RELIABILITY IMPROVEMENT OF RAILWAY INFRASTRUCTURE

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DECLARATION

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ABSTRACT

The railway transportation system is fundamental in sustaining the economic activities of a country, by providing a safe, reliable and relatively affordable means of transporting people and goods; hence, the need to ensure its ongoing reliability is of paramount importance. The principle and applications of rail reliability have been reviewed, and reliability improvement in rail infrastructure has been investigated using failure mode and effect analysis (FMEA).

Reliability improvement is a continuous process that is geared to meeting dynamic changes in operation and stakeholders' expectations. Recently, growth has occurred in the amount of rail transport traffic utilisation undertaken, together with the degradation of the infrastructure involved. Such deterioration has amplified the operating risks, leading to an inadequacy in rail track maintenance and inspection that should have kept abreast with the changes. The result has been increased rail failures, and subsequent derailments.

A case study of the Passenger Rail Agency of South Africa (PRASA) Metrorail maintenance policy was reviewed to evaluate its maintenance strategy and identifying the potential critical failure modes, so as to be able to recommend improvement of its reliability, and, thus, its availability. On the basis of the case study of PRASA Metrorail maintenance strategy and its performance, it is recommended that PRASA Metrorail change its maintenance policy through employing a cluster maintenance strategy for each depot.

Keywords: reliability improvement, railway infrastructure, maintenance management, FMEA, rail track failures.

OPSOMMING

Die spoorwegvervoerstelsel is fundamenteel om die ekonomiese bedrywighede van ’n land te ondersteun deur die voorsiening van ’n veilige, betroubare en betreklik bekostigbare manier om mense en goedere te vervoer. Dus is dit van die allergrootste belang om die voortgesette betroubaarheid daarvan te verseker. Die beginsels en toepassings van spoorbetroubaarheid is hersien en die betroubaarheidsverbetering van spoorinfrastruktuur met behulp van foutmodus-en-effekontleding (“FMEA”) ondersoek.

Betroubaarheidsverbetering is ’n voortdurende proses om tred te hou met dinamiese bedryfsveranderinge sowel as verskuiwings in belanghebbendes se verwagtinge. Die hoeveelheid spoorvervoerverkeer het onlangs beduidend toegeneem, terwyl die betrokke infrastruktuur agteruitgegaan het. Dié agteruitgang het die bedryfsrisiko’s verhoog, en lei tot ontoereikende spoorweginstandhouding en -inspeksie, wat veronderstel was om met die veranderinge tred te gehou het. Dit gee aanleiding tot ’n toename in spoorwegfoute en gevolglike ontsporing.

’n Gevallestudie is van die instandhoudingsbeleid van die Passasierspooragentskap van Suid-Afrika (PRASA) Metrorail onderneem om dié organisasie se instandhoudingstrategie te beoordeel en die moontlike kritieke foutmodusse te bepaal. Die doel hiermee was om verbeteringe in stelselbetroubaarheid en dus ook stelselbeskikbaarheid voor te stel. Op grond van die gevallestudie van die PRASA Metrorail-instandhoudingstrategie en -prestasie, word daar aanbeveel dat PRASA Metrorail sy instandhoudingsbeleid verander deur ’n klusterinstandhoudingsplan vir elke depot in werking te stel.

Trefwoorde: betroubaarheidsverbetering, spoorweginfrastruktuur, instandhoudingsbestuur, FMEA, spoorwegfoute

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Finally, I am grateful to God for the ability, empowerment and grace granted me to pursue this noble study.

"Buy the truth, and sell it not; also wisdom, and instruction, and understanding."
-Proverbs 23:23-

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LIST OF ABBREVIATIONS

BS	British Standard
CBM	Condition-Based Maintenance
CDF	Cumulative Distribution Function
CM	Corrective Maintenance
CTC	Centralised Traffic Control
EMPAC	Enterprise Maintenance Planning and Control
EN	European Standard
FMEA	Failure Mode and Effects Analysis
FMECA	Failure Mode, Effects, and Criticality Analysis
FTA	Fault Tree Analysis
KPI	Key Performance Indicator
LCC	Life Cycle Cost
MAD	Mean Absolute Deviation
MDBF	Mean Distance between Failures
MDT	Mean Downtime
MGT	Million Gross Tonnes
MLD	Mean Logistic Delay
MPH	Miles per Hour
MRT	Mean Repair Time
MTBF	Mean Time between Failures
MTBM	Mean Time between Maintenance
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
NASA	National Aeronautics and Space Administration
NHPP	Non-Homogeneous Poisson Process
OECD	Organisation for Economic Co-Operation And Development
OEE	Overall Equipment Effectiveness
PA	Public Address
PDF	Probability Distribution Function

PERWAY	Permanent Way
PM	Preventive Maintenance
PPIAF	Public–Private Infrastructure Advisory Facility
PRASA	Passenger Rail Agency of South Africa
RAM	Reliability, Availability, and Maintainability
RAMS	reliability, availability, maintainability, and safety
RCF	rolling contact fatigue
RCM	reliability-centred maintenance
RPN	risk probability number
RSR	Rail Safety Regulator
RTF	run-to-failure
SLA	service level agreement
TFR	Transnet Freight Rail
UIC	*Union Internationale des Chemins de fer* (International Union of Railways)
US	United States

CHAPTER ONE

1. INTRODUCTION

1.1 BACKGROUND

The railway transportation system plays a vital role in sustaining the economic activities of a country by providing a safe, reliable, and relatively affordable means of transporting both people and goods. Rail transport in South Africa is a major means of transportation, transporting about 2.4 million passengers per day (PRASA, 2011).

As railway transport system operations and customers' expectations have evolved over the last several decades, railway service operators have been finding ways of improving their operations, so as to ensure the maintenance of a safe and reliable railway transport system at a relatively low cost, and within the terms of the service level agreement (SLA). At the same time, rail transport, especially in South Africa, has been experiencing challenges regarding its operation, especially in terms of the reliability of its aged infrastructure, and the increased utilisation of its physical assets (Conradie, 2012). The reliability of railway infrastructure is fundamental for ensuring the efficient and effective operation of rail transport.

The reliability and maintenance of the railway system infrastructure has been a subject of research by several scholars (Åhrén & Parida, 2008; Inazu, 2003; Marco *et al.*, 2012; PPIAF, 2011; RAIL, 2002). Most studies have tended to utilise performance measurement to evaluate the reliability of the railway system. Such models as that of life cycle cost (LCC) have been used for making maintenance decisions, and for assessing conditions of reliability, availability, maintainability, and safety (RAMS). Additional models include the optimum maintenance strategy and failure mode effects and criticality analysis (FMECA), among many others.

Railway infrastructure design modification, and the change management of its system, is a challenging process that requires ongoing attention after the initial design and installation, because most of the infrastructure concerned, such as rail track, is designed for a lifetime of about 30 - 60 years (Michas (2012) and Tranco, (2013)). The lifetime involved depends on the environment and on the usage concerned, even though a maintenance strategy is used to extend some of the physical assets' lifespan. A variety of strategies are used in many railway system for the maintenance of the different systems involved, including those that are regulated by government standard, as well as those that require preventive and condition-based maintenance (CBM). However, due to the complexity of railway system dependability, no single global method, or standard of maintenance management system, is best suited for all railway transport systems. This is because of the different operating conditions, the varied skills levels required, and the prevailing environment, as such a maintenance strategy has to be developed on the basis of the existing circumstances.

The railway infrastructure consists of such components as tracks (railway lines), bridges and platforms, signalling infrastructure (robots, points machines, and relay rooms), telecommunications systems (surveillance cameras, public address [PA] systems, and centralised traffic control [CTC]), and electrical systems (cables, power lines, and gantries) (Espling, 2007). These components are maintained according to diverse maintenance strategies that have been developed over the years. Due to their integrated reliance on each other, the reliability of a subsystem is critical to the total reliability of the overall railway transport system.

1.2 PROBLEM STATEMENT AND MOTIVATION

Railway transport operation is both capital and labour-intensive; therefore, railway managers are continuously researching maintenance management improvement techniques, while they are striving to provide high-quality service. In this way, they make an effort to keep the operation competitive, despite the rising cost of maintenance, and the possibility of a deteriorating infrastructure (ORR, 2010). It has, accordingly, become imperative to evaluate the current maintenance strategy system with regard to reliability, safety, and the key performance indicators (KPIs) that are used to measure the performance of the infrastructure system that supports the service needs.

With performance measurements being used to appraise the reliability of a system, a consistent and objective measuring system is required. Such performance measurement uses a benchmarking system to evaluate the different scenarios that can affect the reliability of the railway system. The problem with the former system is that railway infrastructure systems are impacted by variables that are specific to a location, such as the operating environment, the traffic volume, and usage, among others (Patra, 2009).

The annual expenditure on the railway maintenance of Japan JR East, which operates 12 000 trains per day, is 29% of its annual operating expenditure (Inazu, 2003). Such expenditure forms part of a global trend in the upkeep of railway systems throughout the world, with similar investment having taken place in the South African passenger railway system, in regards to its extended capacity in terms of its infrastructure and rolling stock (PRASA, 2012). However, together with the massive sums that are required to be spent in terms of capital investment, it is important to find ways of optimising the current maintenance strategy, and of using the historical data, and the relevant information, to improve the reliability of the future railway infrastructure.

The cost of delays, of customer dissatisfaction, of inefficient service, of lost revenue, and of lost time due to railway infrastructure failures cannot be overemphasised. An example of a case study of the Metrorail South Africa infrastructure highlights the fact that weaknesses in the infrastructure contribute to 2% of the cancellations and 21% of the delays experienced in the Western Cape rail system (Conradie, 2012). The aging of most South African railway infrastructure assets beyond their anticipated economic lifetime has resulted in significantly high costs in terms of required refurbishment and maintenance (PRASA, 2011). See APPENDIX A for details of the capacity of the South African train commuter service.

1.3 RESEARCH OBJECTIVES

The main objectives of this thesis are to:

a) Investigate the improvement of railway infrastructure reliability by highlighting areas of risk and non-conformity.
b) To get an improved categorization of the most critical failure modes in railway track infrastructure.

1.4 SCOPE OF STUDY

The scope of the current study is limited to improvement in the railway infrastructure, with an emphasis on railway track. The interaction of subsystems, as it affects the reliability of the whole railway transport system, was not evaluated.

1.5 RESEARCH METHODOLOGY

The study approach is based on applied research i.e. both quantitative and qualitative methods to obtain improved categorization of the most critical failure modes in railway track infrastructure.

The information was gathered from literature study, railway depot visitation, discussions and consultation with reliability engineers from Passenger Rail Agency of South Africa (PRASA).

The theoretical frame work for the research was based on Reliability centred maintenance (RCM) functional failure analysis procedure:

- collect and analyse field data
- perform functional partitioning – by selecting region to be analysed
- identify functions, functional failures, failures mode, effects and criticality analysis
- evaluate failure consequence using risk priority numbers
- recommend maintenance strategy

1.6 THESIS OUTLINE

The layout of this thesis is structured into seven chapters and three appendices. The sequence is aligned to the research objectives and the research design.

