drainage distribution;
- The curvature distribution.

Assets' functions and purposes, asset deterioration principles and maintenance strategies for track assets were discussed earlier in this study, and are not discussed in detail again. However, a high-level summary is provided in the next paragraph.

The railway track provides the support structure for trains to move from one point to another. Due to repeated traffic loading on the track, the track geometry deteriorates forming irregularities, which influence the operational requirements of the business. A condition based maintenance strategy can be applied to determine maintenance needs specifically for track tamping, utilising geometry condition measurements. Tamping as a maintenance activity lifts and aligns the track to a desired geometric level, mitigating irregularities and deviations in the track geometry.

3.5.2 Condition data analysis

A condition based maintenance strategy is followed in this study, as it was determined from the literature study that it will assist in the optimisation of maintenance requirements. Before analysis can be conducted, the operational requirements should be taken into account, understanding the need from business to ensure an effective service can be provided. Knowing the requirements, one needs to determine condition based intervention limits to assist in identifying the maintenance areas that should be considered for maintenance. The maintenance intervention limits and how they were determined are discussed in the paragraphs below.

Determining tamping maintenance intervention limits

From Esveld (2001) it is apparent that tamping will improve the vertical profile and horizontal alignment when applied to the track structure. It is also known (see chapter 2) that the super-elevation and twist parameters are calculated from the vertical profile measurements. Therefore improving the vertical profile will also result in the improvement of these parameters. For the analysis in this study, it was therefore decided to utilise the vertical profile and horizontal alignment parameters to analyse the status of the geometric condition of the track.

Track Quality Index (TQI) and Track Quality Index for Tamping ($\mathrm{TQI}_{\mathrm{TAMP}}$) are familiar condition indices utilised in the railway environment. In this study, the author defines two Track Quality Indices for Tamping that are not standard in the railway industry. Therefore in this study they are termed Roughness for Profile Tamping ($\mathrm{R}^2_{\mathrm{profile\ tamp}}$) and Roughness for Alignment Tamping ($\mathrm{R}^2_{\mathrm{alignment\ tamp}}$). These indices are presented in equations (2) and (3) below.

$$R^2_{\mathit{profile\ tamp}} = \frac{\left[R^2_{\mathit{profile\ left}} + R^2_{\mathit{profile\ right}} \right]}{2} \tag{2}$$

$$R^2_{\mathit{alignment\ \ tamp}} = \frac{\left[R^2_{\mathit{alignment\ left}} + R^2_{\mathit{alignment\ right}} \right]}{2} \tag{3}$$

From these indices it is required to calculate the maintenance limits for each of the tamping parameters for use in the analysis phase. From the operational needs phase it was determined that an average of about 25 trains are running per day from Pietermaritzburg to Durban. These trains have an average length of between 30 and 40 trucks, amounting to 18 MGT per year. It was also identified that the future requirement will be to increase the yearly gross tonnage to a value of 63 MGT, probably within a period of five to ten years. This is in line with current traffic on the Coal export line from Witbank (Mpumulanga) to Richards Bay in KwaZulu-Natal.

Knowing the future requirement of increased yearly gross tonnage, it was decided to use maintenance limits that are currently implemented on the Coal line as a starting point to determine the current maintenance limits that should be used on the line from Pietermaritzburg to Durban.

According to Gräbe and Maree (1997), the maintenance intervention limits used on the Coal line are a standard deviation value of 1.6 mm for vertical profile and a standard deviation of 2.0 mm for horizontal alignment. As roughness can be defined as the variation of mid-ordinate measurements, the above-mentioned values can be translated to a Roughness profile intervention value of 2.56 mm^2, and a Roughness alignment intervention limit of 4.00 mm^2.

As the current traffic on the Pietermaritzburg to Durban section is only running at an annual gross tonnage of 18 MGT, it was decided to utilise the latest condition measurement data on the Coal line and to plot the standard deviation parameters in a frequency plot diagram. From this diagram, the percentile values will be determined from the maintenance intervention limits as used on the Coal line to derive the maintenance intervention limits for the Pietermaritzburg to Durban section.

The diagram presented in Figure 3-17 (below) represents the frequency plot of the latest measurement for the profile parameter standard deviation values in millimetres on the Coal line in 2008.

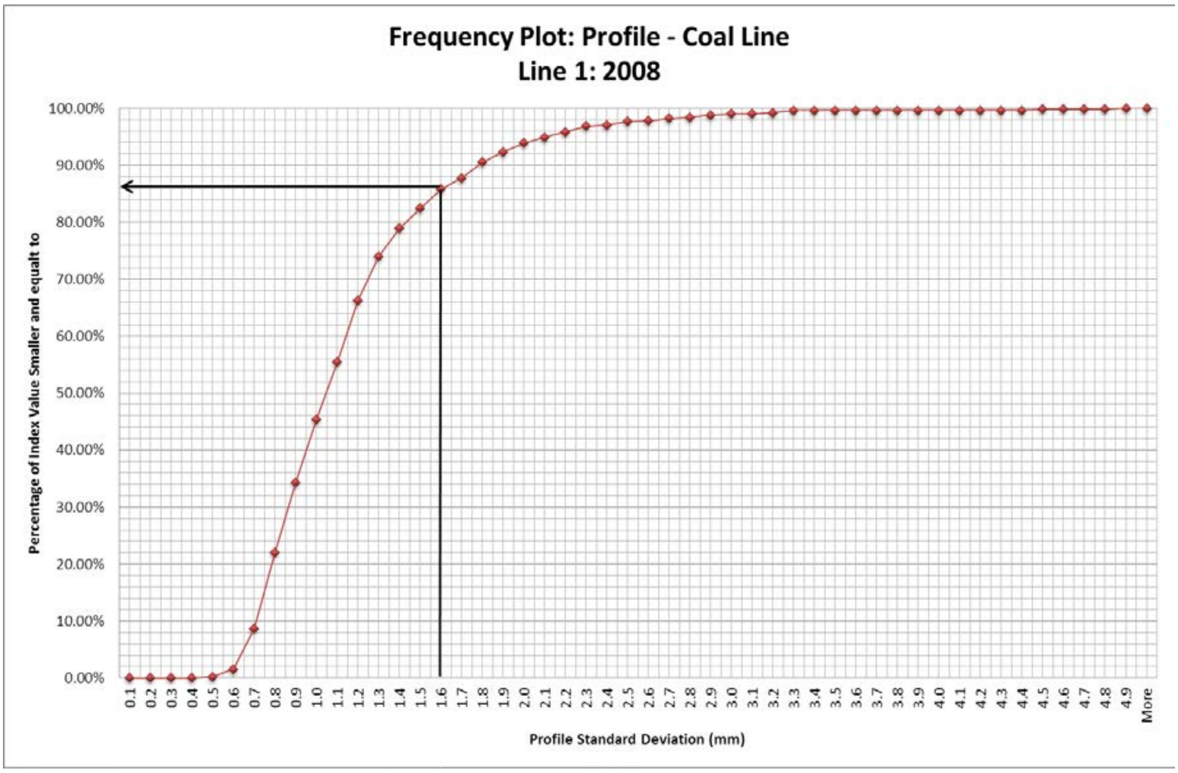


Figure 3-17: Percentile for profile standard deviation equal to 1.6 mm

From the diagram the profile standard deviation’s percentile was calculated as 86%.

As for the profile standard deviation, the same process was followed to calculate the percentile value for the alignment parameter standard deviation values. From Figure 3-18, it was determined that the percentile for the alignment standard deviation of 2.0 mm was just over 94%.

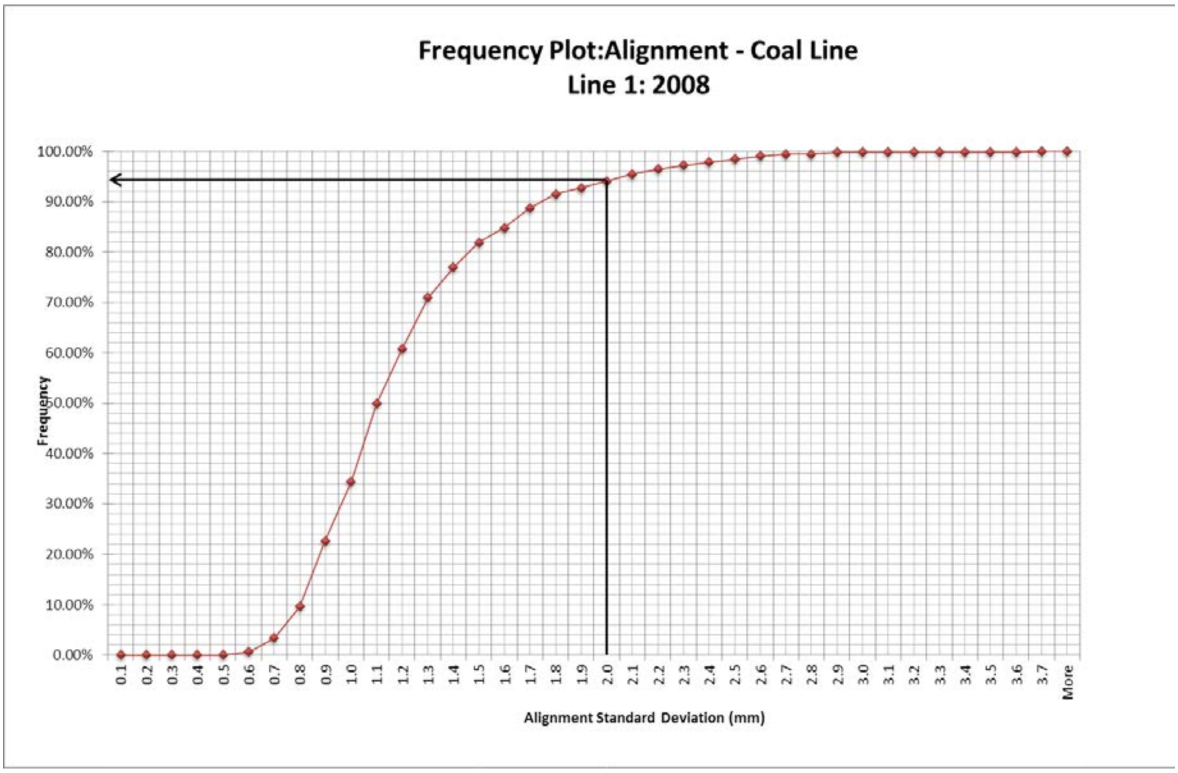


Figure 3-18: Percentile for profile standard deviation equal to 2.0 mm

In the next step, the frequency plots for the profile and alignment standard deviation parameters are calculated and presented. From these plots respectively, the 86% percentile and 94% percentile values were utilised to determine the maintenance intervention limits for both parameters.

From Figure 3-19, the profile intervention limit for profile standard deviation was calculated as 4.2 mm, whilst the alignment maintenance intervention in Figure 3-20 was 5.6 mm.

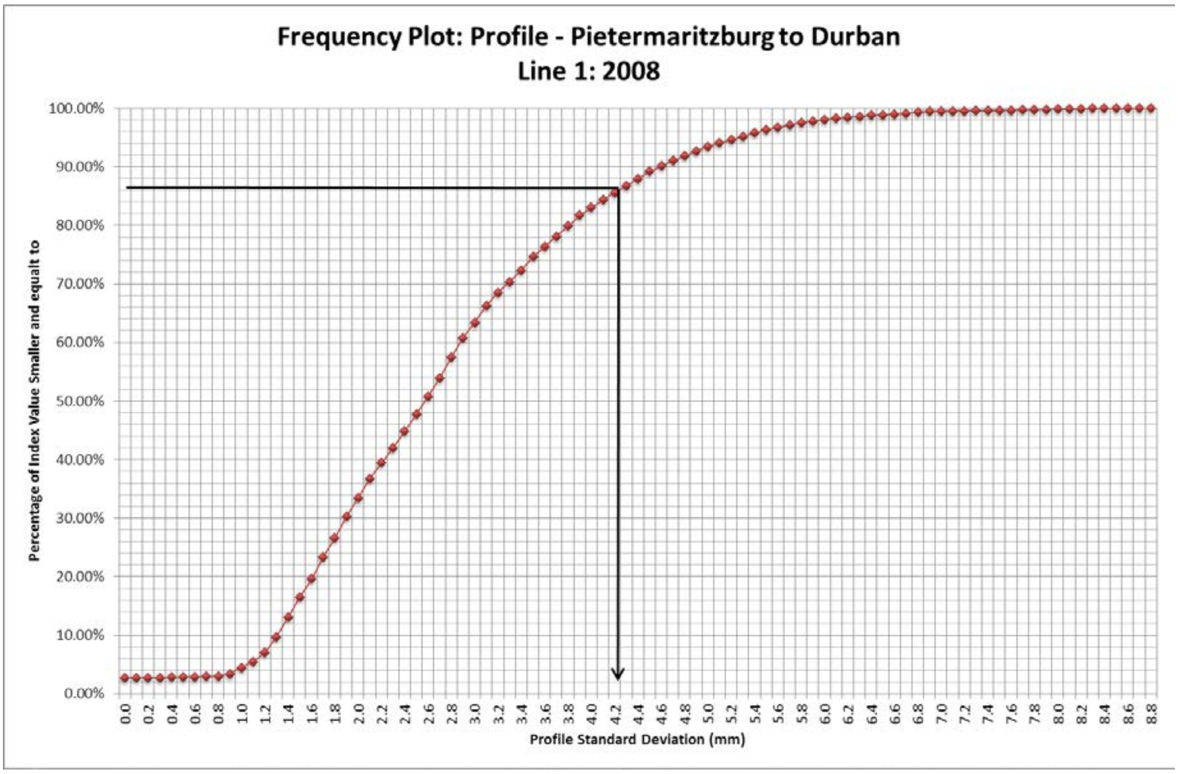


Figure 3-19: Profile standard deviation for percentile equal to 86%

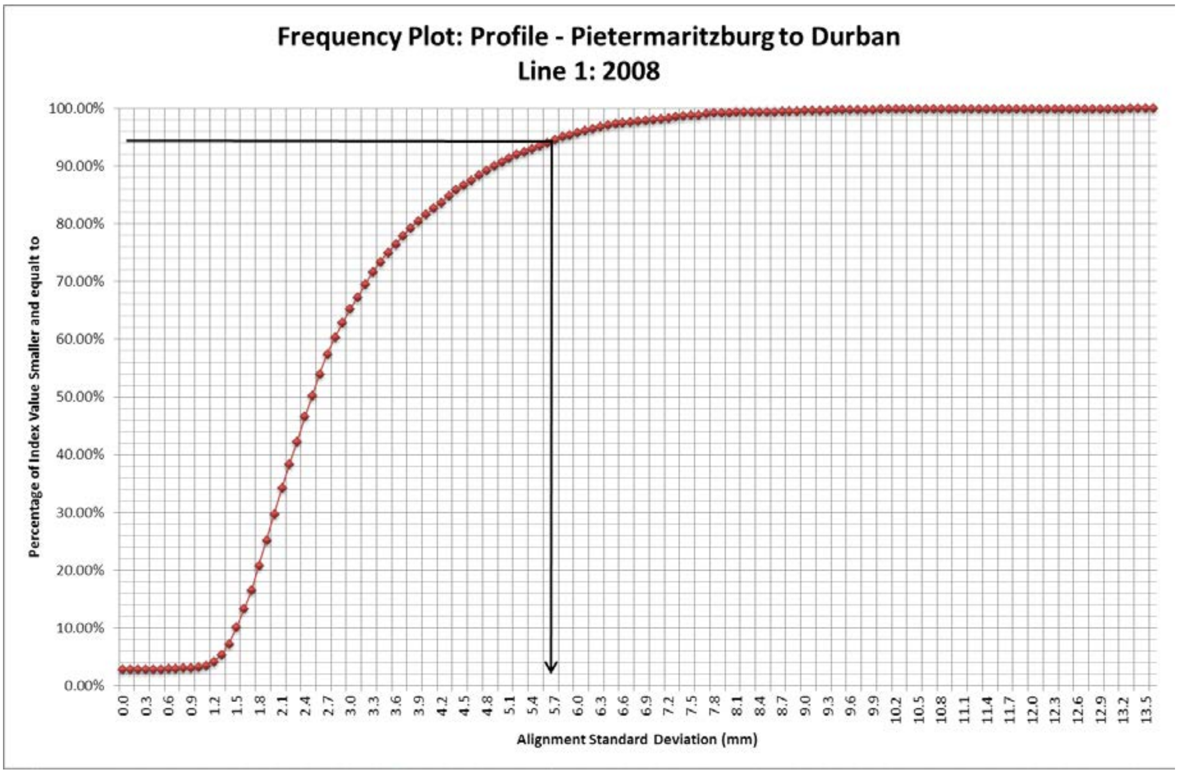


Figure 3-20: Alignment standard deviation for percentile equal to 94%

From the values obtained, the Roughness for Profile Tamping ($R^2_{profile\ tamp}$) and Roughness for Alignment Tamping ($R^2_{alignment\ tamp}$) were calculated as 17.64 mm^2 and 31.36 mm^2 respectively. For condition based analysis purposes, it was decided to be conservative and the following Roughness intervention limits were used:

- $R^2_{profile\ tamp}$ – 17 mm^2
- $R^2_{alignment\ tamp}$ - 30 mm^2

3.5.3 Effective maintenance needs

3.5.3.1 Condition Based intervention maintenance needs

Using condition based maintenance intervention limits and the analysis of condition data in the previous section; it provides the decision maker with a list of areas identified for maintenance requirements. From this list, effective maintenance requirements should be identified and optimised according to maintenance activity rules, thus ensuring an optimised production of the maintenance activity type. In this section, the author focuses on optimising effective track tamping.

To ensure an optimisation of track tamping activity, it was decided to adhere to the following process:

- Step 1: Identify maintenance needs using the $R^2_{profile\ tamp}$ and $R^2_{alignment\ tamp}$ intervention limits (Figure 3-21, below);
- Step 2: Use a cluster length concept to ensure that where maintenance needs are identified for distances smaller than the defined cluster length, the maintenance needs will be optimised to group these maintenance needs to be one area/group requiring maintenance (see Figure 3-22, below);
- Step 3: After this result, use radius configuration information to ensure that if a portion of a curve needs tamping, the result would be extended to include the total curve (see Figure 3-23, below);
- Step 4: Compare $R^2_{profile\ tamp}$ and $R^2_{alignment\ tamp}$ and determine final tamping requirements to ensure all needs are adhered to.

The specifics of each step are discussed in the sections to follow. Note the above-mentioned process is not part of the Transnet Freight Rail IAMM system, and was specifically developed for this study to assist in the analysis and optimisation of track tamping.

The model assists in identifying maintenance needs through condition parameters that can be defined by the user to provide agility to the maintenance identification requirements. The parameters in the analysis model consist of:

- A selection of up to five *condition parameters* to calculate an index, for example the $R^2_{\text{profile tamp}}$ and $R^2_{\text{alignment tamp}}$. Each parameter can be multiplied with a weighted average, and the results of these are added together;
- The *maintenance intervention* limit is a variable needed for the analysis model. In this study it was calculated to be 17 mm^2 for $R^2_{\text{profile tamp}}$ and 30 mm^2 for $R^2_{\text{alignment tamp}}$;
- The *cluster length* is also a user-defined variable and during the analysis in this study was set as 200 m;
- An option to include *radius configuration* data for ensuring that the result is applied to the extent of the curve.

Step 1: Work identification through intervention limits

Figure 3-21 comprises of two graphical areas, the top being a linear track chart/schematic layout displaying the asset features present on the right-of-way. This track chart portrays a 6 kilometre section starting at kilometre 20, ending at kilometre 26. The asset features displayed are:

- Track segment – solid black line (one selected and indicated as active)
- Tunnels – a rectangular shape with a black outline and grey fill
- Culverts – a rectangular shape with a cerise outline and transparent fill
- Bridges – a rectangular shape with a blue outline and blue fill
- Platform - a solid purple line
- Km Posts – black triangle
- Level crossings – a rectangular shape with a grey outline and transparent fill
- Overhead Track Equipment / Catenary Poles – a black circle
- Signal – Green signal symbol

The bottom part of the graphic shows the result from the analysis algorithm executed. It displays all locations where the calculated index value $R^2_{\text{profile tamp}}$ is greater than the specified maintenance intervention limit value of 17 mm^2. These locations indicate areas requiring maintenance input and are presented by the solid black lines.

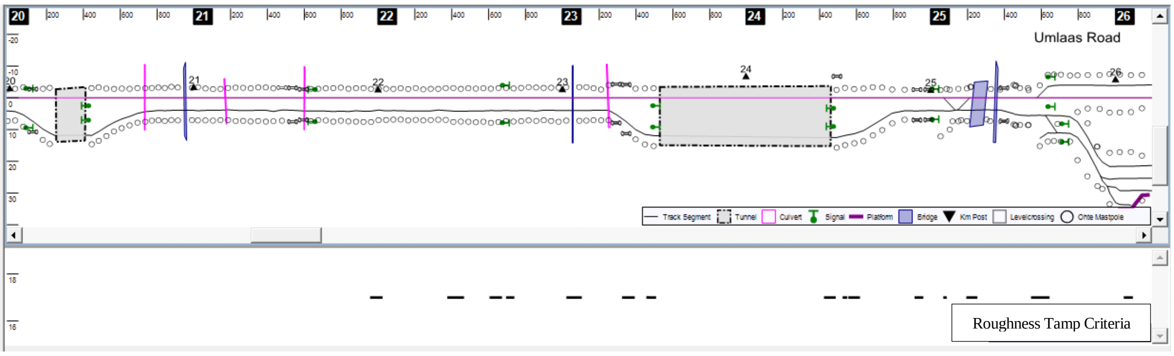


Figure 3-21: Identify maintenance needs utilising $R^2_{\text{profile tamp}}$ limit 17mm^2

Step 2: Grouping of maintenance activities based upon cluster length

Figure 3-22, a third graphical window displays a solid blue line indicating the result when a cluster length is added to the analysis algorithm. The cluster length function groups the maintenance intervention locations into continuous locations, when the identified maintenance intervention locations are within a specified distance from each other. In the analysis the cluster length was set at 200m.