Chapter 1: Introduction

Chapter 1 is the introductory section which provides the description of the research background, research problem, research objectives and lastly the thesis layout.

Chapter 2: Literature Review

Chapter 2 provides literature review of key concepts in reliability methods, performance measures, reliability improvement and benchmarking. The literature review is focused on the overview of major components that constitute reliability improvement methods and fundamentals of railway track reliability in railway infrastructure.

Chapter 3: Reliability Availability Maintainability & Safety (RAMS)

Chapter 3 describes reliability improvement methodologies of reliability availability and maintainability (RAM) and discusses the applicability of these strategies in railway track reliability. The role of RAMS and factors affecting RAMS as a strategic planning tool for railway track were discussed.

Chapter 4: Reliability Centred Maintenance (RCM)

Reliability centred maintenance (RCM) program and principles are elaborated. These strategies are used by maintenance managers to improve system reliabilities.

Chapter 5: Railway Track Failures

Chapter 5 provides failure statistics of railway track and classification. The section also evaluated rail track failures.

Chapter 6: Reliability Improvement

Chapter 6 describes the concept of reliability improvement and introduces principle, and purpose of FMEA.

Chapter 7: Reliability Improvement

Chapter 7 describes the frame work of reliability improvement and case study of PRASA Metrorail failures modes and effects.

Chapter 8: Conclusion and Recommendation

Chapter 8 provides a summary and discussion of this research objective, its applicability and closed with concluding remarks and recommendations for further study.

CHAPTER TWO

2. KEY RELIABILITY CONCEPTS

Reliability is the probability that an item will perform its intended function for a designated period of time without failure, under specified conditions (Singpurwalla, 2013). In terms of such a perspective, unreliability in public transport can be defined as the shortcomings that take place in a transport system, in which the actual departure and arrival times deviate from those that are given on the official timetable (Rietveld, Bruinsma & Van Vuuren, 2001). Reliability in a railway system is often differently described by users, in comparison to how it is described by network operators. The rail user/passenger tends to see such reliability in terms of the transport system operating in line with set schedules that are not subject to delay. In contrast, for the network operator, reliability can be defined in several different ways, depending on the SLA, and on the key performance index, involved (OECD, 2010). Reliability in railway systems requires benchmarking according to the same standards of measurement. Therefore, the distance travelled and the axle loads need to be taken into consideration before the performance of a particular railway system can be evaluated.

The reliability of a system can be improved by avoiding failure. Such avoidance of failure can be achieved by improving the availability, the components design, and the maintenance of the individual components concerned. Understanding the failure mechanism, and identifying the critical components and the subsystems involved, would also assist in improving the reliability of the system, as doing so would contribute towards the development of a periodical maintenance and inspection strategy (Barabady, 2005). Reliability can also be improved through the adoption, and through the implementation, of effective policies early on in the design stage of railway system components. The policies concerned relate to such items as the product development cycle, RAMS, reliability modelling, and others.

2.1 RELIABILITY AVAILABILITY MAINTAINABILITY & SAFETY (RAMS)

The railway infrastructure consists of several fixed physical assets that support the transportation of passengers and freight. Railway infrastructure systems like track, signal and train control, and electrification are maintained according to such diverse maintenance strategies as RAMS, with the techniques concerned being used to forecast system failures that become apparent from the analysis of operational field data. The subsequent paragraphs contain a discussion and review of reliability and rail maintenance strategies.

Simoes' (2008) dissertation included a RAMS analysis of railway track infrastructure using the RAMS technique for forecasting failure, as well as their associated cost. In Arjen and Egbert's (2001) study, which was aimed at improving the performance of rail during the design phase of railway construction, the two authors emphasised the importance of RAMS in the phase concerned.

Patra (2009) conducted a study of RAMS and LCC, in which the researcher demonstrated the application of RAMS in railway maintenance planning. In the same study, he also presented methods and models for estimating RAMS targets, based on the service quality requirements of the railway infrastructure. However, the study omitted to cover the interaction effects of the maintenance decision made on the different subsystems of railway infrastructure.

Railway availability is one of the performance measures in terms of which railway stakeholders evaluate the reliability of a railway system. Patra *et al.*'s (2010) paper on the availability targets of a rail infrastructure system was based on capacity and punctuality requirements. The data obtained for their study was used to develop a model using Monte Carlo simulation and Petri-Nets to establish the relationship of availability, capacity, and punctuality, and how the relationship concerned affects the infrastructure availability, in terms of train delays and capacity.

The RAMS concept and its applicability in railway infrastructure would be further discussed in CHAPTER THREE.

2.2 RELIABILITY CENTRED MAINTENANCE (RCM)

Reliability-centred maintenance (RCM) is another method that is used by maintenance managers in public and private organisations to improve OEE, while controlling the life cycle and quality assurance involved (NASA, 2008). RCM principles and techniques have been used by the National Aeronautics and Space Administration (NASA) to improve, and to manage, more than 44 million square feet of facilities and the associated billions of US dollars of collateral equipment. This was achieved by using predictive testing and inspection, FMEA and many other improvement techniques.

RCM is currently used extensively in developing maintenance strategies for railway tracks (RAIL, 2002). RCM concept and its applicability in railway infrastructure would be further discussed in CHAPTER FOUR.

2.3 PERFORMANCE MEASURES

Performance measures are used to motivate for improvement, and also to benchmark performance across similar systems. Performance measures in railway systems have traditionally been evaluated in terms of such metrics as mean time between failures (MTBF) and mean time to repair (MTTR). Thomas and Uday (2004) undertook a study on the use of maintenance performance indicators on railway infrastructure, using Sweden Banverket as their case study. In their case study they identified four maintenance performance indicators within a hierarchical goal structure. In addition, they also concluded that a link-and-effect model is required to define critical strategic areas that must be supported by a number of performance indicators, so as to cover the whole spectrum of both the performance, and the outcomes from the maintenance process.

Improving reliability on surface transport networks derived from the Organisation for Economic Co-operation and Development (OECD) (2010) highlights the reliability perspective from the perspective of both the user and the network provider. The indices concerned, require aligning and integrating to obtain a unified benchmark that is acceptable to both parties. Figure 2-1shows the schema of integrating reliability from the perspective of both.

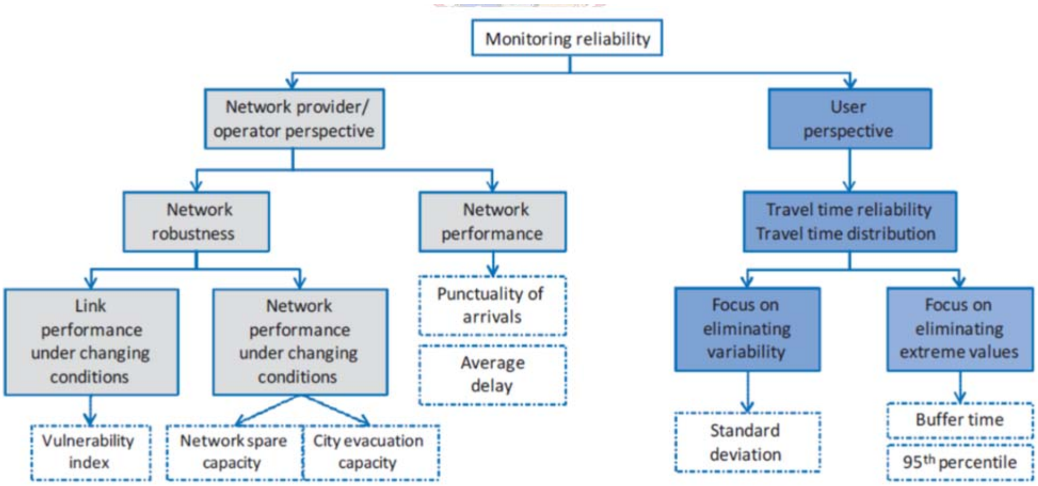


Figure 2-1: Network and User Perspective of Reliability (OECD, 2010).

2.4 RELIABILITY IMPROVEMENT

The reliability analysis and the evaluation of physical assets is usually performed during the design phase of the equipment, after the design and the commissioning have taken place, with reliability becoming part of the quality improvement process (Billinton & Allan, 1992). Hence, reliability is a continuous task that must be undertaken to ensure that a system continues to operate according to the appropriate design and operational requirements. Marco *et al.* (2012) undertook a study of reliability improvement, using a methodology consisting of a family-based approach aimed at achieving equipment reliability. The purpose of the study was to identify families of railway items that could be assigned the same reliability targets, as well as being used to build a taxonomy of the features of railway infrastructure systems.

Blischke and Murthy (2003) assert that reliability is one of the most important considerations defining the quality of a product or system. The two researchers describe how reliability can be achieved by means of the exertion of design and quality assurance efforts, as well as by means of the choice of materials, production, proper maintenance, and other related decisions and activities. Accordingly, it can be seen that achieving the high reliability of a product, or of a system, is a combination of such interrelated and interdependent disciplines as engineering science, statistics, computer science, operational analysis, and management, among others.

Famurewa (2012), in his dissertation, identified maintenance improvement as the basis for capacity enhancement in railway network. Such improvement can be achieved by introducing changes to the concept, the procedure, the techniques, the methods, the resources, and the level of maintenance. Rietveld *et al.* (2001) enumerated the attributes of reliability measures in railway systems as consisting of the following:

- The probability of punctuality of train arrival.
- The probability of an early departure.
- The mean difference between the expected arrival time and the scheduled arrival time.
- The mean delay of an arrival, given that one arrives late.
- The mean delay of an arrival, given that one arrives more than X minutes late.
- The standard deviation of arrival times.
- The adjusted standard deviation of arrival times (ignoring early arrivals).

Various other more complex measures were also enumerated to represent the seriousness of the unreliability involved.

2.5 BENCHMARKING

Benchmarking is a method that is used to compare similar business process and performance metrics with best industry practices. Different benchmarking methodologies (Camp, 1989; NASA, 2008; OECD, 2000; PPIAF, 2011) exist. Camp (1989), one of the pioneers of benchmarking, described twelve stage guides for benchmarking a process or system. NASA (2008) also highlights benchmarking in its RCM guide, in terms of which KPIs are used to establish benchmarking methodologies.

Benchmarking is used in the industry for the business improvement of such programmes as maintenance, overall equipment effectiveness (OEE), RCMs, and cost-effectiveness. Benchmarking in the railway industry is defined as: “the process of comparing performance of one entity (the subject railway) to the performance of other entities (the benchmark companies) to identify best practices and opportunities for improvement” (PPIAF, 2011).

Benchmarking is both a qualitative indicator, and a quantitative analysis, of industry best practice, in terms of which it compares the statistics of one Railway Company with those of another, using the same metrics indices. Figure 2-2 is a flow diagram showing the process undergone in the benchmarking cycle (Adeney *et al.*, 2003). The flow diagram shows how benchmarking can be used to improve business process, quality of service, and effectiveness, as well as to encourage change management.

Figure 2-2: Benchmarking Cycle (Adeney et al., 2003).

The Public–Private Infrastructure Advisory Facility (PPIAF) (2011) describes how detailed railway benchmark indicators can be used to measure, and to improve, performance. Benchmarking in railway systems is, hence, important for achieving reliability improvement, because it provides the information that is required to show the shareholders the performance of their company, as compared to the performance of other railway industries, and to the source investment supplied by the government.