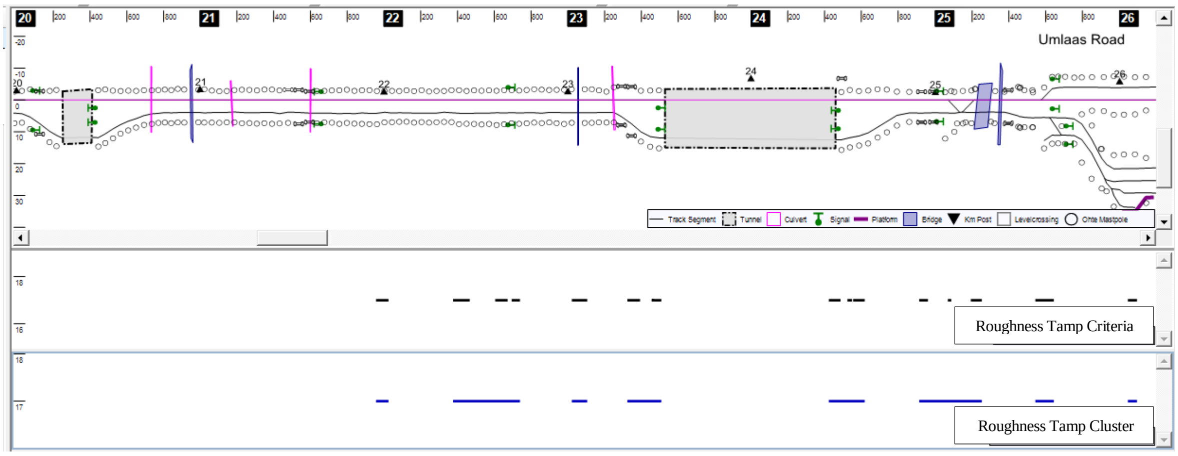


Figure 3-22: Optimise maintenance needs utilising cluster length parameter (200 m)

Step 3: Maintenance activities based on radius configuration

In step 3 of the optimization process, the analysis algorithm provides the option to group the cluster maintenance locations according to curvature/radius configuration. If this option is utilized, the maintenance location will be extended to include the full extent of the curvature/radius if a maintenance location identified is partially within a curve. Figure 3-23 depicts the result when adding the curvature/radius configuration to the analysis. Two additional windows are added to the graphical presentation. The first additional window shows the curvature/radius configuration for the specific section, while the second indicates the result of the optimised maintenance locations calculated (solid red line).

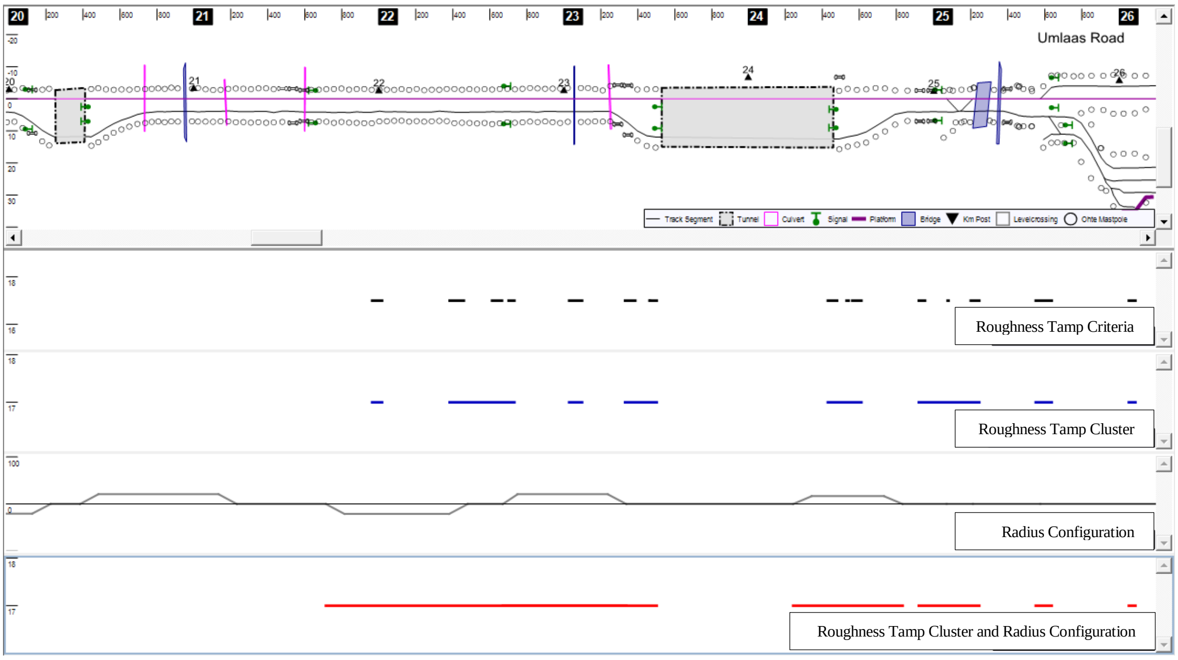


Figure 3-23: Optimise maintenance needs adding curvature configuration details

Compare with Transnet Freight Rail Maintenance Identification Areas

From Figure 3-24 it is clear that the calculated maintenance intervention limits and the maintenance need process optimise a continuous maintenance action (tamping), when compared with the Transnet Freight Rail maintenance exception data. This confirms that the model will provide a result ensuring that the majority of exceptions will be attended to during the maintenance activity execution. It also demonstrates that the analysis model can be used for effective maintenance management identification.

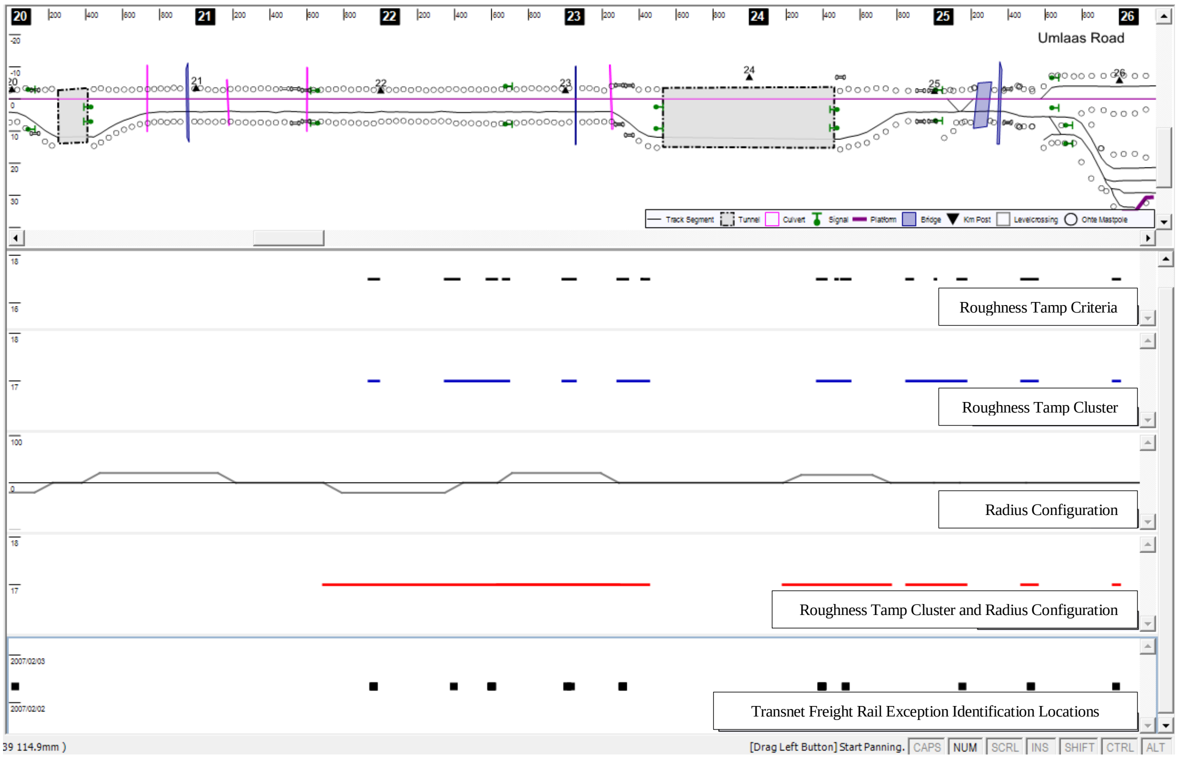


Figure 3-24: Optimise maintenance needs related to Transnet Freight Rail Exception Data

Step 4: Compare $R^2_{\text{profile tamp}}$ and $R^2_{\text{alignment tamp}}$

By comparing the $R^2_{\text{profile tamp}}$ and $R^2_{\text{alignment tamp}}$, a final combined maintenance requirement plan for tamping can be developed. In Figure 3-25 the $R^2_{\text{profile tamp}}$ (solid black line) and $R^2_{\text{alignment tamp}}$ (solid blue line) are presented separately as well as in a superimposed view (solid red line), to indicate the final tamping requirements for the section.

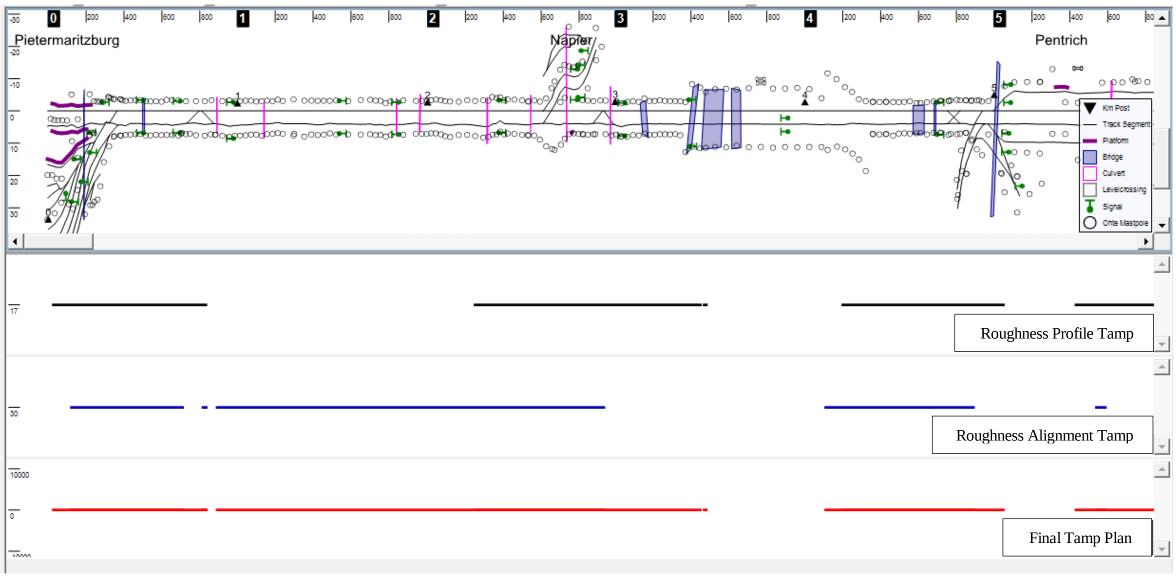


Figure 3-25: $R^2_{\text{profile tamp}}$ and $R^2_{\text{alignment tamp}}$ superimposed to indicate the tamping requirements.

3.5.3.2 Condition Performance Based intervention maintenance needs

A new method developed, is proposed by the author. The method proposed will assist in the continuous improvement of track geometry conditions. The model assists in identifying maintenance needs through the identification of areas where the condition deteriorates at a rate above a specified intervention limit. A condition index is calculated through two condition parameters (R^2_{n-1} and R^2_n) that can be defined by the user to provide agility to the maintenance identification requirements. These two parameters are subtracted from each other to determine the rate of change over a period that results in the Condition Performance Index (CPI) also known as Delta Roughness. In areas where the Condition Performance Index is greater than zero, the condition state deteriorated from the previous assessment at a rate equivalent to the CPI value and presents areas requiring maintenance input. If areas were maintained effectively the CPI values will be negative, signifying these areas improved, resulting in an overall improvement of track quality for the section.

The author is of the opinion that if this process is continuously implemented, the total track quality would improve over time, until it reaches its optimum condition (where the condition cannot be further improved). Thereafter it will be necessary to sustain the optimum condition.

The CPI methodology is described in the following process:

- Step 1a: Compare year-on-year roughness data by subtracting the consecutive yearly condition assessment data from each other to determine the areas that deteriorated over the past year

(Calculate change in Condition Performance - CPI). The result is presented in the following equation (4) below.

$$\Delta R^2 = R^2_{n-1} - R^2_n \tag{4}$$

Where:

ΔR^2: Rate of Change in Condition Performance (CPI), also known as Delta roughness. All values smaller than zero indicates an improvement;

R^2_{n-1} : Roughness condition index for the period n-1;

R^2_n : Roughness condition index for the period n.

- Step 1b: Identify maintenance needs using the $\Delta R^2_{\text{profile tamp}}$ and $\Delta R^2_{\text{alignment tamp}}$ intervention limits (Figure 3-26, below);
- Step 2: Use a cluster length concept to ensure that where maintenance needs are identified for distances smaller than the defined cluster length, the maintenance needs will be optimised to group these maintenance needs to be one area/group requiring maintenance (see Figure 3-27, below);
- Step 3: After this result, use radius configuration information to ensure that if a portion of a curve needs tamping, the result would be extended to include the total curve (see Figure 3-28, below);
- Step 4: Compare $\Delta R^2_{\text{profile tamp}}$ and $\Delta R^2_{\text{alignment tamp}}$ and determine tamping requirements to ensure all needs are adhered to.
- Step 5: Compare the condition based and performance based analysis and develop a holistic final tamping requirements plan.

The specifics of each step are discussed in the sections to follow.

The parameters in the analysis model (algorithm) consist of:

- A selection of up to five *condition parameters* to calculate a condition index for two distinct periods/condition assessment campaigns. Each parameter can be multiplied with a weighted average, and the results of these are added together to calculate the condition parameter;
- The two calculated condition parameters are subtracted from each other and results in the CPI that will be used to calculate maintenance areas.
- The *maintenance intervention* limit is a variable specified for the analysis model to identify all areas where the rate of change is above the allowable rate as determined by the subject matter

expert. In this study it was set as 3 mm^2 per annum for both $\Delta R^2_{\text{profile tamp}}$ and $\Delta R^2_{\text{alignment tamp}}$ (The maintenance intervention limit specified for the analysis model is based on the author’s experience in the subject matter, it should be noted that it was not scientifically calculated as it is not part of the scope of this dissertation);

- The *cluster length* is also a user-defined variable and during the analysis in this study was set as 200 m;
- An option to include *radius configuration* data for ensuring that the result is applied to the extent of the curve.

Step 1: Work identification through intervention limits

Figure 3-26 comprises of three graphical areas, the top being a linear track chart/schematic layout displaying the asset features present on the right-of-way. This track chart portrays a 6 kilometre section starting at kilometre 20, ending at kilometre 26. The asset features displayed are:

- Track segment – solid black line (one selected and indicated as active)
- Tunnels – a rectangular shape with a black outline and grey fill
- Culverts – a rectangular shape with a cerise outline and transparent fill
- Bridges – a rectangular shape with a blue outline and blue fill
- Platform - a solid purple line
- Km Posts – black triangle
- Level crossings – a rectangular shape with a grey outline and transparent fill
- Overhead Track Equipment / Catenary Poles – a black circle
- Signal – Green signal symbol

The second window in the graphic displays the CPI index ($\Delta R^2_{\text{profile tamp}}$) calculated for the condition parameter Roughness Profile for the period 2006 to 2007, where the rate of change is greater than zero it indicates deterioration in the condition of the track. CPI values smaller than zero presents the locations where the condition improved for the period. The third window shows the result from the analysis algorithm executed. It displays all locations where the calculated index value $\Delta R^2_{\text{profile tamp}}$ is greater than the specified maintenance intervention limit value of 3 mm^2. These locations indicate areas requiring maintenance input and are presented by the solid black lines.

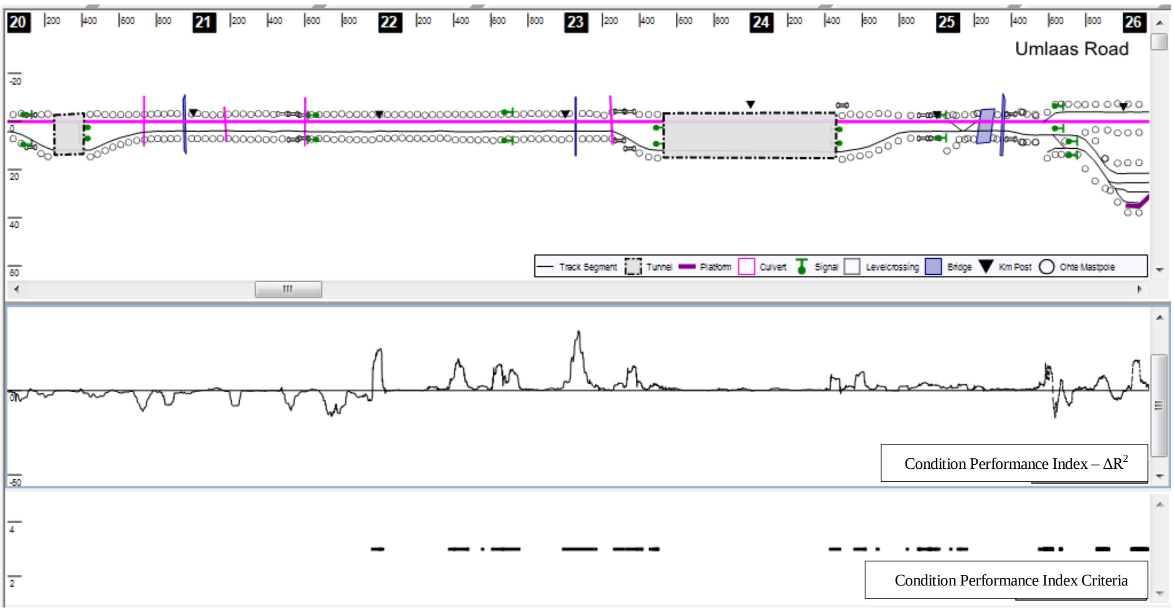


Figure 3-26: Identify maintenance needs utilising CPI $\Delta R^2_{profile\ tamp}$ limit 3mm^2

Step 2: Grouping of maintenance activities based upon cluster length

Figure 3-27, a fourth graphical window displays a solid blue line indicating the result when a cluster length is added to the analysis algorithm. The cluster length function groups the identified maintenance intervention locations into continuous locations, when the maintenance intervention locations are within a specified distance from each other. In the analysis the cluster length was set at 200m.

Figure 3-27: Optimise CPI maintenance needs utilising cluster length parameter (200 m)

Step 3: Maintenance activities based on radius configuration

In step 3 of the optimization process, the analysis algorithm provides the option to group the cluster maintenance locations according to curvature/radius configuration. If this option is utilized, the maintenance location will be extended to include the full extent of the curvature/radius if a maintenance location identified is partially within a curve. Figure 3-28 depicts the result when adding the curvature/radius configuration to the analysis. Two additional windows are added to the graphical presentation. The first additional window shows the curvature/radius configuration for the specific section, while the second indicates the result of the optimised maintenance locations calculated (solid red line).

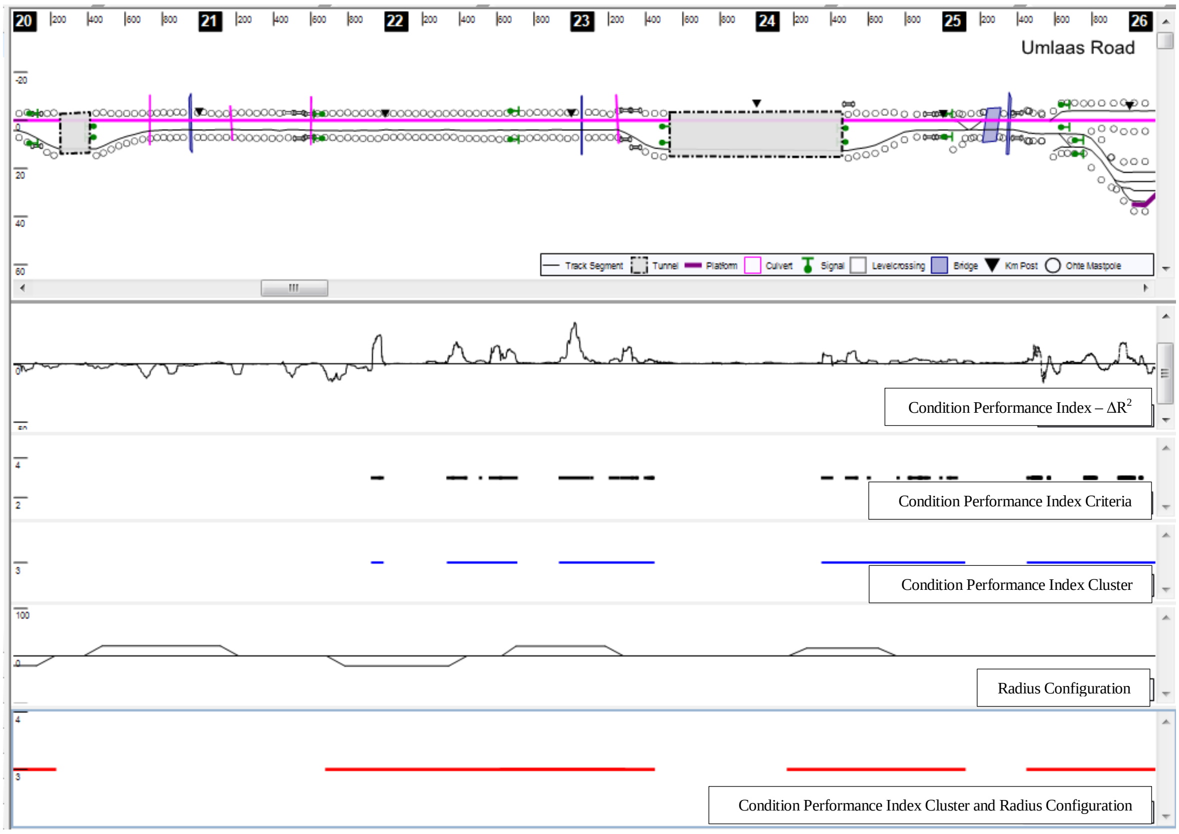


Figure 3-28: Optimise CPI maintenance needs adding curvature configuration details

Step 4: Compare $\Delta R^2_{\text{profile tamp}}$ and $\Delta R^2_{\text{alignment tamp}}$

By comparing the $\Delta R^2_{\text{profile tamp}}$ and $\Delta R^2_{\text{alignment tamp}}$, a final combined maintenance requirement plan for tamping can be developed. In Figure 3-29 the $\Delta R^2_{\text{profile tamp}}$ (solid black line) and $\Delta R^2_{\text{alignment tamp}}$ (solid blue line) are presented separately as well as in a superimposed view (solid red line), to indicate the final tamping requirements for the section.