Benchmarking is also used as a tool for charging fares relating to the regulation and monitoring of contractual performance (Adeney *et al.*, 2003). Caution needs to be applied when benchmarking different railway industries, because the performance indicators are dependent on such variables as climatic conditions, demographic structure, differences in culture, national administration, statistical definitions, and the location of the railway station (OECD, 2000). Therefore, benchmarking has to be done objectively, by comparing similar railways with closely similar characteristics and operating conditions. The PPIAF (2011) describes the characteristics involved as:

- Size/capacity
- Traffic volume and type
- Traffic mix and journey types (e.g. passenger or freight)
- Traffic density
- Standardised technology level

Hence, benchmarking is useful in regulating costs, as well as in matters of trend development in the industry, best practice, and cost-effectiveness.

2.6 CHAPTER SUMMARY

Chapter Two provides the context of the problem statement with the aim of introducing the several areas of interest which this study touches on. A literature review of RAMS, RCM, reliability improvement and benchmarking was conducted and presented in this chapter. The literature review showed that research work is required to develop a frame work of railway track benchmarking and also a dynamic reliability improvement strategy.

CHAPTER THREE

3. RELIABILITY, AVAILABILITY, MAINTAINABILITY, & SAFETY (RAMS)

RAMS is one of the techniques that is used by maintenance managers to make effective maintenance decisions. Use of the technique helps to identify the different maintenance options that are required to ensure that the equipment operates within its design, safety, and service requirements. RAMS, in terms of the railway system, is used to define the level of confidence involved, so that the system(s) can guarantee a defined amount of rail traffic within a set time period.

Figure 3-1 shows the relationship of dependability and attributes during a system life cycle.

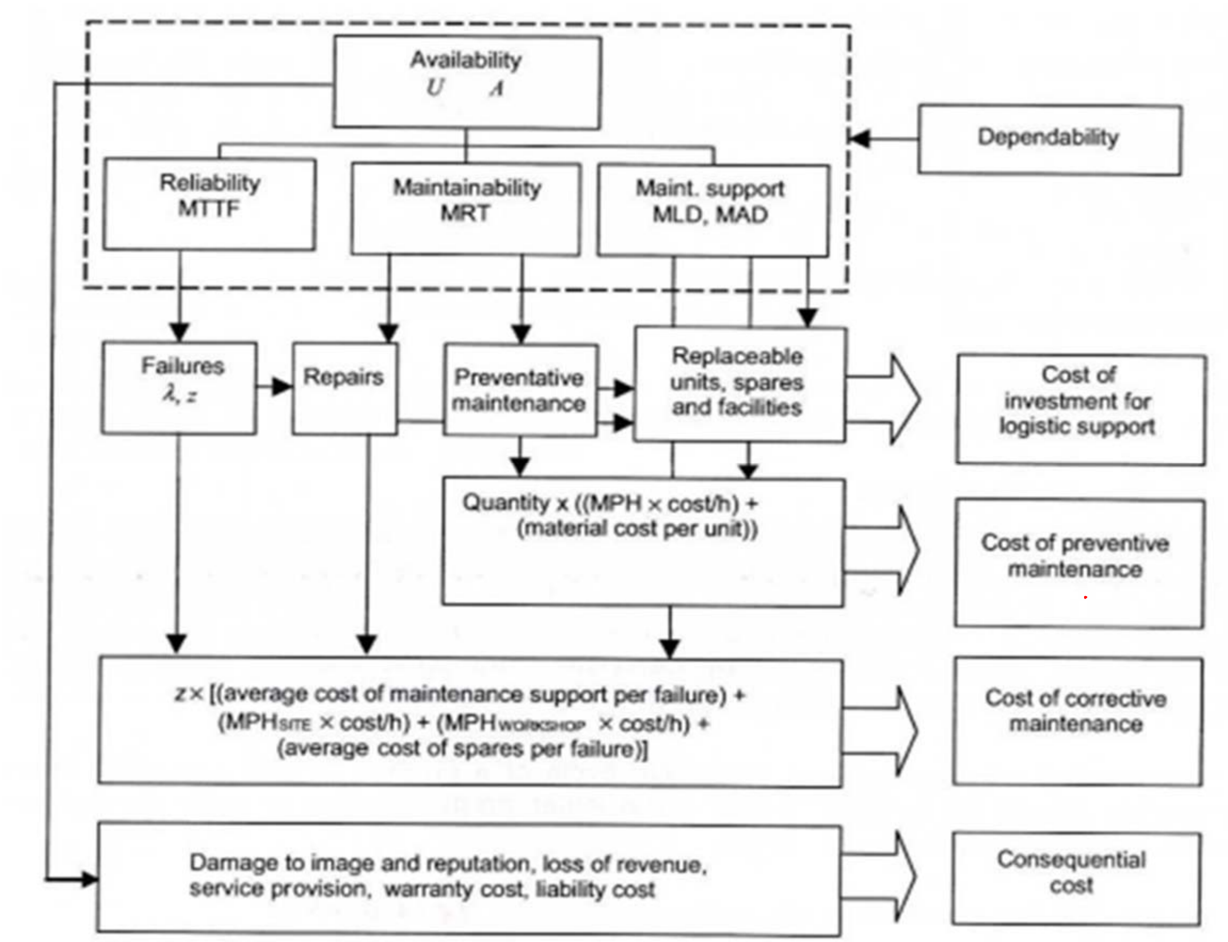


Figure 3-1: Dependability Relationships (IEC 60300:3-3, 2004).

The flow diagram above shows that dependability is a function of a system's reliability, availability, maintainability, and maintenance support.

Reliability is defined by *Gold Book IEEE STD 493, 2007* as the ability of a component or system to perform required functions under stated conditions for a stated period of time. Reliability is generally calculated using failure rate data $\lambda_s(t)$ over a time interval ($t_1 \rightarrow t_2$) by applying the following equations:

$$R_s(t_1 \rightarrow t_2) = \exp\left(-\int_{t_1}^{t_2} \lambda_s(t)\,dt\right) \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Reliability is traditionally quantified as MTBF for a repairable system, and as mean time to failure (MTTF) for a non-repairable system. The following equations hold true in this respect:

$$\text{MTBF} = \frac{\text{Total time}}{\text{Number of failures}} \ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

$$\text{MTTF} = \frac{\text{Total time}}{\text{Number of units under test}} \ldots\ldots\ldots\ldots\ldots\ldots \text{(3)}$$

MTBF is not a true picture of system reliability, despite it being an average failure rate, as it does not give the picture of failure range within a specified period of time. As a result, the use of a probability computation is preferable.

Dhudsia (1992) illustrates how a reliability programme can impact on the life cycle cost (LCC) of equipment. In Figure 3-2, it can be seen that a well-established reliability study can improve the total LCC of equipment, thus reducing the operational cost involved. This information is important during the design or procurement phase of equipment or a system.

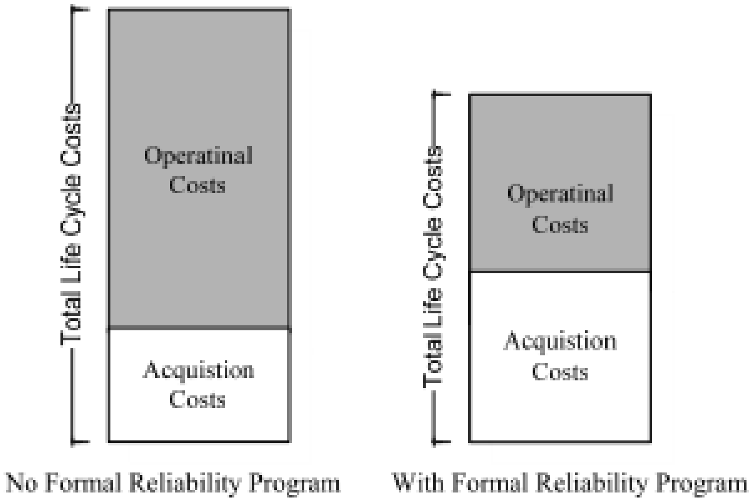


Figure 3-2: Impact of the Reliability Implication on LCC (Dhudsia, 1992).

Bagowsky (1961) defines reliability "as the probability of a device performing its purpose adequately for the period of time intended under the operating conditions encountered". In terms of this definition, the different components of reliability can be grouped into the following clusters:

- Probability of desired performance
- Period of use
- Operating conditions

The bathtub curve is used to describe failure rate versus the duration of the service life of equipment, using RAMS (Simões, 2008). Figure 3-3 below indicates the reliability bathtub curve. It is used as a graphic model to show the three key periods of system failure during the lifespan involved.

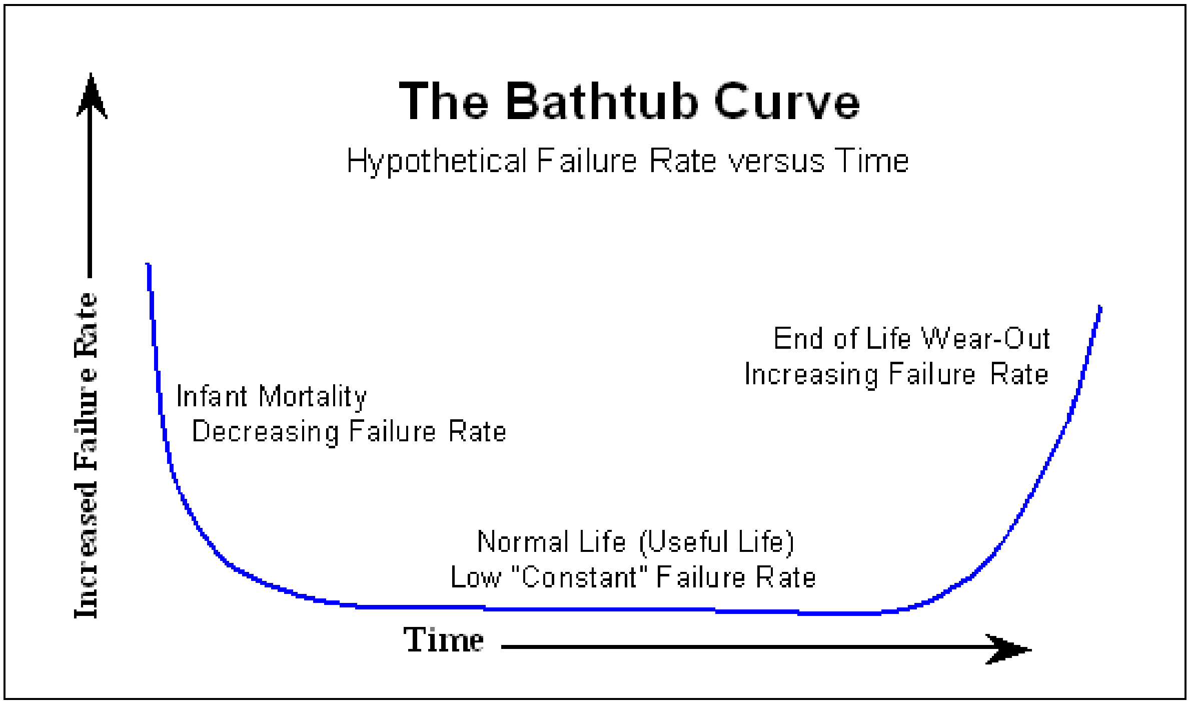


Figure 3-3: Reliability Bathtub Curve (Wilkins, 2002).