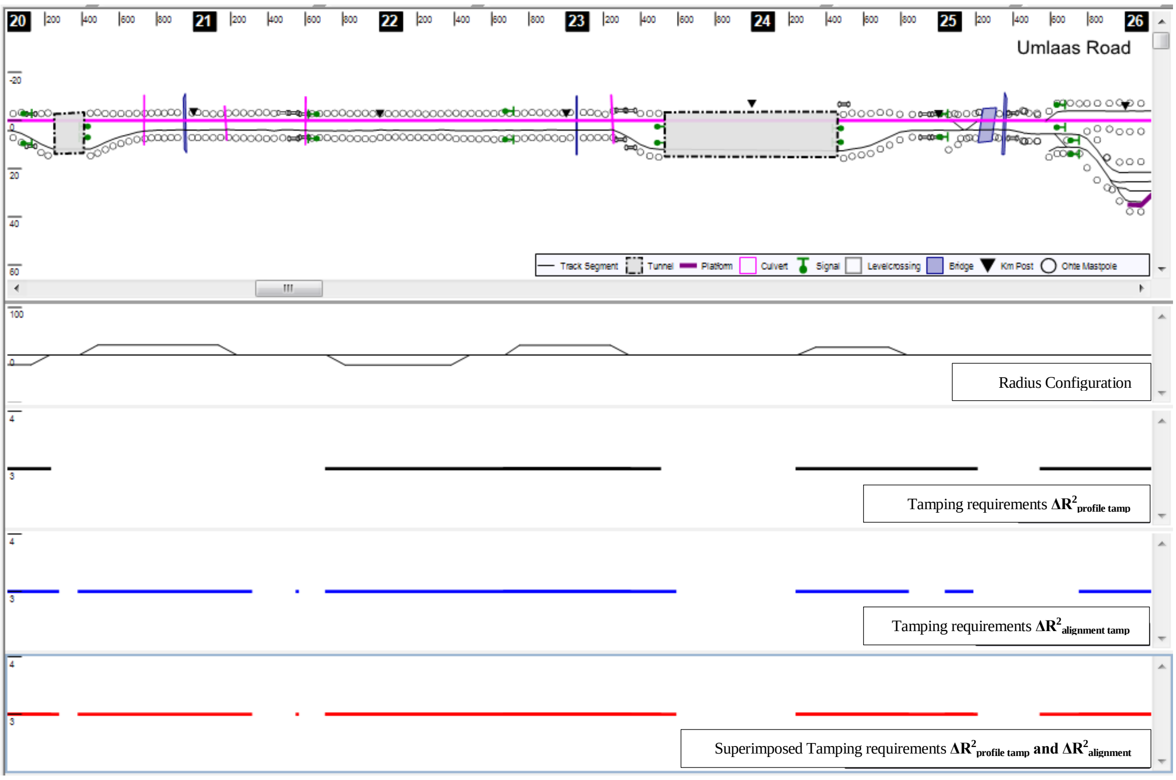


Figure 3-29: $\Delta R^2_{profile\ tamp}$ and $\Delta R^2_{alignment\ tamp}$ superimposed to indicate the tamping requirements.

Step 5: Compare the condition based ($R^2_{profile\ tamp}$ and $R^2_{alignment\ tamp}$) and performance based ($\Delta R^2_{profile\ tamp}$ and $\Delta R^2_{alignment\ tamp}$) analysis and develop a holistic final tamping requirements plan

By comparing the condition based ($R^2_{profile\ tamp}$ and $R^2_{alignment\ tamp}$) and Condition Performance Index ($\Delta R^2_{profile\ tamp}$ and $\Delta R^2_{alignment\ tamp}$), a final combined maintenance requirement plan for tamping can be developed. In Figure 3-30 the $R^2_{profile\ tamp}$ (solid black line), $R^2_{alignment\ tamp}$ (solid blue line), $\Delta R^2_{profile\ tamp}$ (solid grey line) and $\Delta R^2_{alignment\ tamp}$ (solid light blue line) are presented separately as well as in a superimposed view (solid red line), to indicate the final tamping requirements for the section. From Figure 3-30 it is apparent that for $R^2_{alignment\ tamp}$ (solid blue line), there are no data, and it is due to the condition for this section of track being below the specified 30mm^2 intervention limited. It is a valuable example, illustrating the value of the CPI analysis. In this instance the $\Delta R^2_{alignment\ tamp}$ (solid light blue line) reveals areas requiring maintenance due to the rate of change being above the specified 3mm^2 assisting in a proactive maintenance strategy.

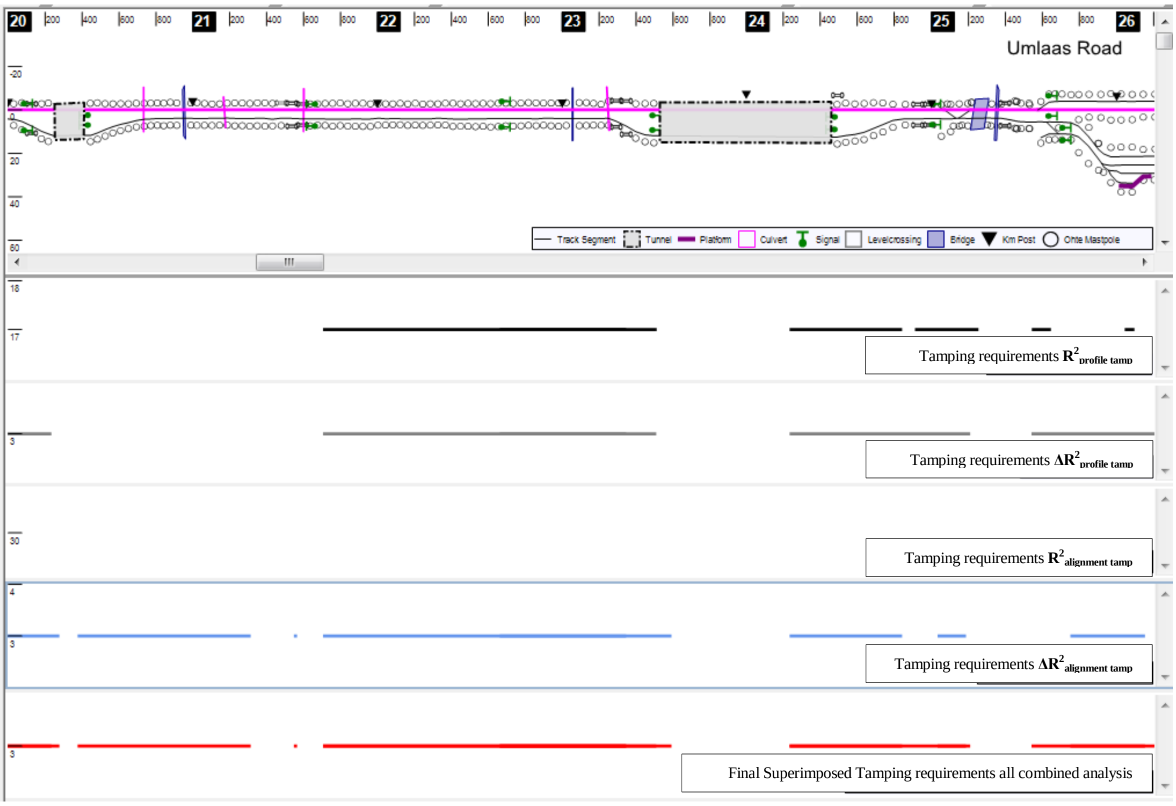
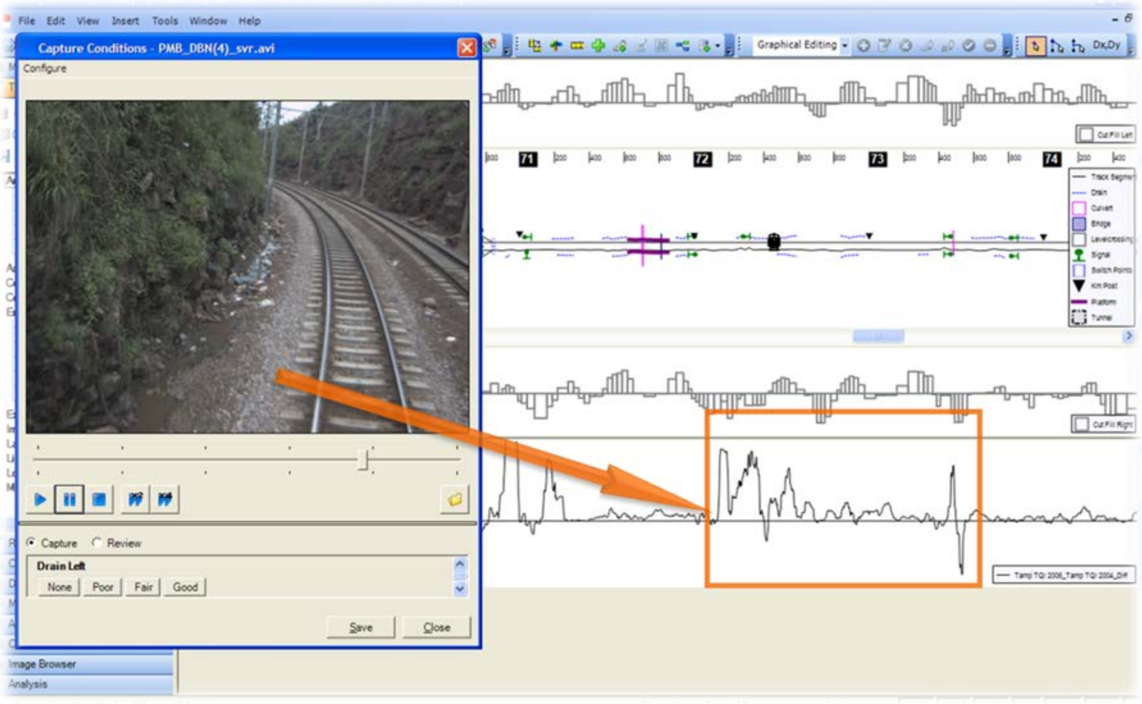


Figure 3-30: $R^2_{profile\ tamp}$, $R^2_{alignment\ tamp}$ $\Delta R^2_{profile\ tamp}$ and $\Delta R^2_{alignment\ tamp}$ superimposed to indicate the tamping requirements.

3.5.3.3 Condition Performance Based intervention results

For demonstration purposes, on the Pietermaritzburg – Durban section km 71 to km 74, it is assumed that maintenance should be applied to areas where the Condition Performance Index values (*Delta Roughness*) is greater than 3 mm^2. Using equation (4) for the period 2004 to 2006 it resulted in the maintenance requirements for the area depicted in Figure 3-31 (below).



● Capture ○ Review

Drain Left

None | Poor | Fair | Good

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Figure 3-31: *Delta Roughness* for the period 2004 to 2006

If effective maintenance had been applied to the section indicated in Figure 3-31, the same section should not require maintenance input for the period 2006 to 2008. Figure 3-32 presents the analysis ($\Delta R^2_{tamping}$) for the period 2006 to 2008, indicating that effective maintenance was performed. If the condition based ($R^2_{tamping}$) analysis still indicates this area requiring maintenance, it will confirm that root case analysis is required to determine the underlining problem at this area. It can also show a permanent defect, built into the railway structure at the location that will result in its existence for the remaining life of the railway line.

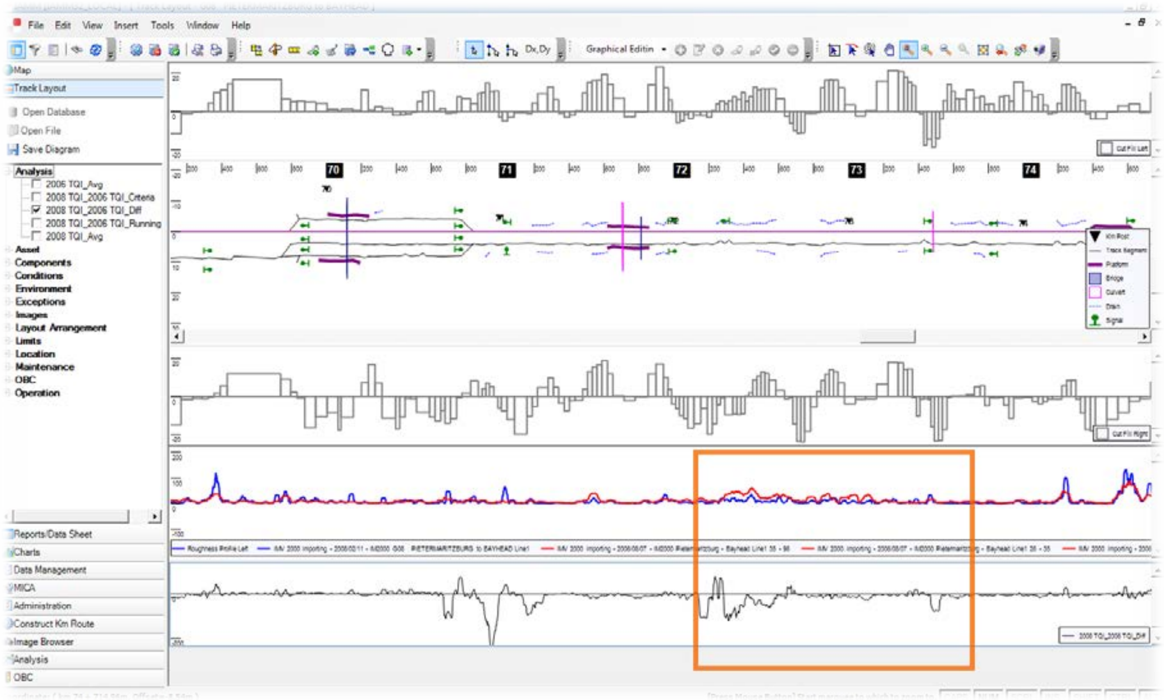

Figure 3-32: *Delta Roughness* for the period 2006 to 2008

If all areas where *Delta Roughness* greater than 3 mm^2 were improved, the total track quality would improve. This improvement will result in the increase of the track quality ensuring a theoretical establishment of an optimum condition, from where the condition cannot be improved.

3.5.4 Preliminary Maintenance Plan

From the results above, a preliminary maintenance plan can be compiled to provide details for management on maintenance requirements. The advantages of this maintenance plan include the following:

- It is systematically process driven;
- It is determined scientifically – Condition based orientated;
- Maintenance details are provided in terms of locations, from where to where should the maintenance needs be implemented;
- A maintenance resource plan can be drawn up;
- A budget can be determined;
- From the budget and analysis, it can be shown that maintenance is required to ensure asset availability and a state of good repair;
- It can demonstrate that maintenance needs were optimised and will ensure effective maintenance practices.

3.5.5 Compile detail maintenance plan (Final plan and schedule)

Although not discussed in detail in this study, the next step in the maintenance process is to combine multiple maintenance plans into one final detail maintenance plan and schedule to be executed.

3.5.6 Execute maintenance

We have devoted valuable time, human and financial resources in the development of a complete and detail maintenance plan. Numerous railways' lack of focus and commitment during execution, result in a fragmented implementation of well-developed maintenance plans. It leads to a loss of valuable time, energy and resources that is recapitulated as a loss in effectiveness and efficiency. Maintenance plan execution should be closely managed. Various railway companies utilise work management systems in conjunction with well-defined documented standard operating procedures and job plans, per maintenance activity type, to assist in controlling and monitoring the execution of the maintenance plan.

3.5.7 Measure performance

We have systematically completed the analysis process with in the maintenance model, namely:

- Understand Operational input requirements;
- Condition Analysis;
- Identify maintenance need;
- Set up/Compile a preliminary maintenance plan (Plan and schedule);
- Set up/Compile maintenance plan (Final plan and schedule);
- Execute maintenance

The final step in the analysis process is to measure performance. Although as with sections 3.6.5 and 3.6.6, the measurement of performance is not forming part of the dissertation. The author realise the importance of performance measurement and will discuss the purpose of it in the process for the completeness of the study.

To this point we have spent considerable time, energy and resources to assist in maintenance management optimisation, to ensure this added value to the business and its asset management optimisation program, we need to measure the effectiveness of the maintenance function. This can only be done through the measurement of the function's performance. To measure the performance of the maintenance function the basic starting point will be to measure the planned against the actual. In other words, to measure the planned activities and schedule against what was actually executed and realised.

Typical measurements to determine the maintenance function's performance could include (although not limited to):

- Corrective maintenance to preventive maintenance ratio
- Preventative maintenance hours as a percentage of total maintenance hours.
- Percentage of preventative maintenance tasks completed by due date
- Mean Time to Repair (MTTR)
- Percentage of preventive maintenance cost
- Maintenance cost per unit (example is cost per kilometre)

The result of the function's performance should be utilised to position the set targets and improve performance where set targets are not met. It should be noted that targets that are set should be achievable, as the function and its employees can become frustrated when they continually fall short of the targets. Continuously reviewing performance towards targets and resetting the targets to encourage smaller incremental improvements may work much better to ensure sustainable continuous improvement over time. Lastly performance measurements should be simple to use and easy to understand.

3.5.8 Continuous Improvement Methodology

For the purpose of this study, the continuous improvement methodology is included as the author wants to explain the next step in the asset optimisation process. This will assist the business in achieving its objectives. It is not discussed in the analysis chapter of this study, as it is outside the identified scope of the dissertation and requires further research. Only the theory of continuous improvement will be discussed, in order to provide a holistic approach to the study.

The purpose of continuous improvement is to assist the maintenance function to improve its added value to the business objective on an on-going basis. The theory is that throughout the life and maintenance management process of an asset, the need will arise to achieve better performance in maintenance management effectiveness. If the right maintenance requirements are addressed through root-cause analysis, failures will be eliminated, resulting in new constraints appearing as presented in the *Theory of Constrains* (Goldratt, 2004). This will require new intervention limits to be developed.

From this, it is possible that intervention limits might reduce to improve reliability and availability of the track. With this in mind, there must be limits on the intervention periods to ensure the required productivity is obtained. The best practical example to explain this phenomenon was through the frequency plot discussed in Figure 3-17 and Figure 3-19 previously shown in this chapter.

For illustration only, the author focuses on the profile frequency plot for both the Pietermaritzburg to Durban (Figure 3-19) and the Coal line (Figure 3-17) sections. Earlier in this chapter, a need was identified to increase future operations utilisation of traffic levels on the Pietermaritzburg - Durban section. This increase results in an annual gross tonnage similar to what is currently required on the Coal line. This result in the limits currently applied on the Coal line to be used as the calculated maintenance intervention limits on the Pietermaritzburg - Durban section.

In Figure 3-33 the Pietermaritzburg to Durban section and Coal line profile standard deviation frequency plots are superimposed on each other, indicating the goal set on the Natal Mainline within the next five to ten years.

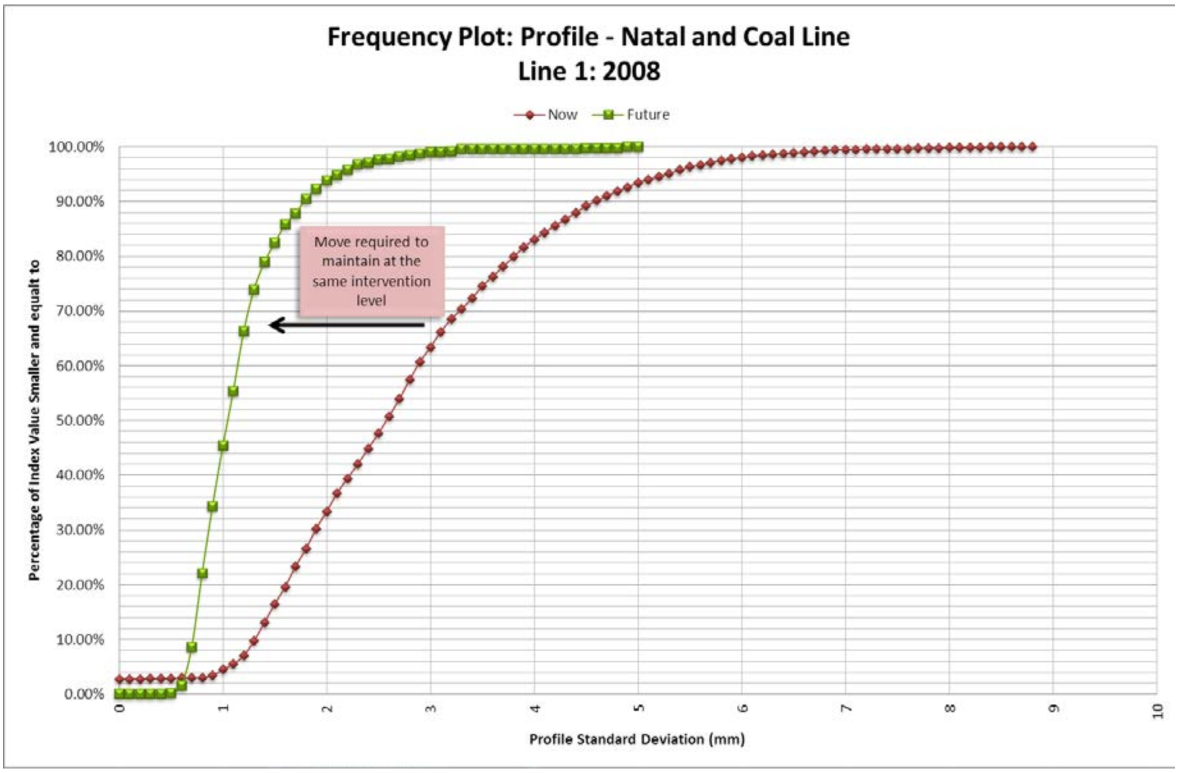

Figure 3-33: Superimposed profile standard deviation frequency plot for the Natal and Coal lines

The question arises as to how to move from the current distribution to that of the Coal line? The expensive solution is to renew the Pietermaritzburg - Durban line and start afresh, as if there was nothing in place. But that does not consider the current traffic that needs to be transported. Therefore the current track condition needs to be improved systematically, year-on-year, to ensure a continuous improvement until the required target is reached. Enabling the move of the Pietermaritzburg - Durban line's condition frequency plot to that of the Coal line over time is the result of continuous improvement.