Availability, as defined by IEC 60050-191, 2002 is the ability of a product to be in a state to perform a required function under given conditions at a given instant of time, or over a given time interval, assuming that the required external resources are provided. Availability is expressed as the following equations:

$$A = \frac{\text{Uptme}}{(\text{Uptime+Downtime})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4)$$

$$A_{\text{inherent}} = \frac{\text{MTBF}}{(\text{MTBF+MTTR})} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$A_{\text{operational}} = \text{MTBM}/(\text{MTBM} + \text{MDT}) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where:

MTBM: Mean Time between Maintenance

MDT: Mean Down Time

.

Equation 5 is used to calculate the availability of a system's inherent availability during a product design phase, whereas equation 6 is used to calculate the availability that is used in an operational environment, because the equation accounts for inadequacies in the plant set-up.

Table 3-1 reflects the relationship between reliability, maintainability, and availability. From the table, an increase in maintainability can be seen to entail a decrease in the amount of time that it takes to perform maintenance actions, and, when the reliability is held constant, it can be seen that it does not directly imply a high availability. As the length of time for repairs increases, the availability of the system decreases. Therefore, a system with a low reliability could have a high availability if the amount of time required for repairs is short.

Table 3-1: Relationship between Availability & Reliability.

Reliability	Maintainability	Availability
Constant	Decreases	Decreases
Constant	Increases	Increases
Increases	Constant	Increases
Decreases	Constant	Decreases

Maintainability is defined by IEC 60050-191, 2002 as the probability that a given active maintenance action, for an item under given conditions of use, can be carried out within a stated time interval, when the maintenance is performed under stated conditions, and using stated procedures and resources.

Maintainability characteristics are usually determined, or recommended, by original equipment manufacturers. The manufacturers concerned usually describe the maintenance procedures that are required to be followed, and also determine the interval time for repair/service. Maintainability, which is traditionally measured by MTTR, is expressed mathematically as:

$$M_{(t)} = 1 - \exp\left(\frac{-t}{\mathrm{MTTR}}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (7)$$

$$M_{(t)} = 1 - \exp(-\mu t) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Where μ is the expected mean maintenance rate (constant for exponential distribution), and MTTR is the average of how fast the system is repaired.

Example of PRASA application of MTTR; for a financial year the maintenance record shows that they were 217 failure events and 34 282 minutes of outage time. PRASA assumes that the failure rate (from historical failure events) is constant, hence exponential distributed.

Therefore the MTTR;

$$\mathrm{MTTR} = \frac{34282}{217} = 158 \text{ minutes}$$

$$\mu(\text{repair rate}) = \frac{1}{\mathrm{MTTR}} = \frac{1}{158} = 0.006 \frac{\text{repairs}}{\text{minute}}$$

Maintainability can then be calculated for 200 minutes using the repair rate:

$$M(200) = 1 - e^{-\mu t} = 1 - e^{-(0.006)(200)} = 0.699$$

Hence there is 70% probability of meeting the maintenance goal at 200 minutes.

Maintenance management is the alignment of technical and administrative management (i.e. the systematic approach to planning, organising, monitoring, and costing) action plans aimed at ensuring system operation, upkeep, and restoration to the state where the system is able to perform its intended function once again. Management is a continuous dynamic strategy that is employed to meet system, or operational, requirements.

Maintenance strategies are continuous activities that are used to ensure that system components are systematically maintained by the most economical and technical means. Some of the strategies concerned are:

- Preventive maintenance (PM)
- Predictive maintenance
- Opportunity maintenance
- Breakdown/unplanned maintenance
- Design out maintenance

The maintenance department in an organisation is responsible for ensuring optimum plant availability and maintenance resource utilisation. The following are some of the functions of a maintenance department:

- Maintenance of installed physical assets
- Installation of new physical assets
- PM tasks of inspection of existing physical assets
- Condition monitoring task of monitoring faults and failures
- Modification of existing physical assets
- Management of inventory

- Supervision of human resources and record keeping

Safety entails ensuring that all maintenance, operation, and design activities do not cause harm to people, to the environment, or to any other assets during their life cycle. Safety, which has become a key concern in any engineering activities, is used to measure the key performance of an operation; thus, it can impact on the reliability and availability of a system. Safety can be grouped into three categories:

- Physical asset protection
- Personal protection
- Environment protection.

Failure mode, effect and criticality analysis (FMECA), which is supplementary to RAM analysis, is extensively used to achieve reliability and safety in railway infrastructure by identifying safety (both passenger and public) and reliability critical systems that affect rail travel availability.

3.1 RELIABILITY STATISTICAL MODELS

As RAM parameters are probabilistic, they are analysed using continuous and discrete random variables, and statistical distributions. In modelling the reliability of a system, a test is usually conducted on the components of the system, or on the basis of failure data that are obtained from the operational history concerned. James (2003) performed a safety and reliability analysis based on mathematical statistics, in terms of which railway infrastructures were analysed, using a stochastic model. Accordingly, the statistical functions involved can be seen to be important in terms of the reliability analysis of railway infrastructure systems.

Table 3-2 below illustrates the cumulative distribution function (CDF), the probability distribution function (PDF), and the failure rate of statistical models that are used in analysing component reliability.

Table 3-2: Reliability Statistical Models.

Name	**Cumulative Distribution Function**	**Probability Distribution Function**	**Failure rate**	**References**
Weibull	$F(x) = \begin{cases} 1 - e^{-\left(\frac{x-\gamma}{\alpha}\right)^{\beta}} & x \geq \gamma \\ 0 & x < \gamma \end{cases}$	$f(x) = \begin{cases} \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta} e^{-\left(\frac{x-\gamma}{\alpha}\right)^{\beta}} & x \geq \gamma \\ 0 & x < \gamma \end{cases}$	$\lambda(t) = \frac{\beta}{\alpha}\left(\frac{1-\gamma}{\alpha}\right)^{\beta-1}$	Simoes' (2008)
Exponential	$F(x) = \begin{cases} 1 - e^{-\lambda} & x \geq 0 \\ 0 & x < 0 \end{cases}$	$f(x) = \begin{cases} \lambda e^{-\lambda x} & x > 0 \\ 0 & x \leq 0 \end{cases}$	$\lambda(t) = \lambda$	Simoes' (2008)
Log-linear (NHPP)	-	-	$\rho_1(t) = \exp(\alpha_0 + \alpha_1 t)$	Vlok (2014)
Power Law (NHPP)	-	-	$\rho_2(t) = \lambda\beta t^{\beta-1}$	Vlok, (2014)

3.1.1 WEIBULL DISTRIBUTION

The Weibull distribution is one of the most widely used distributions in reliability and maintainability analysis (Al-Fawzan, 2000). The distribution is used to model such items as material strength, and times-to-failure of electronic and mechanical components. It is characterised by a minimum value asymptotic distribution, which is useful in the analysis of lifetime data, where the failure time is dependent on the weakest link present. The Weibull distribution has three basic parameters (Chikrel-Mezouar, 2010), namely:

- Shaping parameter
- Scaling parameter
- Location parameter

The Weibull can be used to express the wear-out, or the random failure, period of the bathtub curve.

3.1.2 EXPONENTIAL DISTRIBUTION

The exponential distribution is a continuous probability distribution that describes the time between events in terms of a Poisson process. This is due to its constant hazard rate, which results from combining failure rates into a single number. It is, therefore, widely used in predictions involving electronic equipment, and complex systems, with independent failure rates.

3.1.3 NON-HOMOGENOUS POISSON PROCESS (NHPP) MODEL

NHPP model can address trends, aging or reliability growth of repairable systems. The prerequisite of modelling NHPP is to check the presence of aging in the system (Vlok, 2014). This is carried out by trend analysis using the statistical historical data.

Railway track degrades due to tonnage accumulation on the track from train movement, hence degradation will continue to increase as the cumulative traffic and tonnage continues. Railway track defects and failures are considered a repairable system (Simões, 2008 and Chattopadhyay et al. (2006)) hence it can be modelled as a stochastic point process using Non-homogeneous Poisson process (NHPP).

3.2 FACTORS THAT INFLUENCE RAMS IN RAILWAY INFRASTRUCTURE

The factors that influence RAMS in railway systems, which are shown in Figure 3-4 are grouped into three main categories of condition: system; operating; and maintenance. The conditions concerned interact to affect the overall railway system's RAMS.

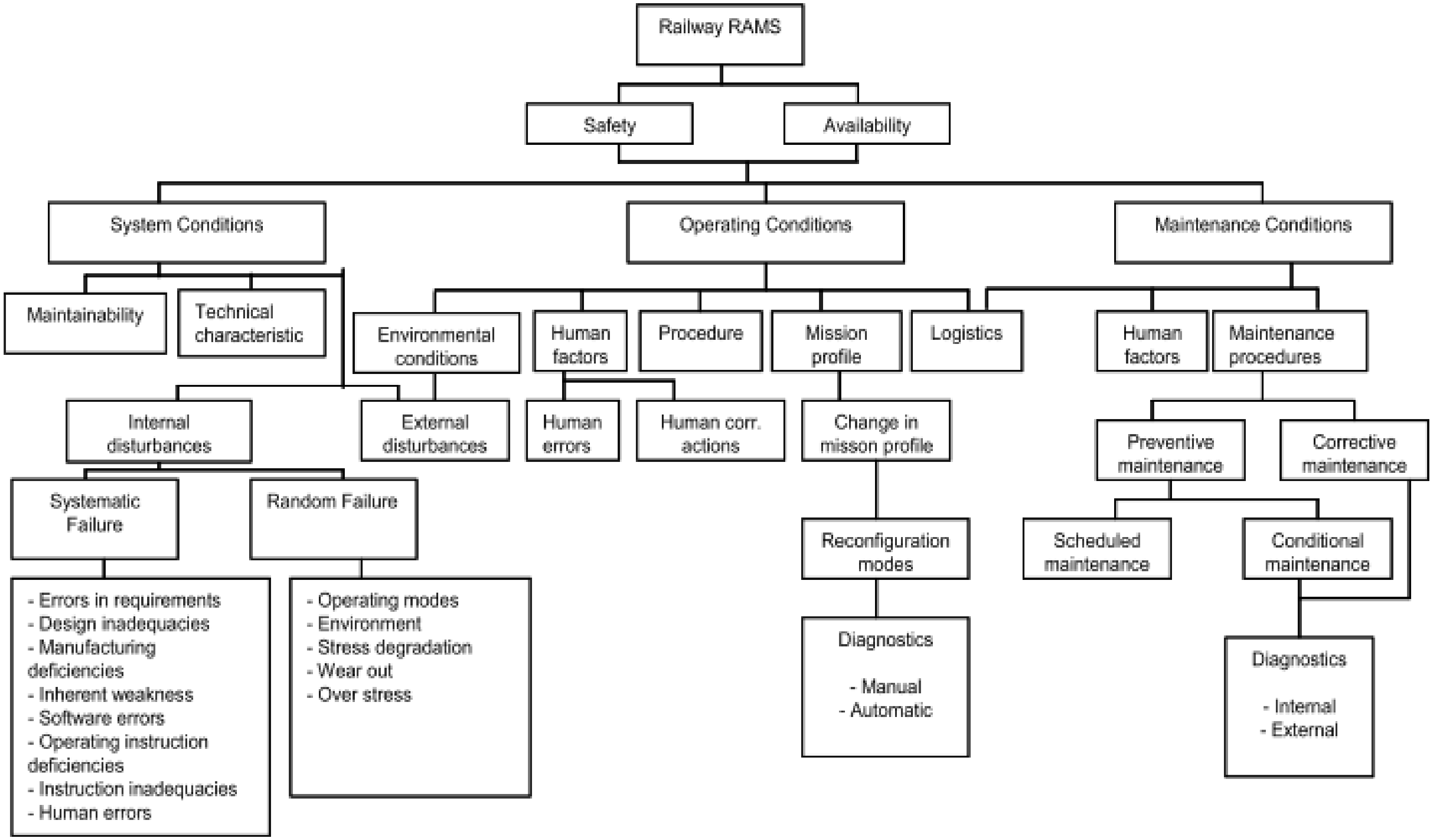


Figure 3-4: Factors Influencing Railway RAMS (BS EN 50126-1, 1999).

3.3 RAMS ANALYSIS OF RAIL TRACK

The RAMS analysis of a railway track comprises several components, including: rails; switches; fasteners; sleepers; tie plates; rail anchors; ballast; and sub-grade. It also includes consideration of each of the following components' failure impact on the reliability, the availability, the maintainability, and the safety of the total rail track system. To perform a RAMS analysis of a track, a good understanding of the failure modes, and of the available analysis tools, as described by the process framework of Guthrie, Farquharson, Bonnett and Bjoro (1990), is crucial.

RAMS analysis of a railway track system is used to optimise the maintenance strategy of the system, and, thus, its reliability. The RAMS process of railway track uses the failure history of the system to extrapolate probabilities of future performance. Table 3-3, which lists the process tools that are used to perform a typical RAM study, refers to such models as the reliability block diagram, which can be used to integrate reliability and maintainability parameters (Patra, 2007).

Table 3-3: RAM Process and Tools (Guthrie *et al.*, 1990).

Management	RAM programme plan RAM review process
Modelling and analysis	Block diagram analysis FMECA FTA Markov analysis Event-tree analysis Cause–consequence analysis Maintenance-engineering analysis Life-cycle cost analysis Sneak-circuit analysis Tolerance analysis Part-count analysis Growth analysis

Testing	RAM test plan Test, analyse, and fix process (growth testing) Environmental stress screening Reliability qualification testing Production reliability acceptance testing
Data collection and analysis	Generic data development Failure reporting, analysis and corrective action system
System design and logistics	Redundancy and diversity Modularity and diagnostics Reliability vs. maintainability trade-off studies Part control programme RAM procurement specifications PM programme Corrective maintenance programme Spare-part programme

3.4 CHAPTER SUMMARY

RAMS was introduced as an analysis tool of a railway track system which can be used to optimise the maintenance strategy of the system, and, thus, its reliability. The RAMS process of railway track uses the failure history of the system to extrapolate probabilities of future performance.

RAM analysis, is extensively used to achieve reliability and safety in railway infrastructure by identifying safety (both passenger and public) and reliability critical systems that affect rail travel availability and finally, the role of RAMS and factors affecting RAMS was discussed.

CHAPTER FOUR

4. RELIABILITY-CENTRED MAINTENANCE (RCM)

Maintenance management strategies have been evolving, with one of the methodologies that have been gaining recognition being RCM. RCM is a continuous decision-making process for identifying the best-suited maintenance requirements, as well as management decisions and actions, for a system, in accordance with its LCC and safety. Such maintenance is also defined as "a method to identify and select failure management policies to efficiently achieve the required safety, availability and economy of operation" (BS EN 60300-3-11, 2009). The definition in BS EN 60300-3-11 encompasses the management of failures, as well as the safety and decision-making process. The basic actions that are undertaken in an RCM programme, which are elaborated on in the subsequent paragraph, are as follows:

- Initiation and planning
- Functional failure analysis
- Task selection
- Implementation
- Continuous improvement

The tasks identified can be applied to any physical asset. The overview of the RCM is shown in Figure 4-1.

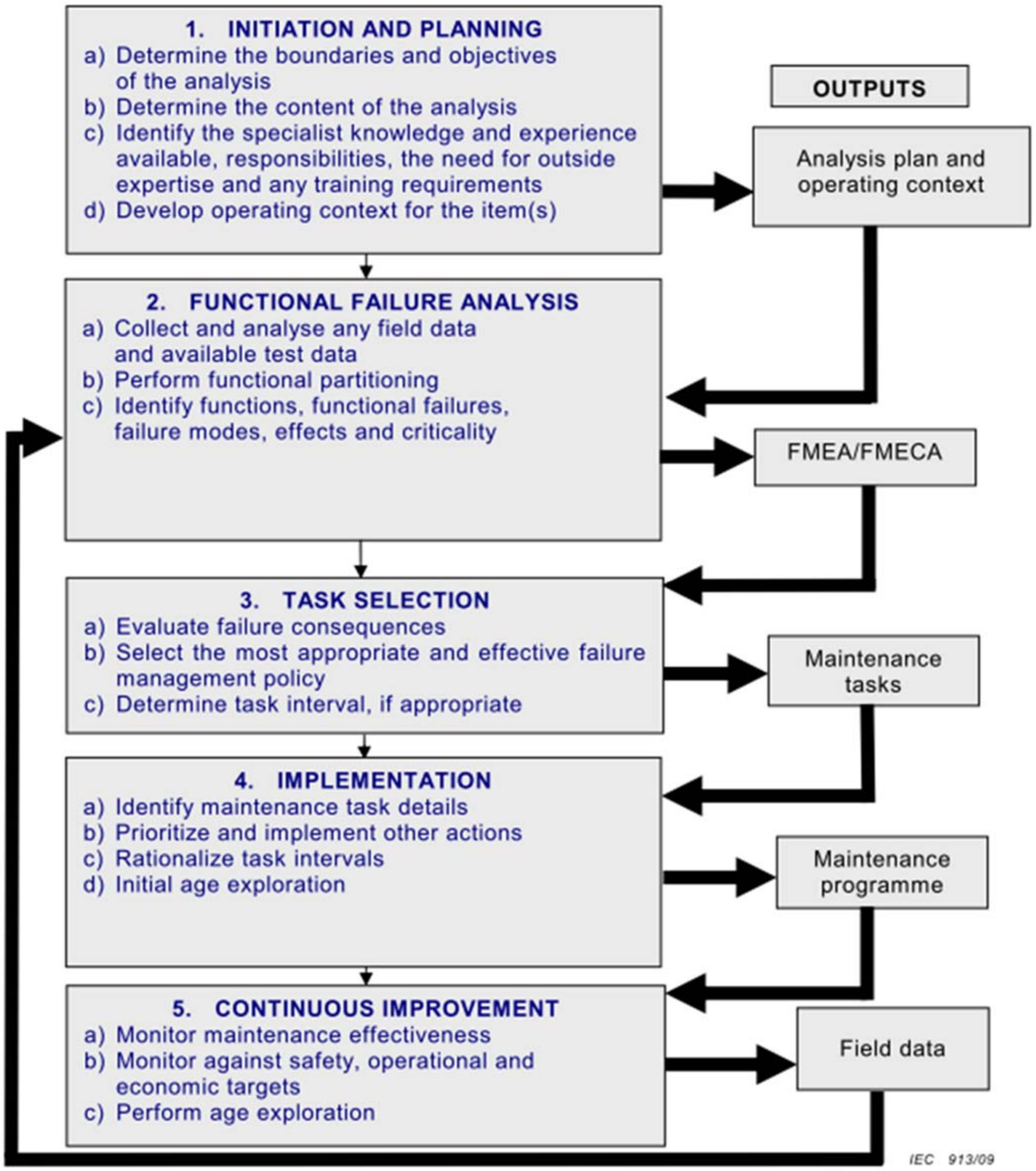


Figure 4-1: Overview of the RCM Process (BS EN 60300-3-11:2009).

The RCM methodology uses identified failure modes in the system to find their causes and occurrence, so that they can be eliminated.

4.1 FAILURE

Understanding failure is critical in establishing an all-encompassing maintenance strategy. Figure 4-2 shows the importance of understanding system performance and failure at different system levels. The P-F curve shown in the graph provides a conceptual degradation detection process for maintenance managers. The graph illustrates the fact that, as a failure starts to manifest itself, the equipment deteriorates to the point at which the failure can be detected. However, if the failure is not detected, it then reaches the point of functional failure. The time in between the point of initial degradation and functional failure provides an opportunity for maintenance to be undertaken. The concept concerned is important in rail inspection, with defects increasingly becoming so difficult to detect that they tend to lead to rail failures and derailments.

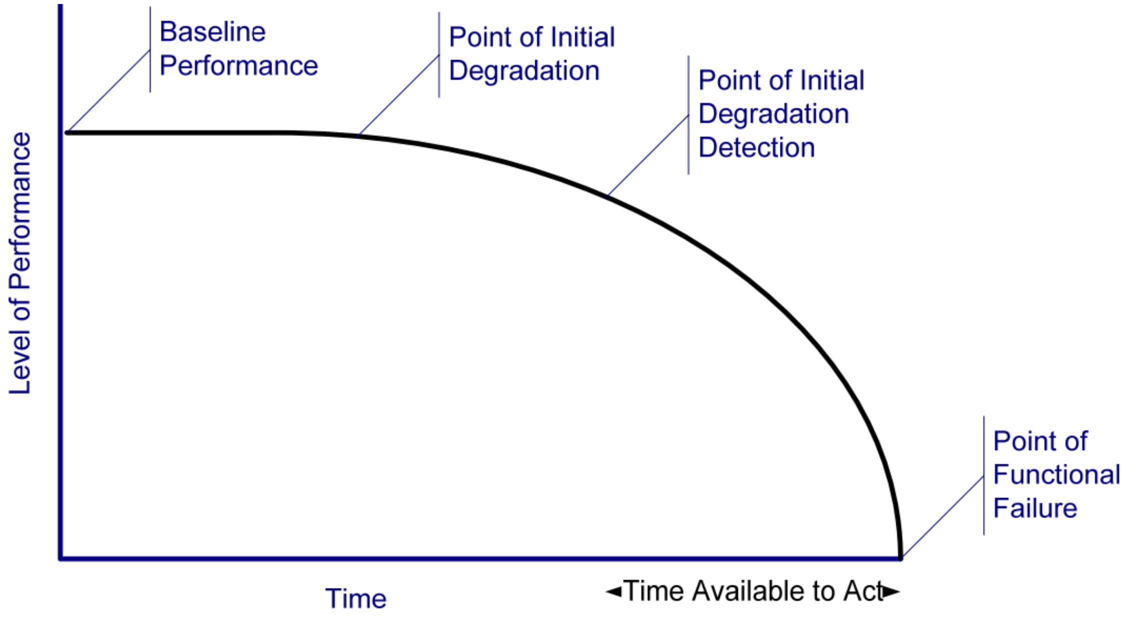


Figure 4-2: P-F Curve (NASA, 2008).