Over time the maintenance strategies and methodologies utilised currently maintaining the Pietermaritzburg - Durban line will need to change to be the same strategies and methodologies utilised on the Coal line today. The process to systematically move from the current maintenance strategies and methodologies to the future maintenance strategies and methodologies is what the author classifies as the *Continuous Improvement Methodology*.

3.6 Conclusion

This chapter used the 100 km section of line between Pietermaritzburg and Durban to discuss and contextualise the need for analysis models to assess maintenance data and operational requirements. The objective is to achieve a favourable return on investment for the business concerned – Transnet Freight Rail. The reader needs to understand and evaluate all the issues at stake in developing an analysis model. This needs to be accomplished before the results derived from the model can be evaluated or considered against available tamping maintenance strategies, which are all discussed in chapter four.

A maintenance management process model was developed to assist in the effective maintenance requirement decision making. The model is referred to as the Continuous Improvement process. Two tamping analysis models, condition based (Maintenance Condition Intervention) and condition performance based (Condition Performance Index – Rate of Change) is introduced and resulted in methods that adds value for determining preventative and proactive maintenance requirements. The author has confidence and advocates a systematic approach and therefore suggests utilising the two methods in phases - depending on the railway's maturity level in utilising condition based maintenance planning practices. It will first ensure the basics are implemented successfully. When the railway has matured in condition based maintenance (R^2) planning, it can advance to the next level of predictive condition performance (ΔR^2) based maintenance planning.

Finally it can be concluded that the Continuous Improvement process will add value over time as operations requirements and asset condition change. The Continuous Improvement process ensures constraints and changes are continuously taken into account to assist in the optimisation of the railway's asset optimisation process. It will enable them to constantly improve current maintenance strategies, intervention limits and maintenance processes.

CHAPTER 4
ANALYSIS RESULTS

4 Introduction

In this chapter, the results obtained from the analysis model are evaluated. Before the evaluation is done, the current tamping maintenance practices on the Pietermaritzburg – Durban line will be discussed. The tamping practices implemented are according to Transnet Freight Rail's current business maintenance strategies. After understanding the current maintenance strategies, a comparison can be made to determine the maintenance effectiveness from the model. The latter is demonstrated using an economic model. This shows how the effective condition based tamping maintenance plan optimises the holistic asset management philosophy the author introduced in this study.

4.1 Current state

There are many tamping maintenance strategies in existence within the rail industry. The majority of railway businesses in general implement a routine based and condition based tamping strategy. From the author's experience, it is known that although many railways acknowledge the use of a condition based maintenance strategy, many fail to utilise the strategy effectively. This is probably due to misinterpretation of condition monitoring data or a lack of skills related to the use of the sophisticated measurements. Whatever the reason, the reality is that the maintenance strategy is not used as it is designed to be.

In Transnet Freight Rail the majority of their tamping requirements on a network level are based on routine based maintenance determined by an equation published by Hall. (1985). In order to determine the time interval requirements for tamping, the equation is dependent on the traffic characteristics of a section as indicated in equation (5) below.

$$Tamping\ Interval \approx \frac{48}{\sqrt{MGT_{section} / year}} \tag{5}$$

From the above, the MGT (million gross tonnes) per annum on the Pietermaritzburg – Durban line is known from earlier in the dissertation to be 18 MGT. Using equation (5), an interval of almost 11.5 months is calculated. In practice, Transnet Freight Rail decided to make the routine based maintenance interval on this section once a year.

In addition to routine based maintenance, Transnet Freight Rail also requires a double tamp action on all curves, as well as tamping of switches (turnout) using a switch point tamper. One switch point is equivalent to 400 m of main line tamping.

From analysis of the Asset configuration, using the Infrastructure Asset Maintenance Management (IAMM) system, a queried report indicates that switches on the number one line total to 81. This is equivalent to 32.4 km of main line tamping. Using these figures, the routine tamping requirements can be summarised as shown in Table 4-1.

Table 4-1: Routine based tamping requirements

Equivalent Routine Based Track Distance Tamping Requirements	Unit	Quantity	Equivalent Tamping Distance (km)
Tangent Track	km	42	42
Curved Track	km	55.5	111
Switches	Number	81	32.4
Total Distance			**185.4**

From Table 4-1 it is calculated that with an assumed tamping rate of 5 km per day, the tamping activity can be conducted in 38 days per year.

4.2 Condition Based Analysis

The maintenance management process and two tamping models discussed in Chapter 3 will be discussed in the following paragraphs. In this section the results of the condition based (R^2) analysis is presented.

4.2.1 Roughness Alignment Tamping

From paragraph 3.5.2, $R^2_{\text{alignment tamp}}$ was determined to be 30 mm^2. Using this intervention limit in the tamping model, the results are summarised in Table 4 - 2 (below).

Table 4 - 2: $R^2_{\text{alignment tamp}}$ requirements

Analysis Summary Pietermaritzburg - Durban Line 1 Roughness Alignment	Distance (km)	Percentage (%)
Roughness Alignment Tamping Criteria 30 mm^2	7.6	8
Roughness Alignment Tamping Criteria 30 mm^2 Cluster Length 200 m	11.3	12
Roughness Alignment Tamping Criteria 30 mm^2 Cluster Length 200 m and Radius	31.2	32
Total Track 1 Mainline Distance	97.4	

From Table 4 - 2 it is evident that 32% - equivalent to 31.2 km of the route distance - requires tamping based on the intervention limit and radius configuration used. In Figure 4-1 below, the analysis results $R^2_{\text{alignment tamp}}$ for the mainline section between km 20 and km 26 are presented as viewed in the IAMM system. In this specific case the results returned, indicates that there is no result as all condition parameter values for $R^2_{\text{alignment tamp}}$ was smaller than the specified 30mm^2. The detail regarding the areas requiring maintenance is presented in Appendix A of the dissertation in tabular format.

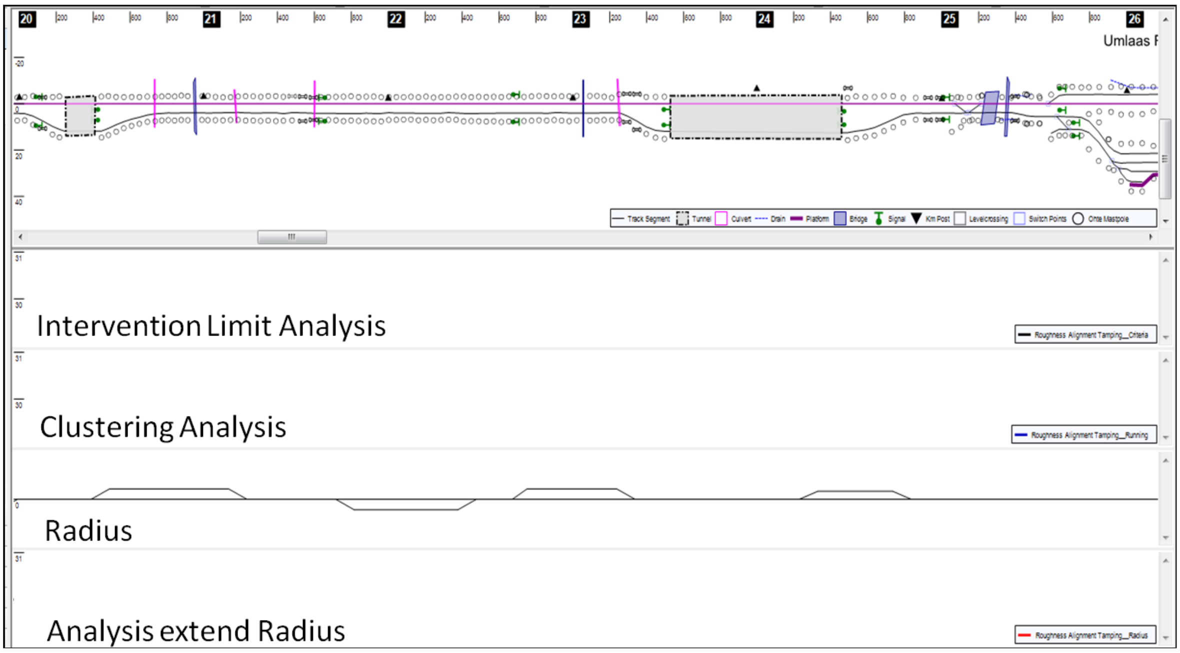

Figure 4-1: $R^2_{\text{alignment tamp}}$ Analysis Results for Mainline 1 from km 20 to km 26

4.2.2 Roughness Profile Tamping

From paragraph 3.5.2, $R^2_{\text{profile tamp}}$ was determined to be 17 mm^2. Utilising this maintenance intervention limit, the tamping model produced the results summarised in Table 4 - 3 below.

Table 4 - 3: $R^2_{\text{profile tamp}}$ requirements

Analysis Summary Pietermaritzburg - Durban Line 1 Roughness Profile	**Distance (km)**	**Percentage (%)**
Roughness Profile Tamping Criteria 17 mm^2	12.8	13
Roughness Profile Criteria 17 mm^2 Cluster Length 200 m	20.8	21
Roughness Profile Tamping Criteria 17mm^2 Cluster Length 200 m and Radius	50.2	52
Total Track 1 Mainline Distance	97.4	

From Table 4 - 3, it can be seen that 52% of the route requires tamping. A detailed list, indicating the areas requiring maintenance, is presented in Appendix A of this study in tabular format. Figure 4-2 below, presents the analysis results $R^2_{\text{profile tamp}}$ for the mainline section between km 20 and km 26 from the analysis module developed in Chapter 3 in the IAMM system.

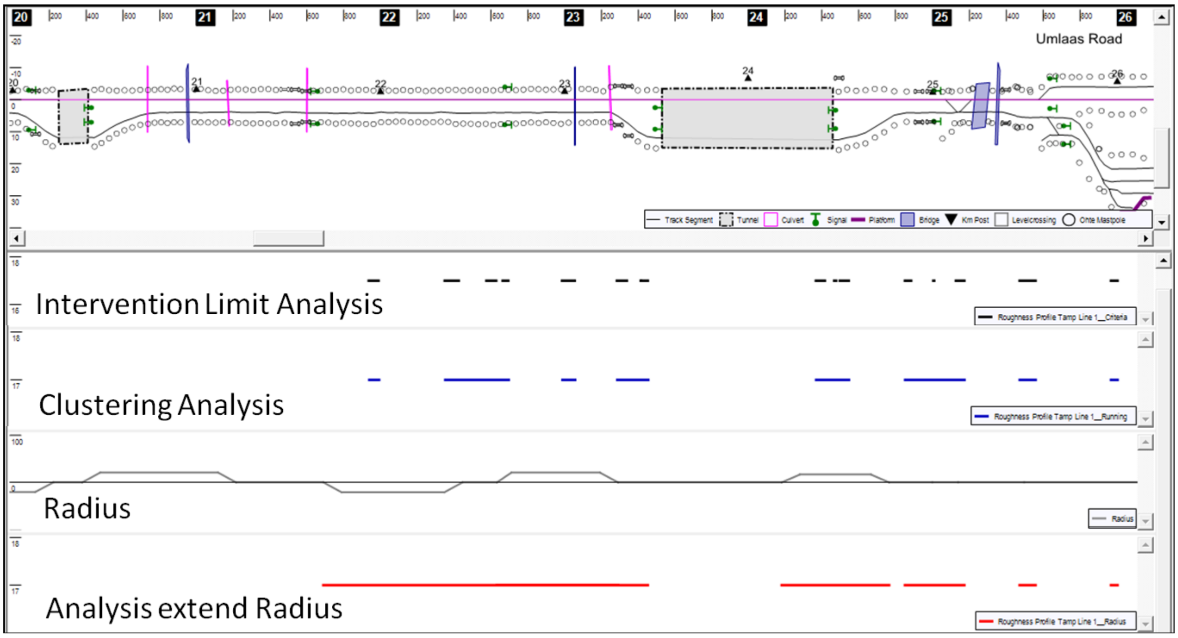

Figure 4-2: $R^2_{\text{profile tamp}}$ **Analysis Results for Mainline 1 from km 20 to km 26**

4.3 Condition Performance Index Based Analysis

The maintenance management process and CPI tamping (ΔR^2) model discussed in Chapter 3 produced results which will be discussed in the following paragraphs.

4.3.1 CPI – Delta Roughness Alignment Tamping

From paragraph 3.6.3.2, $\Delta R^2_{\text{alignment tamp}}$ was set at 3 mm^2. Using this intervention limit in the tamping model, the results are summarised in Table 4 - 4.

Table 4 - 4: $\Delta R^2_{\text{alignment tamp}}$ requirements

Analysis Summary Pietermaritzburg - Durban Line 1 CPI – Delta Roughness Alignment	Distance (km)	Percentage (%)
Delta Roughness Alignment Tamping Criteria 3 mm^2	11.2	11
Delta Roughness Alignment Tamping Criteria 3 mm^2 Cluster Length 200 m	26.8	28
Delta Roughness Alignment Tamping Criteria 3 mm^2 Cluster Length 200 m and Radius	56.5	58
Total Track 1 Mainline Distance	97.4	

From Table 4 - 4 it is evident that 58% - equivalent to 56.5 km of the route distance - requires tamping based on the intervention limit and radius configuration used for the CPI tamping analysis. In Figure 4-3 below, the analysis results $\Delta R^2_{\text{alignment tamp}}$ for the mainline section between km 20 and km 26 are presented as viewed in the IAMM system, indicating the results from the analysis module developed in Chapter 3. The detail regarding the areas requiring maintenance is presented in Appendix A of the dissertation in tabular format.

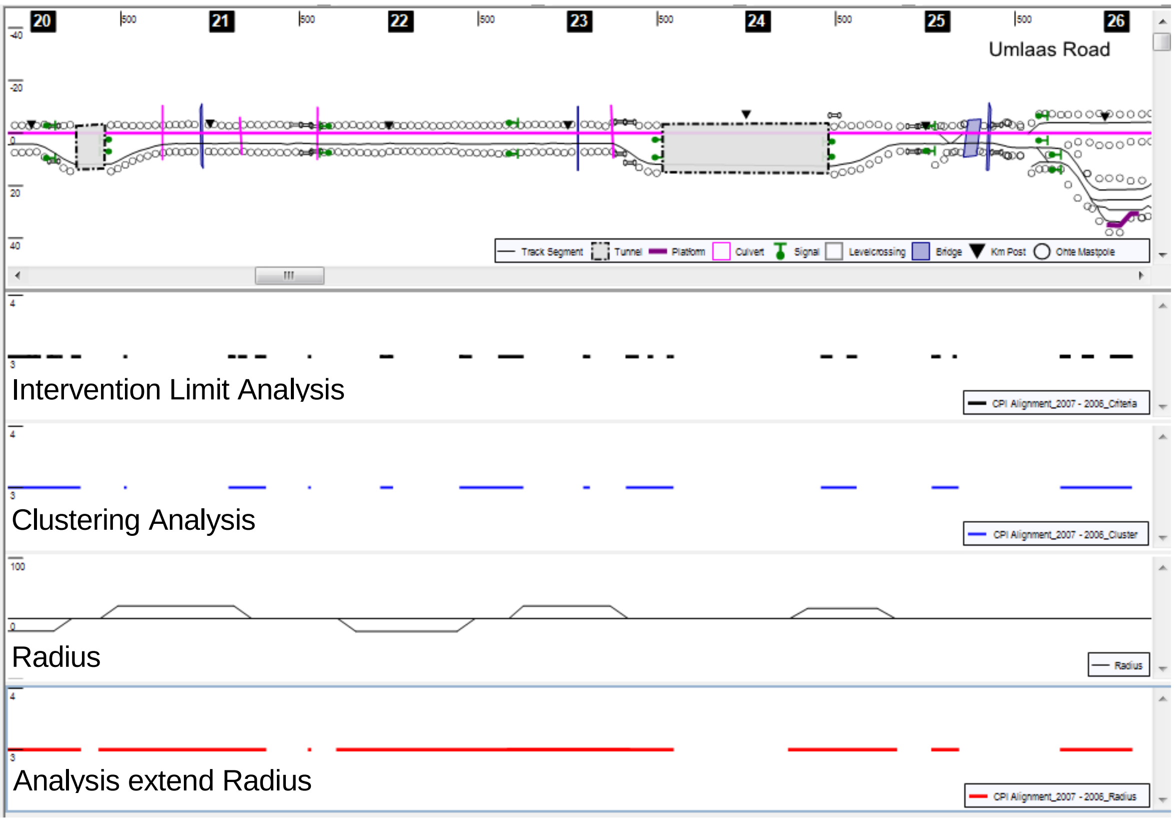

Figure 4-3: $\Delta R^2_{\text{alignment tamp}}$ Analysis Results for Mainline 1 from km 20 to km 26

4.3.2 CPI – Delta Roughness Profile Tamping

From paragraph 3.6.3.2, $\Delta R^2_{\text{profile tamp}}$ was set to 3 mm^2. Utilising this maintenance intervention limit, the tamping model produced the results summarised in Table 4 - 5 below.

Table 4 - 5: $\Delta R^2_{\text{profile tamp}}$ requirements

Analysis Summary Pietermaritzburg - Durban Line 1 Roughness Profile	Distance (km)	Percentage (%)
Delta Roughness Profile Tamping Criteria 3 mm^2	14.9	15
Delta Roughness Profile Criteria 3 mm^2 Cluster Length 200 m	35.3	36
Delta Roughness Profile Tamping Criteria 3mm^2 Cluster Length 200 m and Radius	62.8	64
Total Track 1 Mainline Distance	97.4	

From Table 4 - 5, it can be seen that 64% of the route requires tamping. A detail presentation analysis indicating the areas requiring maintenance is presented in Appendix A of this study in tabular format.

Figure 4-4 below, presents the analysis results $\Delta R^2_{\text{profile tamp}}$ for the mainline section between km 20 and km 26 from the analysis module developed in Chapter 3 in the IAMM system.

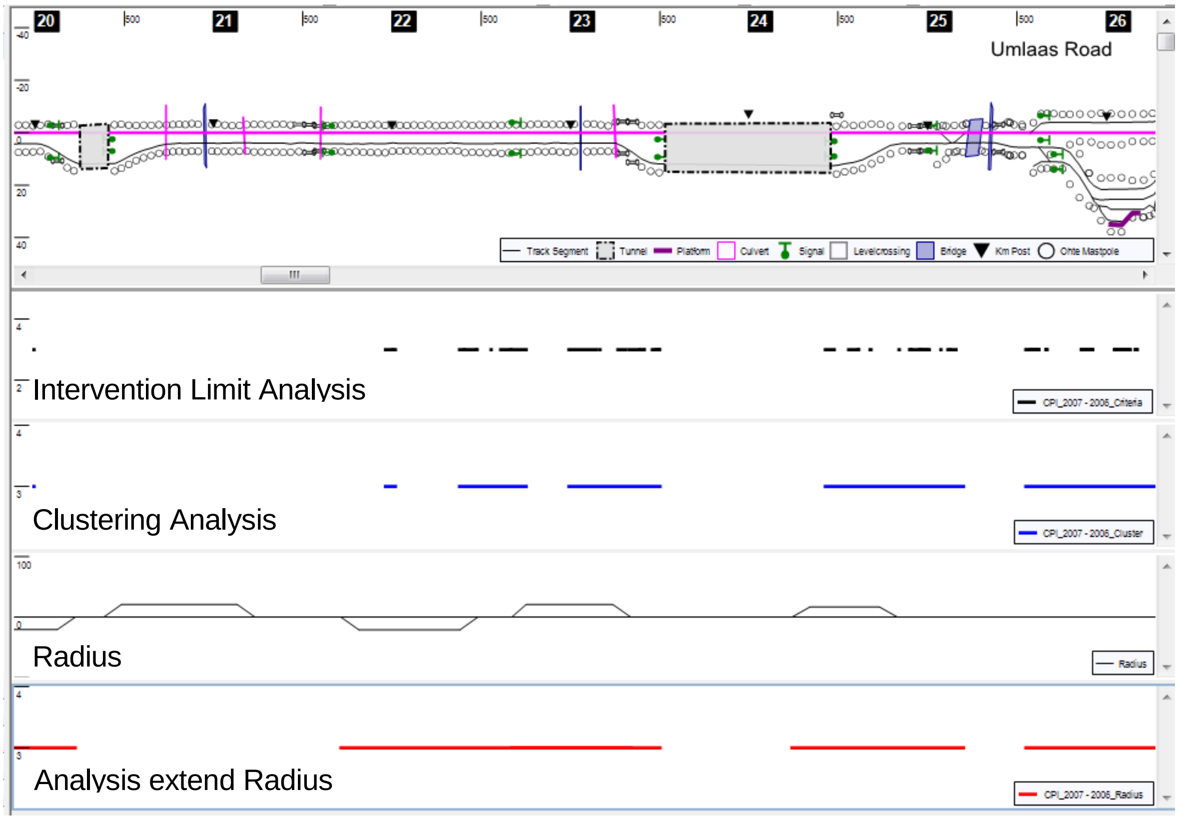

Figure 4-4: $\Delta R^2_{\text{profile tamp}}$ **Analysis Results for Mainline 1 from km 20 to km 26**

4.4 Maintenance Effectiveness: Identify the maintenance needs

As part of the maintenance management process, the maintenance requirements need to be optimised, taking into account both the calculated condition maintenance intervention limits. This is needed as the location of the identified areas may differ for the respective condition assessment analyses.

4.4.1 Maintenance Plan Needs

In this section, the integration of $R^2_{\text{alignment tamp}}$ with $R^2_{\text{profile tamp}}$ and $\Delta R^2_{\text{alignment tamp}}$ with $\Delta R^2_{\text{profile tamp}}$ results are established to ensure all areas requiring maintenance are incorporated into the maintenance plans.

4.4.1.1 Condition Based Maintenance Needs

A summary of the preliminary condition based (R^2) tamping maintenance plan, as determined from the integration of the condition based analysis is provided in Table 4-6. The plan can be supplied to the maintenance supervisor to ensure that maintenance is executed at the correct locations on this section, thus improving the maintenance effectiveness within the maintenance function.

Table 4-6: Tamping maintenance plan: Integration of the R^2alignment tamp and R^2profile tamp results

Analysis Summary Pietermaritzburg - Durban Line 1 Integration Roughness Profile and Roughness Alignment	**Distance (km)**	**Percentage (%)**
Roughness Alignment Tamping Criteria 30mm^2 Cluster Length 200 m and Radius	31.2	32
Roughness Profile Tamping Criteria 17mm^2 Cluster Length 200 m and Radius	50.2	52
Roughness Profile Tamping and Alignment Tamping Cluster Length 200 m and Radius Integration	56.2	58
Total Track 1 Mainline Distance	97.4	

The complete condition based maintenance plan/optimised maintenance requirements are presented in Appendix B. Figure 4-5 below, presents the integrated $R^2_{\text{alignment tamp}}$ and $R^2_{\text{profile tamp}}$ results in the IAMM system for the mainline section between km 20 and km 26 from the analysis module developed in Chapter 3.

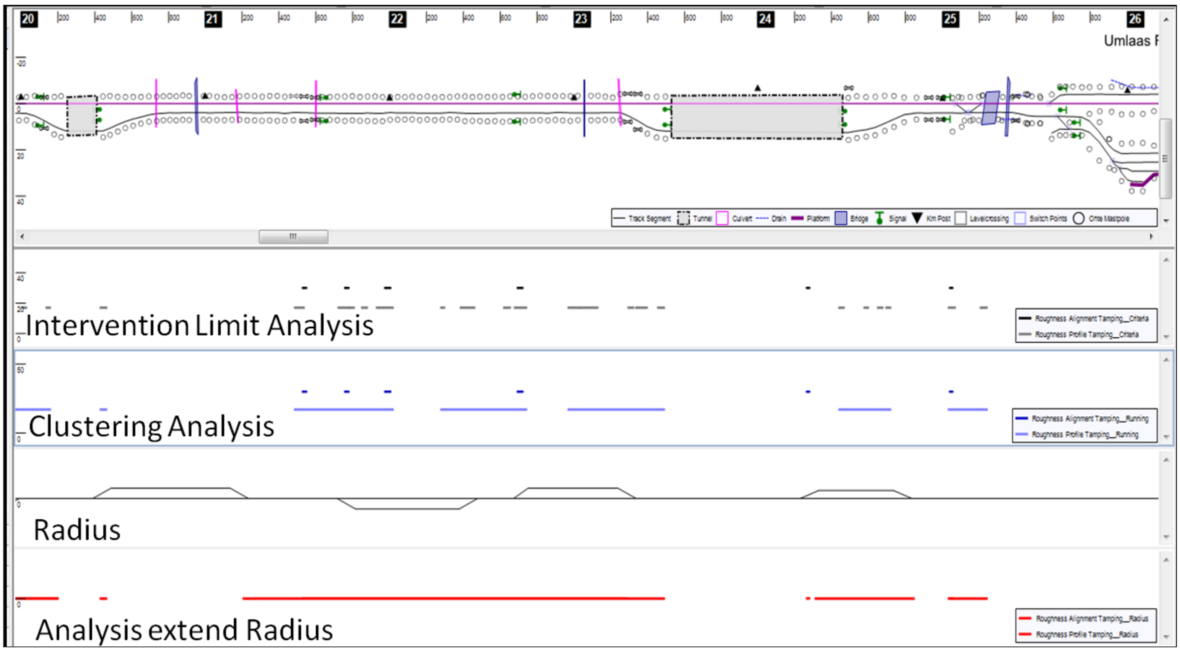

Figure 4-5: $R^2_{\text{alignment tamp}}$ and $R^2_{\text{profile tamp}}$ Analysis Integration for Mainline 1 from km 20 to km 26

From Table 4-6, it is evident that only 56.2 km (58%) of the total track route distance requires maintenance. The increase of the tamping requirements that took place through the maintenance process is also presented.

4.4.1.2 Condition Performance Based Maintenance Needs

A summary of the preliminary condition performance based (ΔR^2) tamping maintenance plan, as determined from the integration of the condition performance based analysis is provided in Table 4-7. The plan can be supplied to the maintenance supervisor to ensure that maintenance is executed at the correct locations on this section, thus improving the maintenance effectiveness within the maintenance function.

Table 4-7: Tamping maintenance plan: Integration of the ΔR^2alignment tamp and ΔR^2profile tamp results

Analysis Summary Pietermaritzburg - Durban Line 1 Integration Delta Roughness Profile and Delta Roughness Alignment	Distance (km)	Percentage (%)
Delta Roughness Alignment Tamping Criteria 3 mm^2 Cluster Length 200 m and Radius	56.5	58
Delta Roughness Profile Tamping Criteria 3mm^2 Cluster Length 200 m and Radius	62.8	64
Delta Roughness Profile Tamping and Alignment Tamping Cluster Length 200 m and Radius Integration	70	72
Total Track 1 Mainline Distance	97.4	

The complete condition performance based maintenance plan/optimised maintenance requirements are presented in Appendix B. Figure 4-6 below, presents the integrated $\Delta R^2_{\text{alignment tamp}}$ and $\Delta R^2_{\text{profile tamp}}$ results in the IAMM system for the mainline section between km 20 and km 26 from the analysis module developed in Chapter 3.

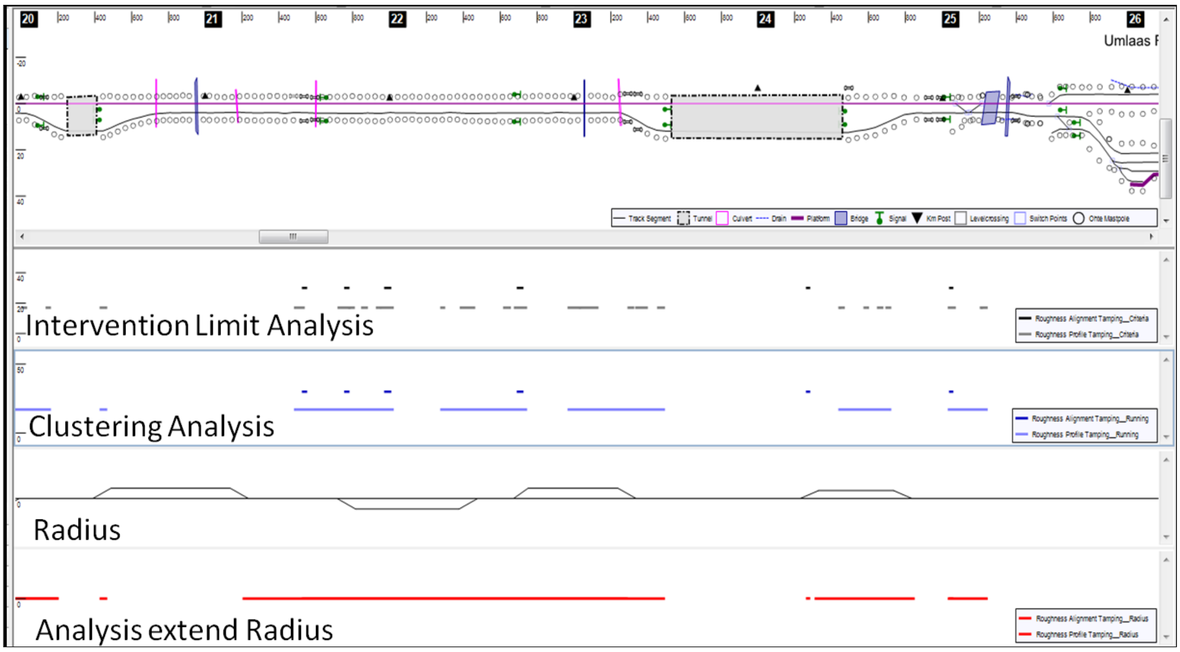

Figure 4-6: $\Delta R^2_{\text{alignment tamp}}$ and $\Delta R^2_{\text{profile tamp}}$ Integration for Mainline 1 from km 20 to km 26

From Table 4-7, it is evident that 70 km (72%) of the total track route distance requires maintenance according to the condition performance (ΔR^2) analysis. The increase of the tamping requirements that took place through the maintenance process is also presented.

4.4.1.3 Integrating Condition and Condition Performance Based Maintenance Needs

The last step in the analysis phase is to integrate the maintenance plans developed for the condition (R^2) and condition performance (ΔR^2) based maintenance plans developed above. This section presents a summarised view of the integration of the two plans in Table 4-8. The integration plan will provide a final maintenance tamping plan for the maintenance supervisor.

Table 4-8: Tamping maintenance plan: Integration of the condition based (R^2) and condition performance based (ΔR^2) results

Analysis Summary Pietermaritzburg - Durban Line 1 Integration Condition Based and Condition Performance Based Maintenance	Distance (km)	Percentage (%)
Roughness Profile Tamping and Alignment Tamping Cluster Length 200 m and Radius Integration	56.2	58
Delta Roughness Profile Tamping and Alignment Tamping Cluster Length 200 m and Radius Integration	70	72
Integration of R^2 and ΔR^2	70.5	72
Total Track 1 Mainline Distance	97.4	

From Table 4-8, it is evident that the condition performance based (ΔR^2) maintenance plan increase with an additional 14 kilometres, an addition of approximately 25% from the total tamping required compared to the condition based (R^2) maintenance tamping plan. When integrating the condition based (R^2) and condition performance based (ΔR^2) maintenance tamping plans, the increase is virtually negligible. Although when analysing the results as presented in Figure 4-7, it is evident that it cannot be neglected. In Figure 4-7 when looking at the area donated with A, it can be seen that at location A1 (solid orange block), there is an improvement in the condition over the period under consideration (ΔR^2, is smaller than zero), resulting in no maintenance requirements. Although at the same location, the condition based maintenance intervention analysis (R^2), indicates that a deficiency at this location is still in existence and requires maintenance input.

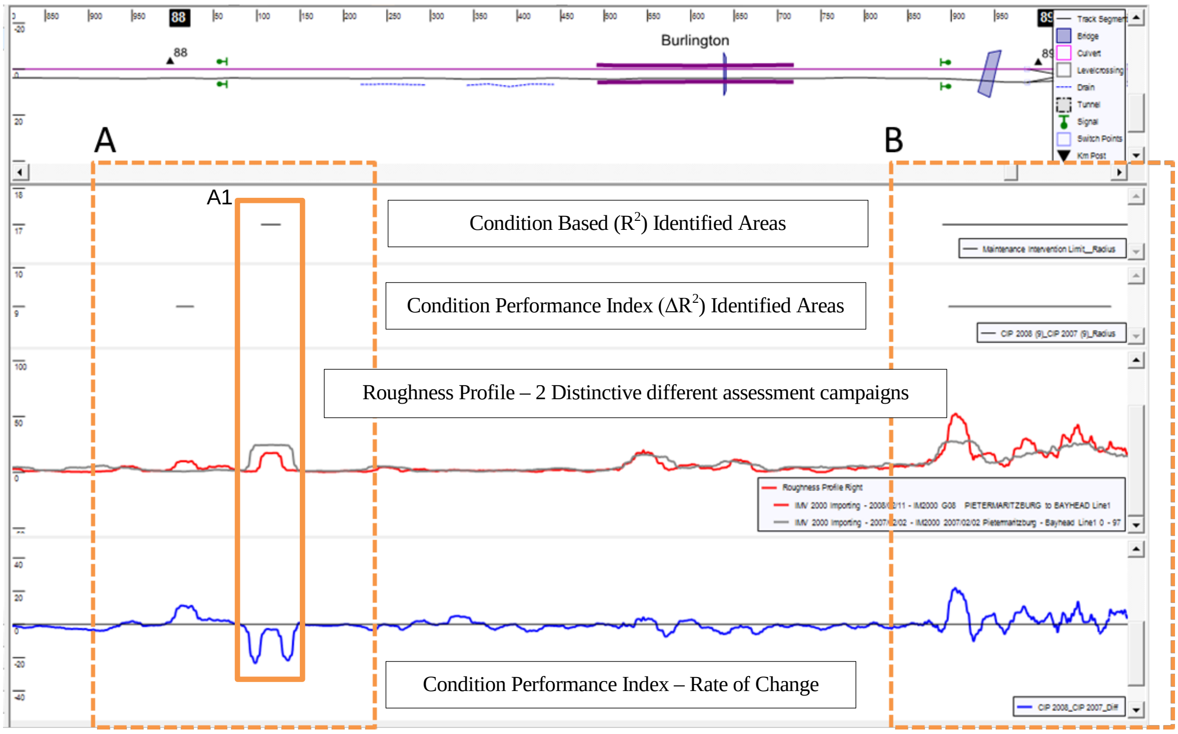

Figure 4-7: Condition Based (R^2) and Condition Performance Based (ΔR^2) comparison.

4.5 Asset Optimisation

From the IAMM system, a queried report shows that sixteen (16) switches on the number one line should not be tamped as they are not within the areas identified for tamping. Another query selecting all the curves that are not within the areas identified for tamping, totals a length of 2.5 km. The total length of curves is 55.5 km, thus the total curved track requiring tamping is 53 km. From the analysis in paragraph 4.3, the optimised condition based tamping requirements can be summarised in the following table.

Table 4-9: Condition based tamping requirements

Equivalent Condition Based Track Distance Tamping Requirements	**Unit**	**Quantity**	**Equivalent Tamping Distance (km)**
Tangent Track	km	17	17
Curved Track	km	53	106
Switches	Number	65	26
Total Distance			**149**

From Table 4-1 and Table 4-9, the savings that can be achieved are presented in Table 4-10 (below).

Table 4-10: Routine based compared to condition performance based (ΔR^2) maintenance

Tamping Activity Type	**Routine Based Distance Requirements**			**Condition Performance (ΔR^2) Based Distance Requirements**		**Savings (%)**
	Unit	**Quantity**	**Equivalent Tamping Distance (km)**	**Quantity**	**Equivalent Tamping Distance (km)**	
Tangent Track	km	42	42	17	17	60
Curved Track	km	55.5	111	53	106	5
Switches	Number	81	32.4	65	26	20
Total Distance			**185.4**		**149**	**20**

Reviewing the information in Table 4-10, it is apparent that the combination of condition performance based maintenance strategies, and a sound maintenance management process, results in maintenance effectiveness and a reduction in maintenance cost.

The information in Table 4-10 suggests a reduction in maintenance requirements, allowing for an increase in track availability. This is anticipated as less time is required to maintain the track, resulting in more time available to operate, and thus an increase in production capability. This adds additional value to the asset management optimisation philosophy.

It should be noted that due to the configuration of the Durban and Pietermaritzburg route, the maintenance savings are restricted due to the vast amount\length of curves totalling approximately 60% of the total route. It is also clear from Table 4-10 that the majority of savings will occur on tangent track. The restriction in curves is due to maintenance business rules, requiring maintenance of an entire curve although only part of the curve emerge as a maintenance necessity.

4.6 Cost Analysis

To quantify the value with regards to operational time, it is assumed that a tamping rate of 5 km per day can be achieved as shown in section 4.1. From this it is calculated that tamping can be done in 30 days. When compared to the 38 days required for routine based maintenance, it results in an occupational time saving of 8 days.

Given that optimisation from routine based to condition performance based tamping saved 8 days of maintenance time, an analysis is needed to determine what monetary value is gained by the business because of the optimisation achieved. Although it seems to be a simplistic calculation, one must remember that a network operation is unlike a piece of equipment in a manufacturing plant that will be out-of-service for the total period in time. At stake is far more than just determining the production saving - in other words by saving 8 days we can assume that 25 trains are affected per day. A simple calculation shows that 200 train trips can take place in 8 days, and that all these trips could not have been undertaken if maintenance was needed.

It is important to note that the section of line in question consists of a double line, and that production can continue while maintenance takes place. This means that it can be ensured that the total line is not completely out of service for the maintenance period. This supports business objectives, with operations continuing with the required production - delivering the required goods to clients.

The author wants to determine the number of trains that would be unable to operate if an 8 day maintenance period were required. Knowing this will highlight the number of trains that can be viewed as a “value add” to the business, as a direct result of maintenance optimisation.

In order to do the calculation the following parameters are known:

- 25 Train trips take place per day on line 1;
- A section of 5 kilometres a day will be out of service during maintenance, resulting in a 5 km section being the constraint in the flow of traffic, as 25 trains per day are also scheduled on the number 2 line.

Theoretically the availability of the line can be calculated if we assume that with 25 trains scheduled on line one and 25 trains on line two, the line is at full capacity. The change in availability can be calculated as 5 km of 97 km that is unavailable, resulting in a reduction of capacity of approximately 5%.

It is now evident that a saving of 8 days of maintenance time, due to the shift from routine based to condition performance based maintenance, assisted the business in optimising production utilisation. This saving allows an additional 16 trains to be operated, meaning that periodic routine based maintenance will have an influence on track availability.

In order to do a monetary value calculation to determine the value added due to the savings made, the following parameters are used:

- D - Distance of track (km);
- T – Number of trains;
- W – Number of wagons per train;
- C – Cost charged per ton/km and
- P – Load per wagon (tons).

From this information, the following calculation can be made as presented in equation (6) below.

$$Income \approx [T \times W \times P] \times D \times C \qquad (6)$$

Table 4-11 (below) indicates the values as determined throughout the study, as well as the values determined by the author in other projects that will be utilised for the calculation in equation 6.

Table 4-11: Parameter values utilised in equation (6) due to maintenance optimisation

Parameter	Unit	Quantity
Number of trains (T)	Number	16
Number of wagons (W)	Number	35
Load per Wagon (P)	Ton	40
Distance of track (D)	km	97
Costs charged (C)	R per (ton/km)	0.4

Using the information in Table 4-11, it is calculated that effective maintenance management resulted in an additional operational income of R 869 120.00.

4.7 Conclusion

We can in summary show from this study, that the value added from an effective maintenance management process and a condition performance based maintenance strategy, can achieve the following for a railway organisation:

- A total maintenance cost reduction of 20%;
- An increase in asset availability of 21% (8 days of 38 days);
- An increase in opportunity utilisation/production of 16 trains due to an increase in availability resulting in an additional operational income of R 869 120.

Theory will put forward that condition performance based maintenance will cover the total length of the route for maintenance required over the life cycle of the assets, i.e. the total route distance will be maintained at least once over the life cycle period. The author is of the opinion that this will not be the situation for all assets and maintenance types, by utilising condition performance based maintenance strategies; the asset management program can be optimized. The author estimates that up to 20% of the total distance will not require maintenance over the life cycle period. In addition he estimates that the total cost saving due to condition performance based maintenance; railway organisations can save up to 35% on its maintenance cost while increasing capacity to approximately the same value. This permits for additional operational income, resulting in a further increase to the bottom line (a decrease in maintenance cost and an increase in operational income). This is based on experience gained in railway maintenance and the influence thereof, in addition is the results obtained in this chapter, where cost reductions are restricted to 20%, due to the vast amount\length of curves present in the line used in this study.

It should also be clear that from the study, that condition based and condition performance based strategies both have its place in the railway environment. They can be utilised individually to determine and identify maintenance requirements, however it is strongly recommended that the two models should be integrated. It is logical that the condition performance based model add additional value to identify additional maintenance requirements and ensure a proactive maintenance regime, what was proven in this chapter however is the value the traditional condition based strategy adds on top of the condition performance based strategy. It clearly indicates that areas where condition improvement is recognised over time, the individual condition parameters are nonetheless above the required intervention limit, therefore still requiring maintenance input. A study can be conducted, to determine the effect of neighbouring assets' deterioration tempo (rate of change) and impact on condition, due to start-stop (maintenance) actions over time.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

The correct integration of modern railway technologies and information technology systems establish effective maintenance management practices and ensure continuous asset management improvement. A systematic process was developed that resulted in the optimisation of effective maintenance requirements specifically related to track tamping.

The development of both condition-based and condition performance-based tamping algorithms led to a reduction, where the latter reduced maintenance requirements with approximately 20% of the extent of maintenance compared to current cyclic practices. This resulted in a reduction of cost and also a 21% increase in operational capacity. The increase in capacity/asset availability and reduction in maintenance cost both contributed to increased return on investment.

5.1 Conclusions

From this dissertation the author can conclude that the literature study provided a platform for reviewing a combination of asset management principles, maintenance management fundamentals and strategies, technology enablers and railway terminology. In particular, the literature review described how the planning of maintenance activities on railway assets involves various aspects, ranging from asset inventory, its condition and utilisation to asset and component maintenance history. The assets that require frequent maintenance due to high loads are located over a large geographic area, resulting in challenges to minimise maintenance visits and resulting costs. Maintenance activities furthermore interrupt the service and reduce the availability of the asset and associated revenue from the service. Although maintenance cost should be minimised, the safety aspect remains critical and minimum service levels should be maintained to ensure business capacity.

The literature review provided the background and understanding that was essential for developing a maintenance management model and issues relating to data collection and maintenance requirement analysis in the railway industry.

In the analysis model phase, the need for an effective analysis model was discussed. The author contextualised methods for data collection and analysis in the study area (a 100 km section of line between Durban and Pietermaritzburg, KwaZulu-Natal, South Africa), with the ultimate aim of producing an effective maintenance plan (specifically for tamping) based on all the available data and the operational requirements for the section of line in question. In the course of this phase, the systematic approach utilised, indicates that the industry need to consider other approaches for better utilisation of available capacity. The integration and efficient utilisation of information is proven to be a major contributor to ensure maintenance effectiveness.

A maintenance management process model was developed during the analysis model phase assisting in effective maintenance requirement decision-making. The maintenance management model is referred to as the Continuous Improvement process. The Continuous Improvement process (a systematic approach) ensures constraints and changes are continuously taken into account assisting in the optimisation of the railway's asset management process. It enables one to continuously improve the current maintenance strategies, intervention limits and maintenance processes.