4.2 RCM MAINTENANCE STRATEGIES

The following factors are used to determine the nature of the railway infrastructure maintenance inspections required:

- Maximum train speed
- Traffic intensity
- Type of traffic
- Climate and environmental conditions
- Geological conditions
- Technical standard of the infrastructure components
- Built-in functional security
- Age and quality of the system

RCM facilitates maintenance management in terms of the type of maintenance strategy that should be implemented in respect of a physical asset. The maintenance strategies that are employed are:

- Run–to–failure maintenance
- Preventive Maintenance
- Predictive maintenance
- Design modification

4.2.1 RUN-TO-FAILURE (RTF)

RTF maintenance, which is also known as reactive maintenance, is a strategy/policy used by organisations to manage physical assets. It entails allowing the component, or part of equipment, to fail without it affecting the safety of the total system. RTF maintenance is mostly applied to non-critical components, in terms of which the consequences of failure do not have a critical impact on production loss, safety, environmental impact, and failure cost. Consequently, RTF management is expected to have minimal LCC, as compared to preventive maintenance (PM) (IAEA-TECDOC-1590, 2007).

The use of RTF, which is a corrective and reactive maintenance strategy, implies that sufficient planning with regard to spares and work orders is required to minimise production downtime.

Corrective maintenance (CM) is grouped as either deferred or immediate maintenance (Anderson, 2002). Deferred maintenance is described as faults that do not impact on major equipment. The faults concerned are relatively small, and are grouped together to be carried out at a planned date. In contrast, immediate maintenance applies to emergency faults, in relation to which actions are carried out instantly. Even though RTF is a CM strategy, it is rarely used in railway infrastructure maintenance strategy. The costs that are associated with RTF maintenance management, which are relatively high, relate to: overtime labour costs; the high cost of spare parts; high machine downtime; inventory costs; and low production/system availability.

4.2.2 PREVENTIVE MAINTENANCE (PM)

PM, which is a type of maintenance that is carried out before a breakdown occurs, includes such activities as inspection, detection, lubrication, and corrective actions, among others. The maintenance concerned is aimed at improving the reliability and the availability of a system, by means of reducing the degradation of a component, or by means of extending its useful life. The objective of PM is to minimise the probability of occurrence of failure.

PM uses the amount of time, or the number of hours of operation, to determine the maintenance frequency. Hence, it is scheduled on the basis of probability of failure distribution, or bathtub curve, in some instances.

PM is classified as being either condition-based or predetermined. Condition-based PM includes the conducting of inspections, and the taking of measures, to mitigate problems relating to the equipment, with respect to the inspection carried out. Predetermined maintenance is used on the parts of equipment whose life cycles can be predicted, leading to a certain periodicity of actions (Anderson, 2002). In terms of the railway infrastructure, PM is carried out on railway track to bring the track circuit back to an acceptable condition. For instance, rail grinding is a planned PM measure that is used to restore the rail profile, and also to remove any surface damage that might have occurred since the previous PM checks (ORR, 2006).

4.2.3 PREDICTIVE MAINTENANCE

Predictive maintenance which is also known as Condition Based Maintenance (CBM), is the philosophy of monitoring the health of a machine by means of analysing various signals collected from different sensors. The monitoring is done in order to attain the minimum maintenance and failure cost that is possible under the given circumstances. Diagnostics, which is a central component of CBM, is defined as the detection of failure and its condition. Predictive maintenance is usually carried out online. One of the advantages of conducting predictive maintenance is that doing so allows for the scheduling of maintenance when it is required, and when it will have the least impact on the system, without having to rely on plant or system life statistics to schedule maintenance.

Turnout systems are one of the most important electromechanical devices in railway infrastructure, and CBM is used extensively to manage the equipment maintenance. Predictive maintenance is classified into two types, according to the methods used for detecting the signs of failure:

- ***Condition-based predictive maintenance*** depends on the continuous, or periodic, monitoring of systems to detect signs of potential failure.
- ***Statistical-based predictive maintenance*** relies on statistical data obtained from the operational history of equipment to detect potential failure.

4.2.4 DESIGN MODIFICATION

Design modification, which is part of an improvement maintenance strategy, is used to eliminate historical equipment failure, and involves redesigning a system that has been proven to be susceptible to frequent system failures. Such modification is implemented when the maintenance life cycle cost (LCC) and the downtime cost of the equipment involved is not economically viable.

4.3 OBJECTIVES OF RCM

The primary objectives of RCM are to increase plant availability, and to reduce maintenance cost, in line with some of the following objectives:

- To ensure that the physical asset function remains within its design and operating requirement
- To provide comprehensive information and data that are required for design improvement geared towards the future design, and modification, of current systems

- To keep effective maintenance at minimal LCC
- To extend the lifespan of physical assets
- To conduct root cause analysis
- To assess the physical assets and the degree of reliability present, when developing a maintenance programme

4.4 PRINCIPLES OF RCM

RCM methodologies, as described by Nowlan and Heap (1978), are based on four system operating conditions: RTF; PM; predictive maintenance; and design modification. RCM is a strategy that is used to optimise maintenance. It is, therefore, important to understand that RCM does not prevent failure, as any physical asset will, inevitably, eventually fail, and also have failure characteristics. Hence, one of the goals of RCM is the identification of component failure characteristics, the coming to an understanding of the characteristics concerned, and the ability to describe the appropriate intervention required. Accordingly, the principles upon which RCM is based are described below (adapted from NASA, 2008). The RCM practitioner should be:

- ***function-oriented***, in that RCM seeks to preserve the system or equipment function by means of focusing on maintenance efforts exerted in relation to functionally critical components.
- ***system-focused***, in that RCM is concerned with maintaining the overall functionality of a system, rather than an individual component function.
- ***reliability-centred***, in that RCM uses failure statistics in an actuarial manner to consider the relationship between the operating lifespan, and the failures experienced. RCM practitioners also seek to know the probability of failure within a specific lifespan.

- ***able to acknowledge design limitations***, in that the objective of RCM is to maintain the inherent reliability of the system design, and also to recognise that changes in reliability are a function of design, rather than being a function of maintenance. Maintenance can only achieve, and maintain, the level provided for by the design concerned.
- ***continuously aware of safety and economics issues***, in that RCM must ensure that safety is its first and utmost priority, with cost-effectiveness being only the secondary goal.
- ***aware of failure as any unsatisfactory condition***, as failure in a system might amount either to a loss of function of the system, or to a loss of defined quality in the system.
- ***a user of a logic tree to screen maintenance tasks***, as such use helps to provide a consistent approach to the maintenance of equipment within a system.
- ***aware that tasks must be applicable***, with the tasks concerned addressing the failure mode, and mindful of its characteristics.
- ***aware that tasks must be effective***, with them both reducing the probability of failure, and being cost-effective.
- ***acknowledge two types of maintenance and RTF tasks***, namely interval- and condition-based.
- ***acknowledge that RCM is a living system***, as it not only gathers data from the results achieved, but also feeds the data back into the system, so as to improve future maintenance management. The feedback forms an important part of the proactive maintenance element of the RCM programme concerned.
-

4.5 RCM ANALYSIS

RCM analysis in a physical asset environment considers the following questions to determine the maintenance requirements:

- What are the functions of the system, and what does it do?
- What functional failures are likely to occur?
- What causes the functional failure?
- What are the likely consequences of the aforesaid functional failures?
- What should be done to minimise the probability of failure, or to predict failure?

4.5.1 RCM IN RAILWAY INFRASTRUCTURE

RCM application in railway infrastructure is implemented differently to the standard industrial system, because a railway network comprises different complex technical subsystems, with different functions (RAIL, 2002). As a result, the analyses and recommendations concerned should be based on a family of similar components, such as permanent way (consisting of bridges and platforms), and rolling stock.

4.5.2 BENEFITS OF RCM IN MAINTAINING RAILWAY INFRASTRUCTURE

One of the important objectives of RCM in maintaining railway infrastructure is to avoid, or to reduce, the consequences of failure, through the implementation of a PM strategy geared towards providing optimal system availability and safety, at the lowest possible cost. Failure consequences, in terms of railway infrastructure, are the effects of failure on operations, including delays to system, personal, and equipment safety, as well as the loss of revenue.

Some of the benefits of applying RCM to both new and existing components of railway infrastructure are the following:

- It provides a platform for the documentation trail that serves to enhance the continuous maintenance strategy optimisation and improvement.
- It improves the reliability and the availability of components of the system.
- It reduces the costs related to the safety and the life cycle of plants.
- It helps to preserve system function, by identifying failure modes that might otherwise produce functional failures.

4.6 ACTIONS IN RCM PROCESS IMPLEMENTATION, IN TERMS OF RAILWAY INFRASTRUCTURE

The actions that are required to be undertaken in RCM process implementation consist of the following:

- Selection of the system
- Definition of the system boundaries
- Description of the system
- Identification of the system functions, and of functional failures
- FMEA
- Selection of tasks
- Programme implementation

4.7 CHAPTER SUMMARY

This Chapter introduces RCM application in railway infrastructure and document how it is implemented differently to the standard industrial system, because a railway network comprises several complex technical subsystems, with different functions and dependencies. As a result, railway track reliability should be based on a family of similar components of families.

The actions required to implement RCM in railway infrastructure was presented. RCM is a continuous maintenance strategy, where the failure modes are identified and a programme of optimised maintenance plan is implemented.

CHAPTER FIVE

5. RAILWAY TRACK FAILURES

Failure mode and mechanism understanding in railway infrastructure is pivotal for maintaining a well-established manufacturing and maintenance strategy, and, thus, an adequate standard of reliability improvement. Rail track infrastructure (i.e. rails; switches; fasteners; sleepers; tie plates; rail anchors; ballast; and sub-grade) failure mechanisms vary. As a result, a statistical data collection of global rail failures is important for determining the trends and factors that affect performance.

The monitoring and inspection of track infrastructure, especially in terms of failures, can assist in the design and the cost optimisation of both personnel and materials. In addition, it can aid in future expansion, as well as help to reduce the potential risk of rail breaks and development. In the United States, track defects are the second leading cause of accidents on railways (Cannon *et al.*, 2003). The statistics relating to broken and defective rails in a railway system are an indication of the overall track quality involved, which might be due to rail age, to fatigue cracks, and to the degrading of track geometry (Sawley & Reiff, 2000).

Rail defect formation, which has been on the increase globally, can be attributed to the significant global mean increase of axle load from 22.5 to 32.5 tonnes (Allen, 1999) without a corresponding increase in the frequency of inspection and maintenance. The increase has given rise to increased risks in rail operation, resulting from rolling contact fatigue (RCF) that is caused by cyclic heavy axle load, track quality degradation, increased dynamic forces and rail wear. The risks that are associated with the above can be controlled by means of coordinated planned rail testing. The testing would aid in maintaining the reliability of the system concerned, by means of identifying defects and by planning for remedial actions such as the replacement of defective rails, repairs, operational philosophy change, and including measures relating to speed and load restrictions.