Part of the maintenance management process is the condition analysis of the assets. Two tamping analysis models, condition based (Maintenance Condition Intervention) and condition performance-based (Condition Performance Index – Rate of Change) models are introduced and results in methods that add value for determining preventative and proactive maintenance requirements. The author suggests utilising the two condition analysis models in phases - depending on the railway's asset management maturity level in utilising condition-based maintenance planning practices. Firstly, ensure the basics are implemented successfully, focusing on the condition-based model. As soon as maturity is accomplished in the preventative condition-based maintenance (R^2) planning, it can then advance to the next level of predictive/proactive condition performance-based (ΔR^2) maintenance planning and the integration of the two models.

The effect of condition-based and condition performance-based maintenance illustrated how these maintenance methodologies increase maintenance effectiveness (doing the right things), resulting in a decrease in maintenance cost. With this in mind it is apparent that with an increase in maintenance effectiveness, less time will be spent maintaining assets. This increases the availability of assets, adding value to the business through increased available capacity. Availability translates into the opportunity to increase production capability. This corroborates the asset management optimisation philosophy of Mitchell *et al.* (2007) - maximising return on investment.

In the analysis phase, results obtained from the condition analysis (tamping) models were analysed. A comparison was made to determine the maintenance effectiveness from the models developed, compared to the general acceptable tamping model used in the railway industry, a routine-based maintenance strategy. From the author's experience, it is known that although many railways acknowledge the use of a condition-based maintenance strategy, many fail to effectively utilise the strategy.

From the analysis results, it is evident that the condition-based (R^2) maintenance model improves maintenance effectiveness with 42%, while the condition performance-based (ΔR^2) maintenance model requires an additional 14 kilometres, an addition of approximately 25%. This results in a total saving of approximately 27.4 km compared to the current routine/frequency-based tamping strategy.

When integrating the condition-based (R^2) and condition performance-based (ΔR^2) maintenance tamping plans, the increase is virtually negligible. Although from detailed analysis, it is evident that it cannot be neglected. The detailed analysis indicates areas/locations where there is an improvement in the condition over the period under consideration (ΔR^2 is smaller than zero), resulting in no maintenance required. The same areas/locations, utilising the condition-based maintenance intervention analysis (R^2), indicate that a deficiency at the same location is still in existence, therefore the area/location requires maintenance input.

In summary, the analysis phase indicates that the condition analysis models increase the effectiveness in maintenance management. By implementing a condition-based and condition performance-based maintenance strategy, the railway organisation can achieve the following:

- A total maintenance cost reduction of approximately 20%, and
- An increase in asset availability of 21%.

In this study, the line analysed resulted in a cost reduction restricted to 20%, due to the vast amount/length of curves present in the line. The author is of the opinion that due to condition-based and condition performance-based maintenance; railway organisations can save up to 30 - 35% on their maintenance costs while increasing capacity to approximately the same value.

5.2 Recommendations

The author is confident in the potential of continuous improvement and the value that this can add to the industry's objectives of creating a profitable and sustainable system. However, a large body of research is required for the comprehensive development of this philosophy. It should be stated that only the concept is introduced as part of this study.

It is recommended that more research should be conducted to establish its true value to the railway industry. The following topics need further investigation within the Continues Improvement process:

- Quantifying acceptable intervention limits for Condition Performance-based “Change in Condition Performance” (ΔR^2) deterioration rates.
- Resulting from the values determined above, determining the Life Cycle Costing of assets due to the effect of pro-active/predictive asset condition performance-based maintenance.
- Optimisation of multiple maintenance management tactics in the railways. In other words, the optimisation of track tamping integrated with other tactics such as ballast screening, drainage cleaning and substructure maintenance activities to improve the track system over its life cycle; and
- Compute the effect of neighbouring assets’ deterioration rate (rate of change) and impact on condition due to start-stop (maintenance) actions over time.

CHAPTER 6

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APPENDIX A

ANALYSIS DETAILS

Table A-1: Roughness Alignment Tamping – Criteria 30mm^2

Roughness Alignment Tamping Criteria 30mm^2							
ID	**Start Distance**	**End Distance**	**From km**	**From m**	**To km**	**To m**	**Distance (m)**
1	126	309	0	122.25	0	305.48	183
2	319	549	0	315.40	0	545.18	230
3	560	560	0	556.28	0	556.53	0
4	821	838	0	817.01	0	834.03	17
5	1038	1141	1	35.97	1	138.33	103
6	1147	1511	1	144.84	1	508.74	364
7	1591	1654	1	588.83	1	652.15	63
8	1718	2040	1	715.72	2	33.74	322
9	2048	2107	2	41.50	2	100.81	59
10	2268	2366	2	261.24	2	359.85	98
11	2470	2487	2	463.72	2	480.74	17
12	2580	2714	2	573.34	2	707.57	134
13	2798	2856	2	791.55	2	849.37	58
14	2873	2877	2	866.56	2	870.80	4
15	2879	2937	2	872.54	2	931.13	58
16	4108	4164	4	109.63	4	165.23	56
17	4359	4415	4	360.08	4	416.43	56
18	4710	4753	4	711.20	4	754.28	43
19	4797	4866	4	798.21	4	867.14	69
20	4871	4874	4	872.40	4	875.15	3
21	4885	4888	4	886.68	4	889.93	3
22	5537	5584	5	539.70	5	587.04	47
23	6000	6116	6	0.97	6	117.26	116
24	6549	6551	6	550.58	6	552.08	2
25	6554	6554	6	554.84	6	555.62	0
26	15858	15882	15	844.04	15	867.86	24
27	15886	15887	15	871.54	15	873.01	1
28	26891	26928	26	904.74	26	941.56	37
29	26999	27002	27	13.66	27	16.87	3
30	27003	27009	27	18.35	27	23.57	6
31	29210	29216	29	223.84	29	229.59	6
32	29219	29227	29	232.53	29	240.82	8
33	29628	29653	29	641.97	29	667.24	25
34	31697	31720	31	714.15	31	737.42	23
35	33397	33462	33	412.57	33	478.01	65
36	33490	33491	33	505.84	33	506.91	1
37	43510	43634	43	528.20	43	653.10	124
38	46873	46875	46	891.35	46	893.60	2
39	46882	46885	46	900.59	46	904.09	3
40	46890	46905	46	908.84	46	924.13	15
41	49042	49050	49	62.25	49	69.48	8

42	49128	49202	49	147.77	49	222.45	74
43	49231	49282	49	250.74	49	301.90	51
44	50986	51040	51	5.81	51	59.71	54
45	51418	51484	51	437.35	51	504.30	66
46	51851	51896	51	870.90	51	915.78	45
47	53819	53821	53	841.48	53	843.24	2
48	54558	54586	54	581.14	54	608.94	28
49	56663	56666	56	726.05	56	729.06	3
50	56670	56818	56	732.82	56	881.70	148
51	56822	56847	56	885.71	56	910.52	25
52	56887	57001	56	949.87	57	39.54	114
53	57020	57143	57	58.09	57	180.74	123
54	57627	57640	57	665.20	57	677.98	13
55	57641	57648	57	679.48	57	686.00	7
56	57665	57727	57	702.79	57	765.45	62
57	57853	57920	57	891.01	57	958.68	67
58	57936	57937	57	974.22	57	975.47	1
59	57958	58012	57	996.28	58	32.17	54
60	58174	58223	58	193.82	58	243.69	49
61	58257	58259	58	277.53	58	279.28	2
62	58282	58289	58	302.34	58	309.61	7
63	58292	58294	58	312.12	58	314.37	2
64	58884	58885	58	904.10	58	905.35	1
65	58907	58971	58	927.40	59	1.72	64
66	58975	58995	59	6.48	59	26.28	20
67	61020	61149	61	48.39	61	177.27	129
68	61247	61288	61	275.38	61	316.68	41
69	62519	62555	62	578.71	62	614.00	36
70	63583	63594	63	645.03	63	655.80	11
71	64030	64102	64	79.11	64	151.18	72
72	66402	66476	66	367.47	66	440.86	74
73	66501	66517	66	466.15	66	482.18	16
74	66569	66718	66	534.28	66	683.53	149
75	66732	66814	66	697.78	66	778.95	82
76	66818	66829	66	783.45	66	794.18	11
77	67901	67950	67	931.98	67	981.66	49
78	69276	69289	69	308.09	69	321.32	13
79	69700	69760	69	732.55	69	792.51	60
80	70629	70701	70	660.74	70	733.01	72
81	70788	70923	70	819.59	70	954.29	135
82	70974	71024	71	13.57	71	63.98	50
83	71467	71491	71	506.67	71	531.00	24
84	71511	71513	71	551.06	71	552.57	2
85	71993	72048	72	31.76	72	86.44	55
86	72163	72546	72	202.06	72	585.06	383
87	72595	72646	72	634.22	72	685.13	51

88	72813	72878	72	851.68	72	917.41	65
89	73417	73493	73	452.36	73	528.63	76
90	73559	73593	73	595.12	73	628.49	34
91	74792	74847	74	828.09	74	883.55	55
92	75556	75575	75	594.66	75	614.22	19
93	75581	75682	75	620.24	75	720.55	101
94	75686	75707	75	724.32	75	746.13	21
95	75843	75845	75	881.56	75	883.31	2
96	75848	75909	75	887.08	75	947.52	61
97	76303	76311	76	343.03	76	350.81	8
98	76415	76439	76	454.13	76	478.96	24
99	76497	76547	76	536.39	76	586.80	50
100	76599	76656	76	638.71	76	695.64	57
101	76978	77013	77	19.15	77	53.77	35
102	77015	77070	77	56.53	77	111.47	55
103	77119	77200	77	160.64	77	241.57	81
104	77951	78061	77	992.67	78	104.33	110
105	78432	78493	78	475.34	78	535.80	61
106	79649	79698	79	689.50	79	738.17	49
107	80370	80438	80	284.84	80	352.82	68
108	80613	80615	80	527.18	80	529.19	2
109	81283	81350	81	326.38	81	393.88	67
110	81353	81356	81	396.89	81	399.40	3
111	84440	84460	84	486.65	84	506.44	20
112	84547	84548	84	593.39	84	594.90	1
113	84550	84708	84	596.40	84	754.58	158
114	84709	84717	84	756.07	84	763.28	8
115	85392	85488	85	408.61	85	503.89	96
116	85617	85675	85	633.01	85	691.18	58
117	86413	86417	86	460.86	86	465.37	4
118	86420	86424	86	468.13	86	472.64	4
119	86425	86436	86	473.14	86	484.18	11
120	86566	86635	86	614.80	86	683.75	69
121	86816	86898	86	864.52	86	946.00	82
122	86918	86994	86	966.06	87	39.14	76
123	87001	87040	87	45.91	87	85.27	39
124	87047	87052	87	91.54	87	96.55	5
125	88778	88827	88	829.13	88	878.02	49
126	88847	89008	88	897.83	89	58.98	161
127	89009	89021	89	59.72	89	71.35	12
128	89332	89382	89	383.10	89	433.21	50
129	91570	91571	91	621.38	91	623.14	1
130	92222	92229	92	273.18	92	280.43	7
131	92249	92266	92	300.68	92	317.93	17
132	92346	92480	92	397.53	92	531.07	134
133	92703	92753	92	754.21	92	804.41	50

134	92986	93046	93	38.19	93	98.69	60
135	93363	93488	93	415.95	93	540.05	125
136	93952	93954	94	2.93	94	4.93	2
137	93956	93966	94	6.93	94	17.18	10
138	94021	94088	94	72.45	94	139.38	67
139	95776	95828	95	827.82	95	879.97	52
Total Distance							7585

Table A-2: Roughness Alignment Tamping – Criteria 30mm^2 and Run-in Length 200m

Roughness Alignment Tamping Criteria 30mm^2 Run-in Length 200m							
ID	**Start Distance**	**End Distance**	**From km**	**From m**	**To m**	**To m**	**Distance (m)**
1	126	560	0	122.25	0	556.53	434
2	821	838	0	817.01	0	834.03	17
3	1038	2937	1	35.97	2	931.13	1899
4	4108	4415	4	109.63	4	416.43	307
5	4710	4888	4	711.20	4	889.93	178
6	5537	5584	5	539.70	5	587.04	47
7	6000	6116	6	0.97	6	117.26	116
8	6549	6554	6	550.58	6	555.62	5
9	15858	15887	15	844.04	15	873.01	29
10	26891	27009	26	904.74	27	23.57	118
11	29210	29227	29	223.84	29	240.82	17
12	29628	29653	29	641.97	29	667.24	25
13	31697	31720	31	714.15	31	737.42	23
14	33397	33491	33	412.57	33	506.91	94
15	43510	43634	43	528.20	43	653.10	124
16	46873	46905	46	891.35	46	924.13	32
17	49042	49282	49	62.25	49	301.90	240
18	50986	51040	51	5.81	51	59.71	54
19	51418	51484	51	437.35	51	504.30	66
20	51851	51896	51	870.90	51	915.78	45
21	53819	53821	53	841.48	53	843.24	2
22	54558	54586	54	581.14	54	608.94	28
23	56663	57143	56	726.05	57	180.74	480
24	57627	58294	57	665.20	58	314.37	667
25	58884	58995	58	904.10	59	26.28	111
26	61020	61288	61	48.39	61	316.68	268
27	62519	62555	62	578.71	62	614.00	36
28	63583	63594	63	645.03	63	655.80	11
29	64030	64102	64	79.11	64	151.18	72
30	66402	66829	66	367.47	66	794.18	427
31	67901	67950	67	931.98	67	981.66	49
32	69276	69289	69	308.09	69	321.32	13
33	69700	69760	69	732.55	69	792.51	60
34	70629	71024	70	660.74	71	63.98	395
35	71467	71513	71	506.67	71	552.57	46
36	71993	72878	72	31.76	72	917.41	885

37	73417	73593	73	452.36	73	628.49	176
38	74792	74847	74	828.09	74	883.55	55
39	75556	75909	75	594.66	75	947.52	353
40	76303	76656	76	343.03	76	695.64	353
41	76978	77200	77	19.15	77	241.57	222
42	77951	78061	77	992.67	78	104.33	110
43	78432	78493	78	475.34	78	535.80	61
44	79649	79698	79	689.50	79	738.17	49
45	80370	80615	80	284.84	80	529.19	245
46	81283	81356	81	326.38	81	399.40	73
47	84440	84717	84	486.65	84	763.28	277
48	85392	85675	85	408.61	85	691.18	283
49	86413	87052	86	460.86	87	96.55	639
50	88778	89021	88	829.13	89	71.35	243
51	89332	89382	89	383.10	89	433.21	50
52	91570	91571	91	621.38	91	623.14	1
53	92222	92480	92	273.18	92	531.07	258
54	92703	92753	92	754.21	92	804.41	50
55	92986	93046	93	38.19	93	98.69	60
56	93363	93488	93	415.95	93	540.05	125
57	93952	94088	94	2.93	94	139.38	136
58	95776	95828	95	827.82	95	879.97	52
Total Distance							11291

Table A-3: Roughness Alignment Tamping – Criteria 30mm^2 and Run-in Length 200m and Radius

Roughness Alignment Tamping Criteria 30mm^2 Run-in Length 200m and Radius							
ID	**Start Distance**	**End Distance**	**From km**	**From m**	**To km**	**To m**	**Distance**
1	126	713	0	122.25	0	709.40	587
2	821	838	0	817.01	0	834.03	17
3	895	2937	0	891.64	2	931.13	2042
4	4108	4888	4	109.63	4	889.93	780
5	5537	5584	5	539.70	5	587.04	47
6	6000	6328	6	0.97	6	328.85	328
7	6549	6554	6	550.58	6	555.62	5
8	15858	15887	15	844.04	15	873.01	29
9	26891	27009	26	904.74	27	23.57	118
10	29070	29689	29	83.72	29	703.00	619
11	31565	31890	31	582.66	31	907.62	325
12	33337	33511	33	352.52	33	526.96	174
13	42937	43921	42	954.52	43	940.04	984
14	46741	46905	46	759.45	46	924.13	164
15	48791	50056	48	810.19	50	76.03	1265
16	50986	51040	51	5.81	51	59.71	54
17	51265	51764	51	284.47	51	784.30	499
18	51851	52284	51	870.90	52	304.30	433
19	53714	54056	53	735.70	54	79.18	342
20	54558	55262	54	581.14	55	285.75	704
21	56609	57421	56	672.60	57	459.58	812
22	57534	58728	57	572.10	58	748.46	1194
23	58732	59249	58	751.76	59	279.82	517
24	60926	61424	60	961.25	61	452.54	498
25	62207	62578	62	266.63	62	636.99	371
26	63464	63680	63	526.12	63	742.41	216
27	64030	64193	64	79.11	64	242.57	163
28	66087	67002	66	51.98	67	33.29	915
29	67795	68304	67	826.12	68	334.75	509
30	69182	69760	69	213.83	69	792.51	578
31	70107	71024	70	138.98	71	63.98	917
32	71467	71513	71	506.67	71	552.57	46
33	71874	72942	71	913.66	72	980.93	1068
34	73208	74424	73	243.84	74	460.00	1216
35	74792	74847	74	828.09	74	883.55	55
36	75480	76716	75	518.54	76	755.61	1236
37	76967	77200	77	8.46	77	241.57	233
38	77899	78596	77	940.67	78	639.28	697

39	78665	79747	78	708.44	79	787.45	1082
40	80012	82787	79	1052.49	82	834.01	2775
41	84440	84717	84	486.65	84	763.28	277
42	85205	85693	85	221.54	85	709.40	488
43	86119	87084	86	167.79	87	129.02	965
44	88650	89021	88	701.00	89	71.35	371
45	89164	89954	89	214.37	90	5.14	790
46	90993	92061	91	44.37	92	112.42	1068
47	92222	92851	92	273.18	92	902.79	629
48	92986	93046	93	38.19	93	98.69	60
49	93363	93567	93	415.95	93	619.29	204
50	93644	94088	93	696.06	94	139.38	444
51	94615	95857	94	666.01	95	908.89	1242
Total Distance							31152

Table A-4: Roughness Profile Tamping – Criteria 17mm^2

Roughness Profile Tamping Criteria 17mm^2							
ID	**Start Distance**	**End Distance**	**From km**	**From m**	**To km**	**To m**	**Distance (m)**
1	31	198	0	27.04	0	194.40	167
2	230	231	0	226.64	0	227.13	1
3	234	235	0	229.86	0	231.10	1
4	238	238	0	234.07	0	234.57	0
5	241	294	0	236.80	0	290.11	53
6	337	400	0	333.00	0	395.80	63
7	420	435	0	416.24	0	431.38	15
8	437	438	0	433.65	0	434.41	1
9	455	469	0	450.81	0	465.19	14
10	491	584	0	487.65	0	580.25	93
11	586	587	0	581.77	0	583.53	1
12	716	768	0	712.73	0	764.20	52
13	776	806	0	771.77	0	802.55	30
14	808	818	0	803.95	0	814.01	10
15	819	820	0	815.26	0	815.76	1
16	823	836	0	819.26	0	832.03	13
17	2600	2703	2	593.36	2	697.10	103
18	2890	2981	2	883.76	2	974.96	91
19	2988	2994	2	981.72	2	987.98	6
20	3466	3478	3	469.19	3	480.46	12
21	4225	4231	4	226.59	4	232.60	6
22	4234	4234	4	235.35	4	235.60	0
23	4237	4295	4	238.11	4	296.21	58
24	4297	4300	4	298.72	4	301.97	3
25	4431	4474	4	432.96	4	475.03	43
26	4620	4674	4	621.29	4	675.39	54
27	4701	4934	4	702.69	4	935.53	233
28	4935	4939	4	936.53	4	940.48	4
29	4995	5046	4	996.51	5	48.15	51
30	5429	5438	5	431.62	5	440.79	9
31	5527	5627	5	529.29	5	629.43	100
32	5649	5768	5	651.49	5	770.47	119
33	5781	5909	5	783.86	5	911.27	128
34	5910	5912	5	912.26	5	914.74	2
35	5949	6006	5	951.92	6	7.16	57
36	6028	6029	6	29.57	6	30.57	1
37	6153	6246	6	153.99	6	246.93	93
38	6264	6319	6	265.42	6	320.13	55
39	6321	6376	6	321.88	6	376.85	55
40	6419	6455	6	420.83	6	456.33	36
41	6461	6467	6	462.83	6	468.83	6

42	6570	6573	6	571.64	6	573.96	3
43	6992	7090	6	993.03	7	91.22	98
44	7099	7156	7	101.04	7	157.62	57
45	7157	7228	7	158.65	7	229.45	71
46	8062	8120	8	70.83	8	128.71	58
47	8124	8137	8	133.36	8	146.28	13
48	8442	8461	8	450.63	8	469.75	19
49	8649	8701	8	658.11	8	709.53	52
50	9138	9234	9	148.32	9	243.93	96
51	9530	9560	9	540.31	9	570.03	30
52	9970	10051	9	979.59	10	63.81	81
53	11919	11966	11	932.96	11	980.24	47
54	13285	13336	13	296.41	13	347.57	51
55	13433	13508	13	444.73	13	520.18	75
56	13584	13597	13	596.15	13	608.55	13
57	14095	14115	14	62.15	14	82.05	20
58	14193	14243	14	160.60	14	210.73	50
59	15405	15427	15	390.85	15	412.82	22
60	15433	15455	15	418.82	15	441.04	22
61	15468	15484	15	454.02	15	470.25	16
62	15578	15580	15	563.88	15	565.63	2
63	15589	15601	15	574.37	15	586.35	12
64	15859	15928	15	844.54	15	914.04	69
65	16181	16182	16	196.15	16	197.40	1
66	16184	16196	16	199.40	16	211.14	12
67	16866	16957	16	880.72	16	971.95	91
68	21949	22003	21	963.59	22	17.72	54
69	22368	22445	22	382.97	22	459.72	77
70	22597	22651	22	611.22	22	665.72	54
71	22687	22718	22	701.72	22	732.22	31
72	23014	23084	23	28.88	23	99.13	70
73	23316	23371	23	331.13	23	386.13	55
74	23448	23449	23	463.13	23	463.38	1
75	23450	23487	23	464.88	23	502.13	37
76	24412	24462	24	429.98	24	480.45	50
77	24513	24524	24	531.43	24	542.43	11
78	24544	24593	24	562.17	24	611.65	49
79	24903	24937	24	921.26	24	955.00	34
80	25059	25064	25	74.62	25	80.11	5
81	25184	25230	25	199.40	25	246.10	46
82	25535	25622	25	551.14	25	638.17	87
83	26038	26074	26	50.97	26	86.97	36
84	26801	26842	26	814.48	26	855.74	41
85	26852	26882	26	865.65	26	895.50	30
86	26884	26884	26	897.64	26	897.89	0

87	26885	26885	26	898.58	26	898.83	0
88	26891	26947	26	904.60	26	960.44	56
89	26956	26958	26	969.27	26	971.28	2
90	26981	27015	26	994.18	27	30.13	34
91	27033	27065	27	47.47	27	79.82	32
92	27071	27101	27	85.43	27	115.91	30
93	27291	27309	27	306.14	27	324.32	18
94	27819	27850	27	833.78	27	864.66	31
95	27854	27886	27	868.67	27	900.88	32
96	27889	27916	27	903.42	27	930.70	27
97	28006	28007	27	1020.80	27	1021.60	1
98	28470	28472	28	461.04	28	463.85	2
99	28473	28476	28	464.65	28	467.46	3
100	28479	28490	28	470.00	28	480.96	11
101	28493	28494	28	484.17	28	485.24	1
102	28497	28523	28	488.04	28	514.65	26
103	28918	28941	28	909.00	28	932.67	23
104	28947	28974	28	938.01	28	965.28	27
105	29199	29279	29	213.14	29	293.24	80
106	29516	29541	29	530.05	29	555.19	25
107	29572	29573	29	585.81	29	586.74	1
108	29573	29620	29	587.14	29	633.68	47
109	29635	29670	29	648.92	29	683.42	35
110	29903	29929	29	916.49	29	942.96	26
111	29945	29962	29	958.88	29	975.86	17
112	30752	30769	30	767.74	30	784.72	17
113	30803	30835	30	818.55	30	850.24	32
114	31693	31718	31	710.14	31	735.42	25
115	31781	31827	31	798.13	31	844.00	46
116	32180	32200	32	195.96	32	216.69	20
117	32261	32289	32	277.13	32	305.35	28
118	32735	32763	32	751.72	32	779.81	28
119	32870	32889	32	886.65	32	905.51	19
120	33041	33067	33	57.16	33	83.39	26
121	33395	33511	33	410.70	33	526.98	116
122	41551	41557	41	565.21	41	571.47	6
123	41658	41688	41	672.06	41	701.84	30
124	42490	42558	42	507.86	42	576.18	68
125	42567	42573	42	584.93	42	590.69	6
126	42840	42850	42	857.49	42	867.50	10
127	43423	43655	43	441.86	43	673.62	232
128	43883	43918	43	901.88	43	937.16	35
129	45968	45972	45	988.61	45	992.62	4
130	46136	46162	46	155.01	46	181.05	26
131	46179	46187	46	198.32	46	205.58	8

132	46845	46894	46	863.62	46	912.83	49
133	46908	46909	46	927.15	46	927.40	1
134	46909	46909	46	927.91	46	928.16	0
135	46910	46911	46	928.41	46	929.42	1
136	46950	46956	46	968.78	46	975.09	6
137	47030	47066	47	47.27	47	83.60	36
138	47795	47796	47	812.35	47	812.85	1
139	47799	47902	47	816.35	47	918.92	103
140	47949	48000	47	966.72	48	19.81	51
141	48048	48077	48	67.61	48	96.39	29
142	48679	48764	48	698.78	48	783.37	85
143	49120	49205	49	139.54	49	225.20	85
144	50671	50716	50	691.36	50	736.50	45
145	50775	50815	50	794.67	50	835.04	40
146	50817	50818	50	837.30	50	838.05	1
147	50821	50825	50	841.31	50	845.07	4
148	50833	51004	50	852.85	51	23.60	171
149	51020	51044	51	39.65	51	63.98	24
150	51049	51167	51	68.49	51	186.84	118
151	51254	51313	51	273.85	51	332.78	59
152	51624	51636	51	644.22	51	655.50	12
153	52055	52102	52	74.79	52	122.18	47
154	53543	53583	53	564.67	53	605.43	40
155	54219	54283	54	241.81	54	306.32	64
156	54407	54425	54	429.85	54	447.61	18
157	54446	54590	54	468.86	54	612.95	144
158	55524	55533	55	547.51	55	557.03	9
159	55890	55941	55	913.72	56	3.92	51
160	55992	56042	56	55.05	56	105.68	50
161	56694	56703	56	756.88	56	765.90	9
162	56705	56715	56	768.66	56	778.19	10
163	56826	56844	56	889.47	56	907.26	18
164	56862	56875	56	925.31	56	937.84	13
165	56898	56913	56	961.15	56	975.94	15
166	56972	57018	57	10.22	57	56.59	46
167	57057	57129	57	95.19	57	167.45	72
168	57713	57717	57	750.91	57	755.17	4
169	57819	57871	57	857.18	57	909.56	52
170	59602	59610	59	632.61	59	641.12	8
171	59648	59650	59	679.15	59	681.41	2
172	61074	61142	61	102.50	61	171.01	68
173	61279	61291	61	307.92	61	319.93	12
174	62498	62552	62	557.44	62	611.25	54
175	63539	63652	63	601.48	63	714.11	113
176	63971	64210	64	20.30	64	259.54	239

177	64215	64321	64	264.29	64	370.65	106
178	64843	64850	64	892.17	64	898.93	7
179	65248	65271	65	294.98	65	317.50	23
180	65513	65537	65	559.75	65	583.27	24
181	66213	66221	66	177.87	66	185.88	8
182	66248	66253	66	213.43	66	218.69	5
183	66255	66257	66	220.70	66	221.95	2
184	66575	66575	66	539.79	66	540.04	0
185	66575	66586	66	540.29	66	551.56	11
186	66702	66802	66	667.28	66	766.97	100
187	66870	66871	66	835.37	66	836.12	1
188	66873	66879	66	838.37	66	844.36	6
189	66880	66914	66	845.61	66	879.56	34
190	67233	67249	67	263.89	67	280.12	16
191	67369	67370	67	399.96	67	400.96	1
192	67370	67433	67	401.45	67	463.87	63
193	67908	67959	67	938.97	67	989.90	51
194	68532	68585	68	562.96	68	615.89	53
195	68600	68686	68	630.86	68	717.00	86
196	68891	68903	68	921.73	68	934.22	12
197	68908	68965	68	939.46	68	996.64	57
198	69301	69369	69	333.55	69	401.72	68
199	69702	69757	69	734.05	69	788.75	55
200	70570	70619	70	601.77	70	650.70	49
201	70641	70655	70	672.28	70	686.34	14
202	70793	70804	70	824.86	70	835.65	11
203	71472	71531	71	511.43	71	570.88	59
204	71882	71968	71	921.77	72	6.43	86
205	72027	72043	72	66.12	72	82.17	16
206	72113	72122	72	151.65	72	161.18	9
207	72230	72299	72	269.28	72	338.00	69
208	72327	72490	72	365.59	72	528.88	163
209	72503	72635	72	541.92	72	674.10	132
210	72727	72768	72	765.90	72	807.28	41
211	72800	72885	72	839.38	72	924.18	85
212	72912	72963	72	950.53	72	1002.21	51
213	72964	73015	72	1003.22	73	50.42	51
214	73039	73096	73	74.75	73	131.46	57
215	73160	73163	73	195.94	73	198.95	3
216	74157	74234	74	193.47	74	270.50	77
217	74474	74649	74	510.86	74	685.73	175
218	74661	74762	74	697.02	74	798.64	101
219	74813	74815	74	849.44	74	850.95	2
220	74839	74847	74	875.27	74	883.30	8
221	74996	75049	75	34.90	75	88.07	53

222	75547	75666	75	585.38	75	705.26	119
223	75837	75839	75	876.04	75	877.30	2
224	75856	75925	75	894.60	75	964.07	69
225	75931	75974	75	969.58	76	13.50	43
226	76426	76477	76	465.92	76	516.08	51
227	76497	76548	76	536.39	76	587.55	51
228	76607	76625	76	646.99	76	664.54	18
229	76627	76627	76	666.80	76	667.05	0
230	77012	77070	77	52.76	77	111.72	58
231	77202	77249	77	243.33	77	290.65	47
232	77916	77966	77	956.87	78	9.19	50
233	77987	78074	78	29.97	78	116.62	87
234	78585	78672	78	628.36	78	715.16	87
235	79659	79699	79	699.78	79	739.17	40
236	79722	79727	79	762.75	79	767.27	5
237	80216	80271	80	130.04	80	185.74	55
238	80326	80327	80	240.93	80	241.94	1
239	80328	80455	80	242.69	80	369.63	127
240	80468	80492	80	382.43	80	406.76	24
241	80502	80516	80	416.80	80	430.85	14
242	80819	80893	80	733.68	80	807.70	74
243	80915	80916	80	829.28	80	830.28	1
244	81414	81469	81	458.11	81	512.81	55
245	82793	82794	82	840.33	82	841.33	1
246	82797	82821	82	843.84	82	868.40	24
247	82823	82827	82	870.65	82	874.66	4
248	82828	82829	82	875.66	82	875.91	1
249	84086	84117	84	132.32	84	163.39	31
250	84289	84341	84	335.54	84	387.67	52
251	84564	84595	84	611.18	84	642.24	31
252	84605	84685	84	652.18	84	731.47	80
253	84694	84695	84	741.16	84	742.15	1
254	84808	84853	84	854.99	84	899.73	45
255	84950	85021	84	997.16	85	37.53	71
256	85370	85424	85	385.99	85	440.17	54
257	85443	85522	85	459.06	85	537.99	79
258	85553	85635	85	568.82	85	650.81	82
259	88042	88090	88	92.65	88	141.30	48
260	88835	88881	88	886.05	88	932.19	46
261	88934	89059	88	985.60	89	110.20	125
262	89114	89160	89	164.58	89	210.69	46
263	90365	90443	90	416.28	90	494.47	78
264	91839	91840	91	890.92	91	891.67	1
265	91841	91858	91	893.18	91	910.23	17
266	92065	92115	92	116.74	92	166.88	50

267	92122	92200	92	173.40	92	251.63	78
268	92242	92291	92	293.93	92	342.68	49
269	92339	92363	92	390.45	92	413.96	24
270	92368	92371	92	419.02	92	422.56	3
271	92373	92383	92	424.83	92	433.93	10
272	92413	92509	92	464.55	92	559.93	96
273	92619	92619	92	670.37	92	670.88	0
274	92671	92757	92	722.33	92	808.93	86
275	92852	92874	92	903.55	92	925.39	22
276	92914	93019	92	965.80	93	71.58	105
277	93032	93051	93	84.38	93	103.45	19
278	93061	93082	93	113.24	93	134.08	21
279	93117	93180	93	169.97	93	232.97	63
280	93383	93492	93	435.78	93	544.80	109
281	93840	93925	93	892.19	93	977.98	85
282	93997	94070	94	48.19	94	121.47	73
283	94124	94165	94	174.82	94	215.93	41
284	94178	94180	94	229.22	94	230.98	2
285	94181	94300	94	232.23	94	350.82	119
286	94462	94477	94	512.52	94	528.32	15
287	94494	94508	94	545.12	94	558.91	14
288	94977	95041	95	28.81	95	93.49	64
289	95043	95043	95	94.74	95	94.99	0
290	95442	95459	95	494.37	95	511.42	17
291	95673	95926	95	725.03	95	978.25	253
292	95974	96090	96	27.17	96	143.22	116
Total Distance							12767

Table A-5: Roughness Profile Tamping – Criteria 17mm^2 and Run-in Length 200m

Roughness Profile Tamping Criteria 17mm^2 Run-in Length 200m							
ID	**Start Distance**	**End Distance**	**From km**	**From m**	**To km**	**To m**	**Distance (m)**
1	31	836	0	27.04	0	832.03	805
2	2600	2994	2	593.36	2	987.98	394
3	3466	3478	3	469.19	3	480.46	12
4	4225	5046	4	226.59	5	48.15	821
5	5429	6573	5	431.62	6	573.96	1144
6	6992	7228	6	993.03	7	229.45	236
7	8062	8137	8	70.83	8	146.28	75
8	8442	8701	8	450.63	8	709.53	259
9	9138	9234	9	148.32	9	243.93	96
10	9530	9560	9	540.31	9	570.03	30
11	9970	10051	9	979.59	10	63.81	81
12	11919	11966	11	932.96	11	980.24	47
13	13285	13597	13	296.41	13	608.55	312
14	14095	14243	14	62.15	14	210.73	148
15	15405	15601	15	390.85	15	586.35	196
16	15859	15928	15	844.54	15	914.04	69
17	16181	16196	16	196.15	16	211.14	15
18	16866	16957	16	880.72	16	971.95	91
19	21949	22003	21	963.59	22	17.72	54
20	22368	22718	22	382.97	22	732.22	350
21	23014	23084	23	28.88	23	99.13	70
22	23316	23487	23	331.13	23	502.13	171
23	24412	24593	24	429.98	24	611.65	181
24	24903	25230	24	921.26	25	246.10	327
25	25535	25622	25	551.14	25	638.17	87
26	26038	26074	26	50.97	26	86.97	36
27	26801	27309	26	814.48	27	324.32	508
28	27819	28007	27	833.78	27	1021.60	188
29	28470	28523	28	461.04	28	514.65	53
30	28918	28974	28	909.00	28	965.28	56
31	29199	29279	29	213.14	29	293.24	80
32	29516	29670	29	530.05	29	683.42	154
33	29903	29962	29	916.49	29	975.86	59

34	30752	30835	30	767.74	30	850.24	83
35	31693	31827	31	710.14	31	844.00	134
36	32180	32289	32	195.96	32	305.35	109
37	32735	33067	32	751.72	33	83.39	332
38	33395	33511	33	410.70	33	526.98	116
39	41551	41688	41	565.21	41	701.84	137
40	42490	42573	42	507.86	42	590.69	83
41	42840	42850	42	857.49	42	867.50	10
42	43423	43655	43	441.86	43	673.62	232
43	43883	43918	43	901.88	43	937.16	35
44	45968	46187	45	988.61	46	205.58	219
45	46845	47066	46	863.62	47	83.60	221
46	47795	48077	47	812.35	48	96.39	282
47	48679	48764	48	698.78	48	783.37	85
48	49120	49205	49	139.54	49	225.20	85
49	50671	51313	50	691.36	51	332.78	642
50	51624	51636	51	644.22	51	655.50	12
51	52055	52102	52	74.79	52	122.18	47
52	53543	53583	53	564.67	53	605.43	40
53	54219	54590	54	241.81	54	612.95	371
54	55524	55533	55	547.51	55	557.03	9
55	55890	56042	55	913.72	56	105.68	152
56	56694	57129	56	756.88	57	167.45	435
57	57713	57871	57	750.91	57	909.56	158
58	59602	59650	59	632.61	59	681.41	48
59	61074	61291	61	102.50	61	319.93	217
60	62498	62552	62	557.44	62	611.25	54
61	63539	63652	63	601.48	63	714.11	113
62	63971	64321	64	20.30	64	370.65	350
63	64843	64850	64	892.17	64	898.93	7
64	65248	65271	65	294.98	65	317.50	23
65	65513	65537	65	559.75	65	583.27	24
66	66213	66257	66	177.87	66	221.95	44
67	66575	66914	66	539.79	66	879.56	339
68	67233	67433	67	263.89	67	463.87	200
69	67908	67959	67	938.97	67	989.90	51
70	68532	68686	68	562.96	68	717.00	154

71	68891	68965	68	921.73	68	996.64	74
72	69301	69369	69	333.55	69	401.72	68
73	69702	69757	69	734.05	69	788.75	55
74	70570	70804	70	601.77	70	835.65	234
75	71472	71531	71	511.43	71	570.88	59
76	71882	73163	71	921.77	73	198.95	1281
77	74157	74234	74	193.47	74	270.50	77
78	74474	75049	74	510.86	75	88.07	575
79	75547	75974	75	585.38	76	13.50	427
80	76426	76627	76	465.92	76	667.05	201
81	77012	77249	77	52.76	77	290.65	237
82	77916	78074	77	956.87	78	116.62	158
83	78585	78672	78	628.36	78	715.16	87
84	79659	79727	79	699.78	79	767.27	68
85	80216	80516	80	130.04	80	430.85	300
86	80819	80916	80	733.68	80	830.28	97
87	81414	81469	81	458.11	81	512.81	55
88	82793	82829	82	840.33	82	875.91	36
89	84086	84341	84	132.32	84	387.67	255
90	84564	85021	84	611.18	85	37.53	457
91	85370	85635	85	385.99	85	650.81	265
92	88042	88090	88	92.65	88	141.30	48
93	88835	89160	88	886.05	89	210.69	325
94	90365	90443	90	416.28	90	494.47	78
95	91839	91858	91	890.92	91	910.23	19
96	92065	93180	92	116.74	93	232.97	1115
97	93383	93492	93	435.78	93	544.80	109
98	93840	94508	93	892.19	94	558.91	668
99	94977	95043	95	28.81	95	94.99	66
100	95442	95459	95	494.37	95	511.42	17
101	95673	96090	95	725.03	96	143.22	417
Total Distance							20786

Table A-6: Roughness Profile Tamping – Criteria $17mm^2$ and Run-in Length 200m and Radius

Roughness Profile Tamping Criteria $17mm^2$ Run-in Length 200m and Radius							
ID	**Start Distance**	**End Distance**	**From km**	**From m**	**To km**	**To m**	**Distance (m)**
1	31	836	0	27.04	0	832.02	805
2	2257	3446	2	250.21	3	448.48	1189
3	3466	3478	3	469.19	3	480.46	12
4	4198	5046	4	199.36	5	48.15	848
5	5429	6573	5	431.62	6	573.96	1144
6	6992	7228	6	993.03	7	229.45	236
7	8062	8137	8	70.83	8	146.28	75
8	8442	8701	8	450.63	8	709.53	259
9	8785	9419	8	794.08	9	429.54	634
10	9530	9560	9	540.31	9	570.03	30
11	9699	10228	9	708.97	10	241.01	529
12	11919	11966	11	932.96	11	980.24	47
13	12401	13597	12	414.03	13	608.55	1196
14	13712	14549	13	723.86	14	515.83	837
15	14704	14853	14	671.35	14	819.89	149
16	15405	15601	15	390.85	15	586.35	196
17	15859	16666	15	844.54	16	680.80	807
18	16771	18135	16	786.12	18	148.75	1364
20	21699	23323	21	714.23	23	337.17	1788
21	22655	23488	22	669.65	23	502.13	592
22	24224	24816	24	242.27	24	834.05	327
23	24903	25230	24	921.26	25	246.10	87
24	25535	25622	25	551.14	25	638.17	36
25	26038	26074	26	50.97	26	86.97	1049
26	26260	27309	26	273.34	27	324.32	706
27	27612	28318	27	626.53	28	309.61	256
28	28325	28581	28	316.26	28	571.90	56
29	28918	28974	28	909.00	28	965.28	619
30	29070	29689	29	83.72	29	703.00	405
31	29828	30233	29	841.65	30	248.72	396
32	30752	31148	30	767.74	31	165.95	325
33	31565	31890	31	582.66	31	907.62	328
34	31961	32289	31	978.16	32	305.35	332
35	32735	33067	32	751.72	33	83.39	8203
36	41551	41688	41	565.21	41	701.84	137
37	42273	42573	42	291.19	42	590.69	300
38	42840	42850	42	857.49	42	867.50	10
39	42937	43921	42	954.52	43	940.04	984
40	45968	46187	45	988.61	46	205.58	219

41	46741	47066	46	759.45	47	83.60	325
42	47081	48077	47	97.92	48	96.39	996
43	48679	48764	48	698.78	48	783.37	85
44	48791	49205	48	810.19	49	225.20	414
45	50671	51764	50	691.37	51	784.30	1093
46	51869	52284	51	889.29	52	304.30	415
47	53543	53583	53	564.67	53	605.43	40
48	54219	55262	54	241.81	55	285.75	1043
49	55524	55533	55	547.51	55	557.03	9
50	55890	56540	55	913.72	56	603.66	650
51	56609	57421	56	672.60	57	459.58	812
52	57534	58076	57	572.10	58	96.15	542
53	59602	59650	59	632.61	59	681.41	48
54	60926	61424	60	961.25	61	452.54	498
55	62207	62578	62	266.63	62	636.99	371
56	63464	63680	63	526.12	63	742.41	216
57	63916	64321	63	978.24	64	370.65	405
58	64843	64850	64	892.17	64	898.93	7
59	65153	65271	65	199.13	65	317.50	118
60	65513	65537	65	559.75	65	583.27	24
61	66087	67002	66	51.98	67	33.29	915
62	67233	67790	67	263.89	67	821.41	557
63	67795	68304	67	826.12	68	334.75	509
64	68468	68686	68	499.37	68	717.00	218
65	68891	68965	68	921.73	68	996.64	74
66	69182	69757	69	213.83	69	788.75	575
67	70107	70810	70	138.98	70	841.94	703
68	71472	71531	71	511.43	71	570.88	59
69	71874	73163	71	913.66	73	198.95	1289
70	73208	74424	73	243.84	74	460.00	1216
71	74474	75411	74	510.86	75	449.81	937
72	75480	76716	75	518.54	76	755.61	1236
73	76967	77249	77	8.46	77	290.65	282
75	77899	79747	77	940.67	79	787.45	1848
76	78665	79747	78	708.44	79	787.45	2775
77	80012	82787	79	1,052.49	82	834.01	36
78	82793	82829	82	840.33	82	875.91	526
79	83815	84341	83	859.97	84	387.66	457
80	84564	85021	84	611.18	85	37.53	488
81	85205	85693	85	221.54	85	709.40	651
82	87874	88525	87	918.49	88	576.32	510
83	88650	89160	88	701.00	89	210.69	127
84	90344	90471	90	395.60	90	522.58	1068
85	90993	92061	91	44.37	92	112.42	1115

86	92065	93180	92	116.74	93	232.97	184
87	93383	93567	93	435.78	93	619.29	864
88	94615	94508	93	696.06	94	558.90	1819
Total Distance							50209

Table A-7: Delta Roughness Alignment Tamping – Criteria $3mm^2$ and Run-in Length 200m and Radius