5.1 RAILWAY TRACK FAILURE CLASSIFICATION

Rail failure is defined as a broken rail, or as a defective rail that is in service, and which is within its service lifespan. A broken rail is described as a rail with a complete breakage, or with a missing part. Defect on rail is identified as a defective rail.

5.2 RAIL FAILURE

Railway track is one of the components in railway transportation that is subject to degradation and failure. Such deterioration is usually due to stresses and fatigue imposed by thermal and wheel–rail contact stresses. According to the International Union of Railways (UIC) code on rail defects (UIC-712, 2002), rail failure is classified into three groups:

- A damaged rail is any rail which is neither cracked nor broken, but which has other defects, generally on the rail surface.
- A cracked rail is any rail which, anywhere along its length and irrespective of the parts of the profile concerned, has one or more gaps of no set pattern, apparent or not, the progression of which could lead to breakage of the rail relatively rapidly.
- A broken rail is any rail which has separated into two or more pieces, or a rail from which a piece of metal becomes detached, causing a gap of more than 50 mm in length and more than 10 mm in depth in the running surface.

Rail defects have been studied, categorised, and codified by the UIC (Profillidis, 2006). Hence, the information pertaining to the type and nature of rail failures, and to their service conditions, is reported, using the UIC rail codifications, by the maintenance personnel. Thus, it is pertinent that the staff are conversant with the UIC codification, so as to enable precise and dependable reporting of the failures.

UIC uses an alphanumerical system of codification of rail failures, in common with many other railway establishments around the world. The code comprises four digits (ACEM-Rail, 2011).

- The first digit indicates:
  - Defects in rail ends
  - Defects away from rail ends
  - Defects resulting from damage to the rail
  - Weld and resurfacing defects
- The second digit indicates:
  - The place in the rail section where the defect originated
  - The type of welding when weld or resurfacing defects are involved
- The third digit indicates:
  - The pattern of the defect, in the case of a broken or cracked rail
  - The nature of the defect, in the case of a damaged rail
  - The cause of the defect in the case of a damaged rail
- The fourth digit makes it possible, as and when required, for a further classification to be made by type of defect.

Rail defects are classified systematically, based on their location of occurrence along the rail length, as is shown in Figure 5-1.

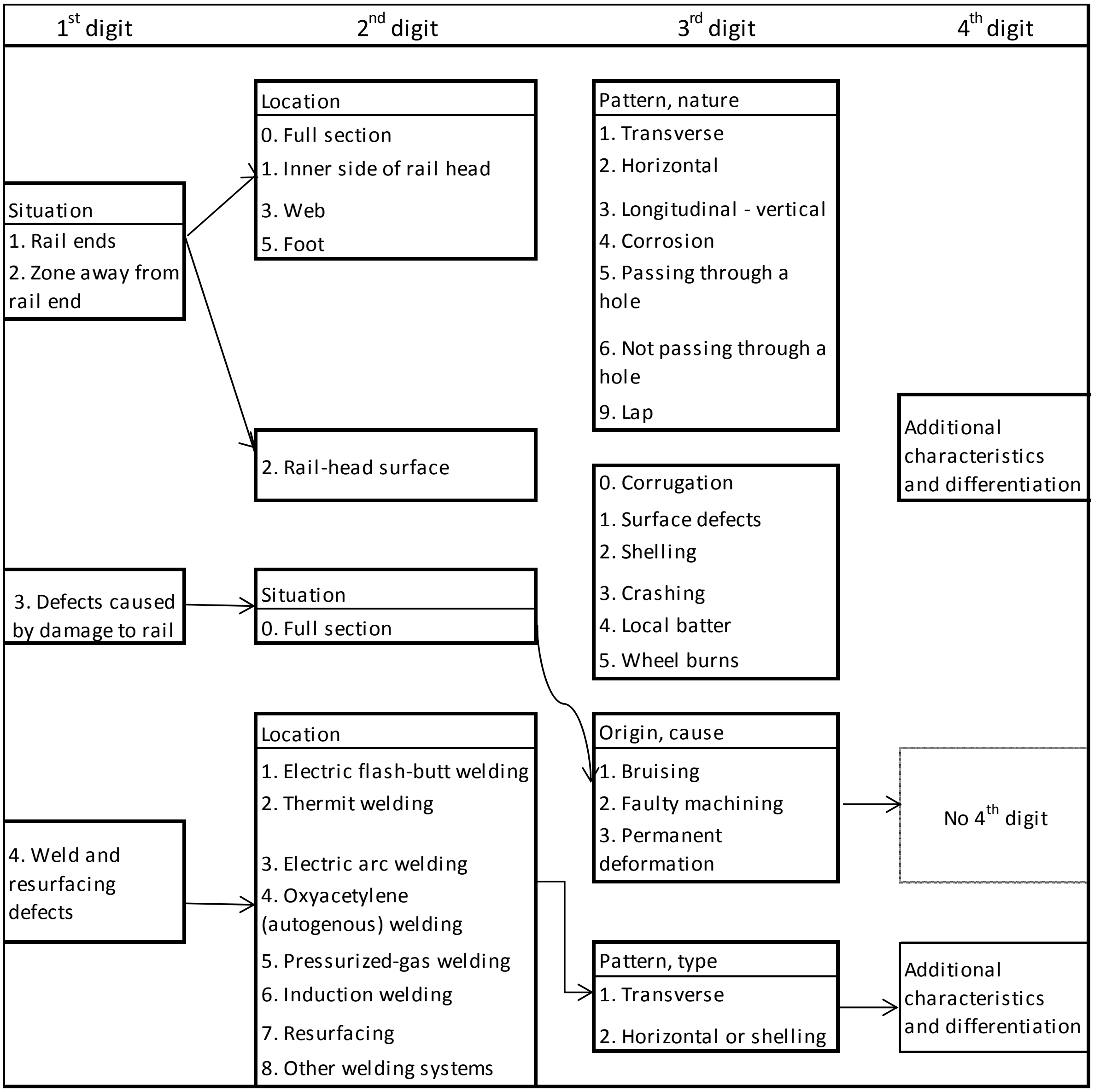


Figure 5-1: Codification of Rail Defects, (Adapted from UIC 712, 2002).

5.2.1 DEFECTS IN RAIL ENDS

Defects in rail ends are defects emanating from such ends, including longitudinal vertical cracking, which is also known as rail defects UIC 113 and UIC 213, which might appear at the railhead, or at the web, in which case UIC 133 and UIC 233 apply. These defects can lead to the expansion, and to the further splitting, of the railhead into two separate parts. The defects concerned usually emanate from manufacturing defects, and are detected by means of ultrasonic equipment. Figure 5-2 shows some of the defects that are found in the industry.

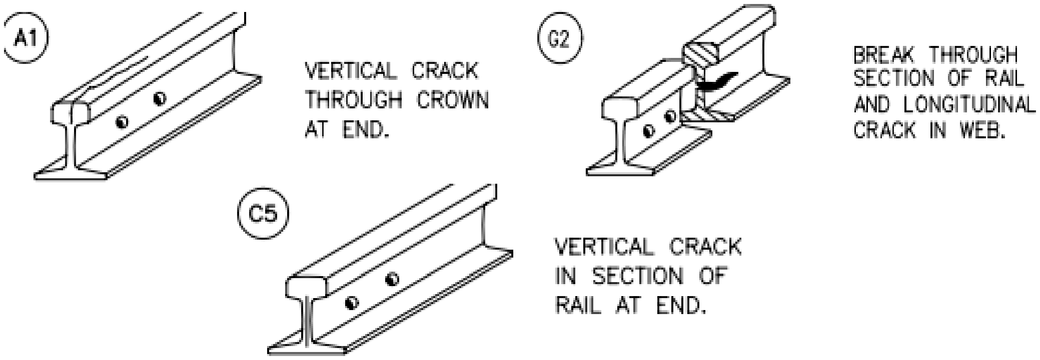


Figure 5-2: Defects in the rail ends (*SPOORNET, 2000*).

5.2.2 DEFECTS AWAY FROM RAIL ENDS

Some of the different types of defects away from rail ends are described below (ACEM-Rail, 2011), namely:

Tache Ovale is a subsurface defect that is formed about 10–15 mm below the railhead (Kumar, 2006). The defect is caused by the thermal effects resulting from hydrogen accumulation during the manufacturing process of the rails, and also when poor rail welding is done, with consequent expansion to reach the rail surface. Thermal and residual stresses also promote the defect concerned. The defect codification is identified as UIC 211. Figure 5-3 shows a typical tache ovale defect in rail. The defect is detected using ultrasonic equipment, or by means of visual inspection.

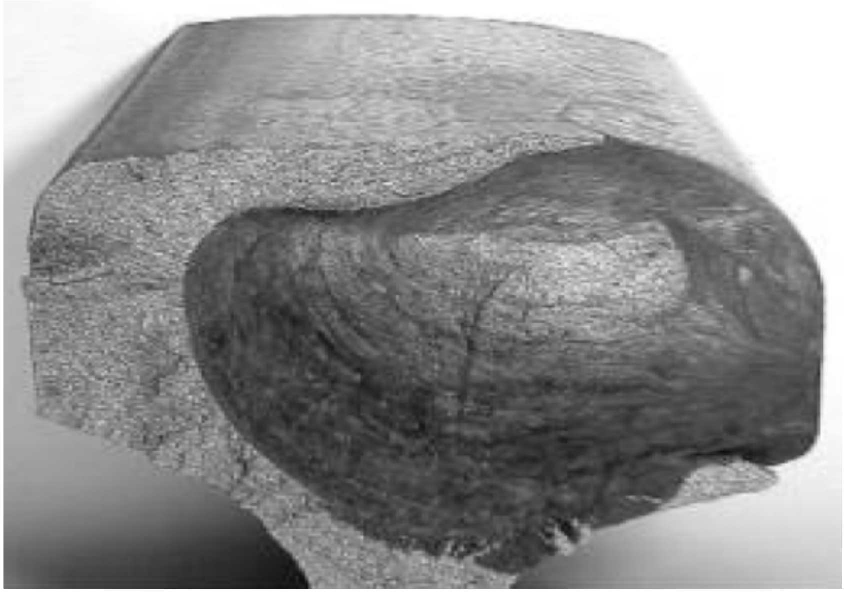
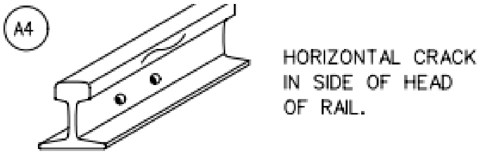
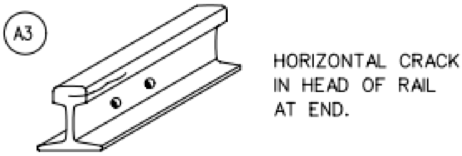


Figure 5-3: Tache Ovale (Kumar, 2006).

Horizontal crack, which is also known as rail defect UIC 212, is a defect that occurs at the rolling surface of a rail. It develops from the manufacturing process, in the form of initial internal discontinuities. The defect is detected using ultrasonic equipment, or by means of visual inspection. See Figure 5-4 below for typical horizontal cracks on rail.