Delta Roughness Alignment Tamping Criteria $3mm^2$ Run-in Length 200m and Radius							
ID	**Start Distance**	**End Distance**	**From km**	**From m**	**To km**	**To m**	**Distance (m)**
1	105	713	0	101.67	0	709.40	608
2	895	2881	0	891.64	2	874.17	1986
3	2970	3446	2	964.11	3	448.48	476
4	3646	5063	3	648.51	5	66.00	1417
5	5528	6575	5	530.77	6	576.55	1047
6	7031	7194	7	33.09	7	195.34	163
7	7246	8166	7	247.18	8	174.96	920
8	8785	9621	8	794.08	9	630.75	836
9	9699	10228	9	708.97	10	241.01	529
10	10421	10432	10	433.84	10	444.17	11
11	10635	10670	10	647.78	10	682.66	35
12	11167	11190	11	180.60	11	203.59	23
13	11481	11663	11	494.51	11	676.66	182
14	12401	13501	12	414.03	13	512.43	1100
15	13712	14935	13	723.86	14	902.19	1223
16	15566	15890	15	551.65	15	875.70	324
17	16771	18135	16	786.12	18	148.75	1364
18	19212	20255	19	133.31	20	268.23	1043
20	20371	21291	20	383.54	21	305.92	920
21	21541	21542	21	556.14	21	557.14	1
22	21699	23323	21	714.23	23	337.17	1624
23	22655	23568	22	669.65	23	582.63	913
24	24224	24816	24	242.27	24	834.05	592
25	25026	25149	25	41.39	25	164.71	123
26	25745	26130	25	760.74	26	143.80	385
27	26260	27027	26	273.34	27	41.91	767
28	27353	27378	27	367.36	27	392.50	25
29	27612	28318	27	626.53	28	309.61	706
30	28325	28581	28	316.26	28	571.90	256
31	28922	29689	28	913.01	29	703.00	767
32	29828	30233	29	841.65	30	248.72	405
33	30311	31148	30	325.88	31	165.95	837
34	31565	31943	31	582.66	31	960.61	378
35	32278	32304	32	294.78	32	319.92	26
36	32560	32562	32	576.14	32	578.01	2
37	32849	33055	32	864.99	33	71.08	206
38	33337	33511	33	352.52	33	526.96	174
39	42781	42821	42	798.67	42	838.47	40

40	42937	43997	42	954.52	44	15.68	1060
41	44025	44753	44	43.59	44	771.56	728
42	44949	45248	44	968.30	45	267.95	299
43	45522	45904	45	542.54	45	924.27	382
44	46142	46193	46	160.77	46	211.34	51
45	46901	46912	46	919.84	46	930.43	11
46	47081	47884	47	97.92	47	901.15	803
47	48291	48309	48	310.12	48	327.89	18
48	48717	48725	48	736.57	48	744.83	8
49	48791	50056	48	810.19	50	76.03	1265
50	50058	50662	50	78.12	50	681.82	604
51	50899	51764	50	918.79	51	784.30	865
52	51849	52284	51	868.64	52	304.30	435
53	53714	54056	53	735.70	54	79.18	342
54	54117	55262	54	140.28	55	285.75	1145
55	55922	56540	55	946.41	56	603.66	618
56	56584	57107	56	646.85	57	144.96	523
57	57534	58728	57	572.10	58	748.46	1194
58	58732	59249	58	751.76	59	279.82	517
59	59737	59785	59	768.24	59	816.54	48
60	60926	61424	60	961.25	61	452.54	498
61	62207	62578	62	266.63	62	636.99	371
62	62873	62923	62	932.11	62	982.67	50
63	64026	64320	64	74.86	64	368.90	294
64	66083	67002	66	47.87	67	33.29	919
65	67795	68304	67	826.12	68	334.75	509
66	68468	68604	68	499.37	68	635.05	136
67	69182	69797	69	213.83	69	829.15	615
68	70107	70810	70	138.98	70	841.94	703
69	70810	71054	70	841.94	71	93.58	244
70	71451	71515	71	490.87	71	554.83	64
71	71874	72728	71	913.66	72	767.26	854
72	72737	72942	72	776.38	72	980.93	205
73	73208	74424	73	243.84	74	460.00	1216
75	74792	75411	74	828.84	75	449.81	619
76	75480	76740	75	518.54	76	779.40	1260
77	76967	77205	77	8.46	77	246.08	238
78	77899	79747	77	940.67	79	787.45	1848
79	78665	79764	78	708.44	79	804.40	1099
80	80012	82825	79	1,052.49	82	872.66	2813
81	84162	84207	84	208.50	84	253.85	45
82	84435	85020	84	481.88	85	35.79	585
83	85205	85693	85	221.54	85	709.40	488
84	86119	86814	86	167.79	86	862.03	695

85	86848	86878	86	896.36	86	925.95	30
86	87874	88525	87	918.49	88	576.32	651
87	88650	89034	88	701.00	89	84.64	384
88	89164	89954	89	214.37	90	5.14	790
89	90023	90471	90	74.03	90	522.58	448
90	90734	90734	90	784.91	90	785.66	0
91	90993	92061	91	44.37	92	112.42	1068
92	92235	93567	92	286.18	93	619.29	1332
93	93644	94079	93	696.06	94	130.26	435
						Total Distance	56519

Table A-8: Delta Roughness Profile Tamping – Criteria 3mm^2 and Run-in Length 200m and Radius

Delta Roughness Profile Tamping Criteria 3mm^2 Run-in Length 200m and Radius							
ID	**Start Distance**	**End Distance**	**From km**	**From m**	**To km**	**To m**	**Distance (m)**
1	31	731	0	27.04	0	726.86	700
2	895	1288	0	891.64	1	285.34	393
3	1308	1557	1	305.23	1	554.72	249
4	1913	2236	1	911.22	2	229.22	323
5	2257	2617	2	250.21	2	610.32	360
6	2634	2881	2	628.07	2	874.17	247
7	2970	3446	2	964.11	3	448.48	476
8	3459	3690	3	462.18	3	693.09	231
9	4163	4942	4	164.73	4	943.19	779
10	5166	6777	5	168.87	6	778.07	1611
11	7004	7842	7	5.44	7	843.82	838
12	8062	9631	8	71.09	9	640.83	1569
13	9699	10228	9	708.97	10	241.01	529
14	10348	10459	10	360.45	10	471.56	111
15	11808	11972	11	822.12	11	986.18	164
16	12401	13483	12	414.03	13	495.37	1082
17	13705	14669	13	717.08	14	635.87	964
18	15133	15335	15	118.92	15	320.34	202
20	15567	15569	15	552.40	15	555.14	2
21	15885	16666	15	871.05	16	680.80	781
22	16771	18135	16	786.12	18	148.75	1364
23	19212	20212	19	133.31	20	224.76	1000
24	21699	23323	21	714.23	23	337.17	1624
25	22655	23486	22	669.65	23	500.88	831
26	24224	25143	24	242.27	25	158.97	919
27	25534	28318	25	549.64	28	309.61	2784
28	28325	30658	28	316.26	30	673.36	2333
29	30742	31148	30	757.58	31	165.95	406
30	31284	33067	31	301.78	33	82.85	1783
31	33337	33511	33	352.52	33	526.96	174
32	41541	41709	41	554.70	41	722.86	168
33	41980	42208	41	993.87	42	225.59	228
34	42273	42515	42	291.19	42	532.75	242
35	42804	42882	42	822.20	42	900.29	78
36	42937	43921	42	954.52	43	940.04	984
37	45522	46662	45	542.54	46	681.30	1140
38	46741	47080	46	759.45	47	97.10	339
39	47081	48324	47	97.92	48	343.15	1243

40	48636	49195	48	654.98	49	215.20	559
41	49221	50662	49	241.30	50	681.82	1441
42	50822	51764	50	841.56	51	784.30	942
43	51869	52284	51	889.29	52	304.30	415
44	52499	52533	52	518.37	52	553.22	34
45	53543	55262	53	564.92	55	285.75	1719
46	55892	56540	55	915.72	56	603.66	648
47	56609	57059	56	672.60	57	97.63	450
48	57534	58728	57	572.10	58	748.46	1194
49	58732	59249	58	751.76	59	279.82	517
50	59597	59614	59	627.85	59	645.37	17
51	60625	61424	60	660.92	61	452.54	799
52	62207	62578	62	266.63	62	636.99	371
53	62873	62922	62	932.86	62	981.66	49
54	63464	64495	63	526.12	64	544.32	1031
55	65031	65302	65	77.76	65	348.78	271
56	65574	65806	65	620.83	65	852.58	232
57	65998	66047	65	1,044.73	66	12.56	49
58	66087	67002	66	51.98	67	33.29	915
59	67314	67790	67	345.28	67	821.41	476
60	67795	68304	67	826.12	68	334.75	509
61	68468	68604	68	499.37	68	635.61	136
62	68863	69058	68	894.27	69	90.11	195
63	69182	69754	69	213.83	69	785.80	572
64	69811	71058	69	843.20	71	97.59	1247
65	71874	73039	71	913.66	73	74.25	1165
66	73208	74818	73	243.84	74	853.95	1610
67	74911	76767	74	947.69	76	806.99	1856
68	76967	77152	77	8.46	77	193.04	185
69	77885	78639	77	926.33	78	681.79	754
70	78665	79759	78	708.44	79	799.13	1094
71	80012	82787	79	1,052.49	82	834.01	2775
72	82867	83297	82	914.45	83	342.58	430
73	83348	83806	83	392.83	83	850.91	458
75	83815	84346	83	859.97	84	392.43	531
76	84547	85037	84	593.39	85	53.18	490
77	85205	85693	85	221.54	85	709.40	488
78	87874	88525	87	918.49	88	576.32	651
79	88650	89069	88	701.00	89	119.47	419
80	89164	89954	89	214.37	90	5.14	790
81	90344	90471	90	395.60	90	522.58	127
82	90993	92185	91	44.37	92	236.34	1192
83	92405	93443	92	456.02	93	496.02	1038

Total Distance	62781

APPENDIX B

MAINTENACE PLAN

Table B-1: Integrated maintenance plan for condition based tamping

Roughness Alignment ($30mm^2$) Tamping and Roughness Profile ($17mm^2$) Tamping Integration						
From km	**From m**	**To km**	**To m**	**Start Distance**	**End Distance**	**Distance (m)**
0	27	0	834	31	838	807
0	892	3	448	895	3446	2551
3	469	3	480	3466	3478	12
4	110	5	48	4108	5046	938
5	432	6	574	5429	6573	1144
6	993	7	229	6992	7228	236
8	71	8	146	8062	8137	75
8	451	8	710	8442	8701	259
8	794	9	430	8785	9419	634
9	540	9	570	9530	9560	30
9	709	10	241	9699	10228	529
11	933	11	980	11919	11966	47
12	414	13	609	12401	13597	1196
13	724	14	516	13712	14549	837
14	671	14	820	14704	14853	149
15	391	15	586	15405	15601	196
15	845	16	681	15859	16666	807
16	786	18	149	16771	18135	1364
21	714	23	337	21699	23323	1624
22	670	23	502	22655	23488	833
24	242	24	834	24224	24816	592
24	921	25	246	24903	25230	327
25	551	25	638	25535	25622	87
26	51	26	87	26038	26074	36
26	273	27	324	26260	27309	1049
27	627	28	310	27612	28318	706
28	316	28	572	28325	28581	256
28	909	28	965	28918	28974	56
29	84	29	703	29070	29689	619
29	842	30	249	29828	30233	405
30	768	31	166	30752	31148	396
31	583	31	908	31565	31890	325
31	978	32	305	31961	32289	328
32	752	33	83	32735	33067	332
41	565	41	702	41551	41688	137
42	291	42	591	42273	42573	300
42	857	42	867	42840	42850	10
42	955	43	940	42937	43921	984
45	989	46	206	45968	46187	219
46	759	47	84	46741	47066	325

47	98	48	96	47081	48077	996
48	699	48	783	48679	48764	85
48	810	50	76	48791	50056	1265
50	691	51	784	50671	51764	1093
51	871	52	304	51851	52284	433
53	565	53	605	53543	53583	40
53	736	54	79	53714	54056	342
54	242	55	286	54219	55262	1043
55	548	55	557	55524	55533	9
55	914	56	604	55890	56540	650
56	673	57	460	56609	57421	812
57	572	58	748	57534	58728	1194
58	752	59	280	58732	59249	517
59	633	59	681	59602	59650	48
60	961	61	453	60926	61424	498
62	267	62	637	62207	62578	371
63	526	63	742	63464	63680	216
63	978	64	371	63916	64321	405
64	892	64	899	64843	64850	7
65	199	65	318	65153	65271	118
65	560	65	583	65513	65537	24
66	52	67	33	66087	67002	915
67	264	67	821	67233	67790	557
67	826	68	335	67795	68304	509
68	499	68	717	68468	68686	218
68	922	68	997	68891	68965	74
69	214	69	793	69182	69760	578
70	139	71	64	70107	71024	917
71	507	71	571	71467	71531	64
71	914	73	199	71874	73163	1289
73	244	74	460	73208	74424	1216
74	511	75	450	74474	75411	937
75	519	76	756	75480	76716	1236
77	8	77	291	76967	77249	282
77	941	79	787	77899	79747	1848
78	708	79	787	78665	79747	1082
79	1052	82	834	80012	82787	2775
82	840	82	876	82793	82829	36
83	860	84	388	83815	84341	526
84	487	85	38	84440	85021	581
85	222	85	709	85205	85693	488
86	168	87	129	86119	87084	965
87	918	88	576	87874	88525	651
88	701	89	211	88650	89160	510

89	214	90	5	89164	89954	790
90	396	90	523	90344	90471	127
91	44	92	112	90993	92061	1068
92	117	93	233	92065	93180	1115
93	416	93	619	93363	93567	204
93	696	94	559	93644	94508	864
94	666	96	487	94615	96434	1819
91	44	92	112	90993	92061	1068
92	117	93	233	92065	93180	1115
93	416	93	619	93363	93567	204
93	696	94	559	93644	94508	864
94	666	96	487	94615	96434	1819
Total Distance						56164

Table B-2: Integrated maintenance plan for condition performance based tamping (Delta Roughness)

Delta Roughness Alignment (3mm^2) Tamping and Delta Roughness Profile (3mm^2) Tamping Integration						
From km	**From m**	**To km**	**To m**	**Start Distance**	**End Distance**	**Distance (m)**
0	27.04	0	726.86	31	731	700
0	891.64	2	874.17	895	2881	1986
2	964.11	3	448.48	2970	3446	476
3	462.18	5	66.00	3459	5063	1604
5	168.87	6	778.07	5166	6777	1611
7	5.44	9	640.83	7004	9631	2627
9	708.97	10	241.01	9699	10228	529
10	360.45	10	471.56	10348	10459	111
10	647.78	10	682.66	10635	10670	35
11	180.60	11	203.59	11167	11190	23
11	494.51	11	676.66	11481	11663	182
11	822.12	11	986.18	11808	11972	164
12	414.03	13	512.43	12401	13501	1100
13	717.08	14	902.19	13705	14935	1230
15	118.92	15	320.34	15133	15335	202
15	551.65	16	680.80	15566	16666	1100
16	786.12	18	148.75	16771	18135	1364
19	133.31	20	268.23	19212	20255	1043
20	383.54	21	305.92	20371	21291	920
21	556.14	21	557.14	21541	21542	1
21	714.23	23	337.17	21699	23323	1624
22	669.65	23	582.63	22655	23568	913
24	242.27	25	164.71	24224	25149	925
25	549.64	28	309.61	25534	28318	2784
28	316.26	31	165.95	28325	31148	2823
31	301.78	33	82.85	31284	33067	1783
33	352.52	33	526.96	33337	33511	174
41	554.70	41	722.86	41541	41709	168
41	993.87	42	225.59	41980	42208	228
42	291.19	42	532.75	42273	42515	242
42	798.67	42	900.29	42781	42882	101
42	954.52	44	15.68	42937	43997	1060
44	43.59	44	771.56	44025	44753	728
44	968.30	45	267.95	44949	45248	299
45	542.54	46	681.30	45522	46662	1140
46	759.45	47	97.10	46741	47080	339
47	97.92	48	343.15	47081	48324	1243
48	654.98	50	681.82	48636	50662	2026
50	841.56	51	784.30	50822	51764	942

51	868.64	52	304.30	51849	52284	435
52	518.37	52	553.22	52499	52533	34
53	564.92	55	285.75	53543	55262	1719
55	915.72	56	603.66	55892	56540	648
56	646.85	57	144.96	56584	57107	523
57	572.10	58	748.46	57534	58728	1194
58	751.76	59	279.82	58732	59249	517
59	627.85	59	645.37	59597	59614	17
59	768.24	59	816.54	59737	59785	48
60	660.92	61	452.54	60625	61424	799
62	266.63	62	636.99	62207	62578	371
62	932.11	62	982.67	62873	62923	50
63	526.12	64	544.32	63464	64495	1031
65	77.76	65	348.78	65031	65302	271
65	620.83	65	852.58	65574	65806	232
65	1,044.73	66	12.56	65998	66047	49
66	47.87	67	33.29	66083	67002	919
67	345.28	67	821.41	67314	67790	476
67	826.12	68	334.75	67795	68304	509
68	499.37	68	635.61	68468	68604	136
68	894.27	69	90.11	68863	69058	195
69	213.83	69	829.15	69182	69797	615
69	843.20	71	97.59	69811	71058	1247
70	138.98	71	93.58	70107	71054	947
71	490.87	71	554.83	71451	71515	64
71	913.66	73	74.25	71874	73039	1165
73	243.84	76	806.99	73208	76767	3559
77	8.46	77	246.08	76967	77205	238
77	926.33	79	799.13	77885	79764	1879
79	1,052.49	82	872.66	80012	82825	2813
82	914.45	83	342.58	82867	83297	430
83	392.83	83	850.91	83348	83806	458
83	859.97	84	392.43	83815	84346	531
84	481.88	85	53.18	84435	85037	602
85	221.54	85	709.40	85205	85693	488
86	167.79	86	862.03	86119	86814	695
86	896.36	86	925.95	86848	86878	30
87	918.49	88	576.32	87874	88525	651
88	701.00	89	119.47	88650	89069	419
89	214.37	90	5.14	89164	89954	790
90	74.03	90	522.58	90023	90471	448
91	44.37	92	236.34	90993	92185	1192
92	286.18	93	619.29	92235	93567	1332
93	696.06	94	565.42	93644	94514	870

94	666.01	96	487.12	94615	96434	1819
					Total Distance	70005

Table B-3: Radius excluded from maintenance plan

Radius Data Excluded from Maintenance Plan						
Start km	**Start m**	**End km**	**End m**	**Description**	**Length**	**Radius Classification**
7	247	7	347	Transition	100	
7	347	7	744	R:1151.02	396.63	800-7000m
7	744	7	844	Transition	100	
15	119	15	159	Transition	40	
15	159	15	171	R:1430.21	12.13	800-7000m
15	171	15	231	Transition	60	
15	231	15	255	Transition	23.88	
15	255	15	280	R:1602.57	25.41	800-7000m
15	280	15	320	Transition	40	
19	133	19	233	Transition	100	
19	233	20	125	R:612.76	799.74	600-800m
20	125	20	225	Transition	100	
20	384	20	484	Transition	100	
20	484	21	133	R:593.55	647.86	400-600m
21	133	21	233	Transition	100	
30	326	30	426	Transition	100	
30	426	30	573	R:1095.54	147.48	800-7000m
30	573	30	673	Transition	100	
31	302	31	402	Transition	100	
31	402	31	511	R:391.25	109.39	250-400m
31	511	31	571	Transition	60	
31	571	31	583	Straight	11.49	
44	44	44	104	Transition	60	
44	104	44	389	R:394.34	285.16	250-400m
44	389	44	489	Transition	100	
44	489	44	493	Straight	4.45	
44	493	44	573	Transition	80	
44	573	44	672	R:395.59	98.37	250-400m
44	672	44	772	Transition	100	
45	61	45	161	Transition	100	
45	161	45	188	R:403.11	27.29	400-600m
45	188	45	268	Transition	80	
45	543	45	643	Transition	100	
45	643	45	824	R:320.29	181.73	250-400m
45	824	45	924	Transition	100	
46	235	46	335	Transition	100	
46	335	46	581	R:444.06	246.1	400-600m
46	581	46	681	Transition	100	
46	759	46	799	Transition	40	
46	799	46	841	R:1354.28	41.59	800-7000m
46	841	46	919	Transition	78.11	
46	919	46	919	Straight	0	

50	198	50	298	Transition	100	
50	298	50	383	Transition	84.83	
50	383	50	602	R:214.84	219.05	175-250m
50	602	50	682	Transition	80	
52	844	52	904	Transition	60	
52	904	53	303	R:355.64	397.19	250-400m
53	303	53	403	Transition	100	
59	408	59	508	Transition	100	
59	508	59	546	R:299.06	37.98	250-400m
59	546	59	624	Transition	78.89	
59	624	59	624	Straight	0	
59	848	59	888	Transition	40	
59	888	59	940	R:704.63	51.96	600-800m
59	940	59	980	Transition	40	
60	661	60	721	Transition	60	
60	721	60	880	R:229.13	158.77	175-250m
60	880	60	960	Transition	80	
60	960	60	961	Straight	1.56	
65	621	65	701	Transition	80	
65	701	65	793	R:319.96	91.75	250-400m
65	793	65	853	Transition	60	
77	423	77	503	Transition	80	
77	503	77	515	R:303.35	12.39	250-400m
77	515	77	575	Transition	60	
82	982	83	81	Transition	100	
83	81	83	263	R:234.55	182.07	175-250m
83	263	83	343	Transition	80	
83	393	83	493	Transition	100	
83	493	83	751	R:230.44	258.08	175-250m
83	751	83	851	Transition	100	
85	771	85	831	Transition	60	
85	831	86	61	R:306.54	197.11	250-400m
86	61	86	101	Transition	40	
87	257	87	317	Transition	60	
87	317	87	429	R:534.2	112.95	400-600m
87	429	87	489	Transition	60	
87	543	87	583	Transition	40	
87	583	87	619	R:1482.8	35.71	800-7000m
87	619	87	659	Transition	40	
90	74	90	154	Transition	80	
90	154	90	203	R:269.88	49.32	250-400m
90	203	90	283	Transition	80	