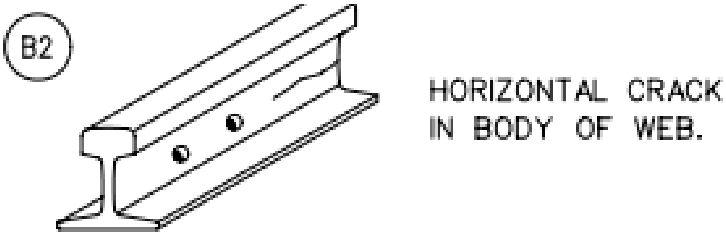


Figure 5-4: Horizontal Cracking Defects (SPOORNET, 2000).

Short-pitch rail corrugation (which is also known as rail defect UIC 2201, see Figure 5-5**)** is a type of wave-type wear on the rail surface, with a wide variety of wavelength (Oostermeijer, 2006). Such wear leads to unpleasant noise, because of the high-frequency oscillations that they produce on tracks, which can give rise to: resonance; cracks at rail supports; the loosening of fastenings; the failure of ballast and sub-grade; and high stress, especially in terms of instances of RCF, like squats. The defect is largely detected by means of rail defect recording equipment, or by means of visual inspection. It is usually repaired by smoothing the rail.

Figure 5-5: Short-pitch Rail Corrugation (Oostermeijer, 2006).

Long-pitch corrugations (which is also known as rail defect UIC 2202, see Figure 5-6**)** normally evolve under relatively high nominal axle load (> 20 tonnes) in mixed freight, or unit train operations (ARTC, 2006). The depth of the corrugations can range from 0.1 mm to over 2.0 mm. Detection and repair are similar to that which is undertaken with short-pitch corrugations. The difference between long-pitch and short-pitch rail corrugation is according to their wavelength.

Figure 5-6: Rail Corrugation (Nielsen & Torstensson, 2010).

Lateral wear (which is also known as rail defect UIC 2203) is caused by the snaking of the lateral movement of the trains, due to the conical shape of the wheels. This kind of wear, after a certain point, becomes dangerous, as it might affect track gauge adversely. Network operators normally specify the allowable range of lateral wear of railhead. Figure 5-7 below indicates a typical rail showing lateral wear.

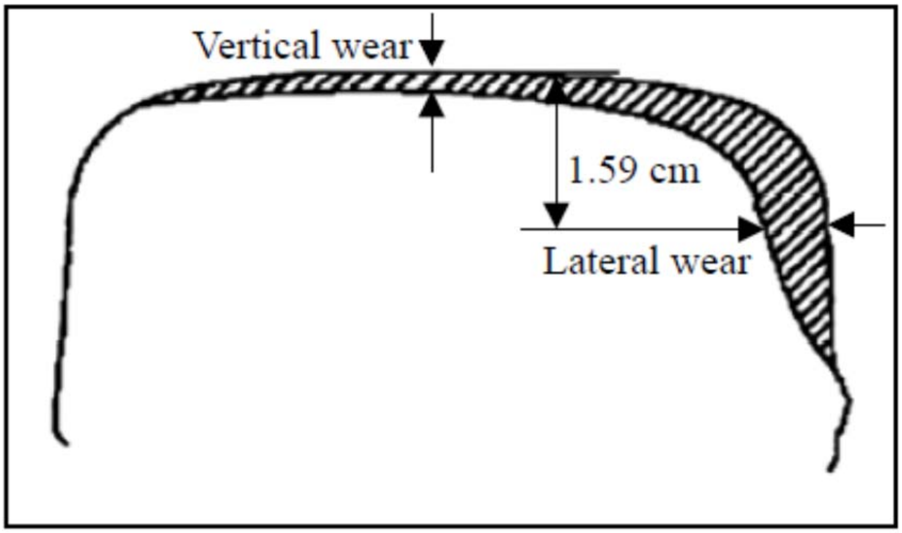


Figure 5-7: Lateral Wear (Sadeghi & Akbari, 2006).

Rolling (running) surface disintegration (which is known as rail defect UIC 221) is a type of defect on rail that causes the gradual disintegration of the rolling surface of the rail. The rolling surface disintegration defect is detected during track maintenance inspections, and the affected rails are replaced during the scheduled maintenance plan.

Shelling of the running surface (which is also known as rail defect UIC 2221) is a type of defect that manifests in deformations of irregular patterns on the rail surface originating from subsurface defects, or at the rail running surface, which can result in considerable dislodgment of the rail parent metal. The deformations are caused by the high shear stress that develops in the wheel/rail contact region when such stress exceeds the allowable limits of the rail material (ARTC, 2006). The defects, which are usually encountered over large spans of tracks, are detectable by means of visual inspection, or with the use of ultrasonic equipment (see Figure 5-8).

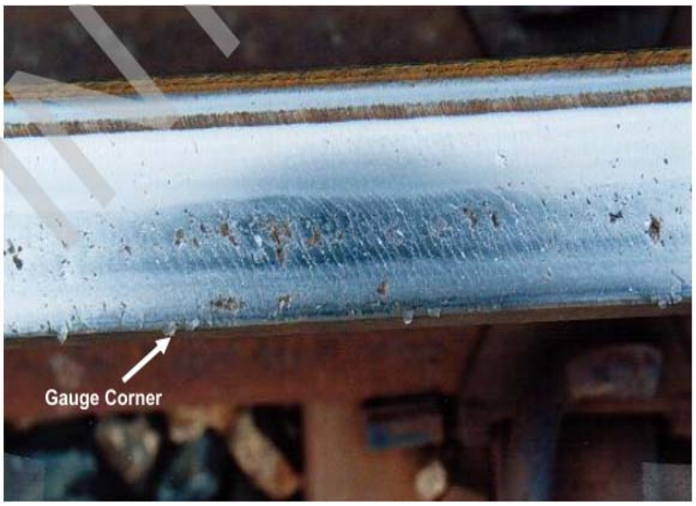


Figure 5-8: Running Surface Defect (ARTC, 2006).

Gauge-corner shelling (which is also known as rail defect UIC 2222) and running surface crack defects are caused by high shear stresses that develop in the wheel/rail contact region, when such stresses exceed the allowable limits of the rail material used. The factors that influence the shear stresses include the diameter of the wheels, the dynamic loading, and the track geometry. The gauge-corner shelling defect, which normally appears on the outside rail curves, can be repaired by means of grinding the rail. (See Figure 5-9 below for an example of such shelling).

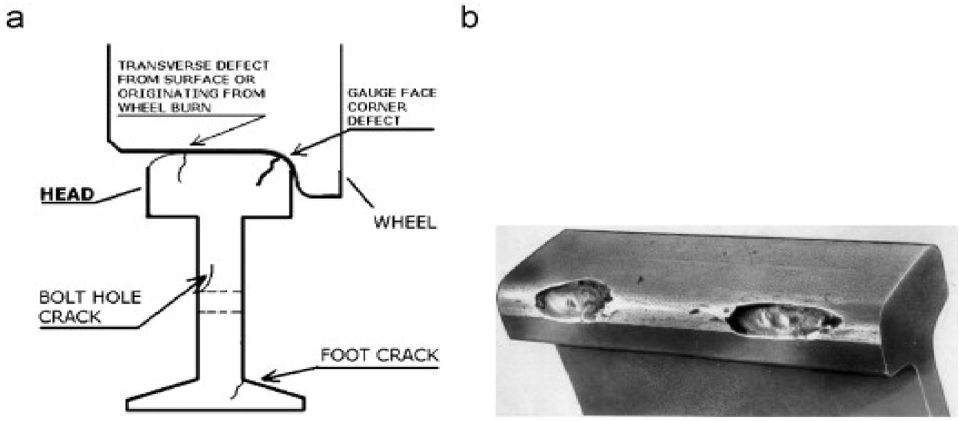


Figure 5-9: Gauge-corner Shelling (Wilson *et al*., 2011).

Head checking (which is also known as rail defect UIC 2223; see Figure 5-10 is caused by high stresses in the rail gauge corners in curves. It usually appears in the curves of radii that are under 1 500 m, and it is usually found around welds (Kumar, 2006). Although grinding may be used to correct head checks, which are surface-created defects, critical defects of this nature might require rail replacement.

Figure 5-10: Head Check Defects (R06C0104, 2006).

5.2.3 DEFECTS CAUSED BY RAIL DAMAGE

The two types of defects that are caused by rail damage are bruising rail defect (UIC 301), and faulty machining rail defect (UIC 302). The former defect is caused by mostly traffic load, which might lead to derailments, damaged wheels, the handling of dragging parts, and arcing, whereas the latter defect, which is also due to traffic load, and might cause drilling of the foot, or the web, of the rail or improper in-track, and faulty cutting (Profillidis, 2006).

5.2.4 WELD AND RESURFACING DEFECTS

Welds are used in railway tracks to join discontinuities, especially on high-speed tracks. The problem with the welds lies in the physical properties involved, such as the thermal expansion of the steel, which affects the integrity of the welds adversely, and which might lead to discontinuity in the welds (Terashita & Tatsum, 2003). Ultrasonic and visual inspections are used to detect weld defects.

5.2.5 RAIL WEAR

Rail wear is defined as a reduction of the railhead, as a result of the abrasive action that takes place between the steel wheels on the steel rail (FRA, 2011). Such wear affects vehicle performance, wheel/rail contact, and the degradation of the rail. Rail defects tend to exacerbate increased stresses in the rail material, which might lead to such defects as cracks. Jendel (1999) and Zakharov (2001) classified rail wear into three modes, with the classifications being based on the wear rate, and on surface and wear debris form and size;

- Mild wear (300 µm)
- Severe wear (500 µm)
- Catastrophic wear (1 000 µm)

Mild wear is usually found on the wheel tread, and in the rail crown area, whereas severe wear is predominantly found in curves, and in dry conditions (Jendel, 1999). Scheduled grinding is used to maintain and correct the deformed profile.

5.2.6 SLEEPER FAILURE

Sleepers in railway infrastructure are one of three types: steel; timber; and concrete. Failures in the track usually manifest on all types of sleepers.

5.2.6.1 STEEL SLEEPERS

Steel sleepers, which are made from pressed steel, are trough-shaped in section, with forged ends to provide anchoring in ballast, so as to ensure transverse track stability. Such sleepers are easily installed on existing ballast, unlike the case with concrete sleepers, which require a new layer of ballast. As steel sleepers require much less ballast than do either concrete or wood sleepers, steel sleepers are therefore cost effective.

The setback with steel sleepers is their susceptibility to chemical attack, particularly in industrial and coastal areas (ACEM-Rail). Such susceptibility can lead to corrosion of the steel, with them also developing cracks in the rail seats during service (Swarnakar, 2012).

5.2.6.2 TIMBER SLEEPERS

Timber sleepers, which are flexible and have better load distribution, are used in the case of poor-quality ballast sub-grades. The pitfall of timber sleepers is their short lifespan, compared to that of concrete and steel sleepers. A defect that can sometimes be found in timber sleepers occurs when the base plate is seated incorrectly, leading to the likelihood of a breakage. Figure

5-11 portrays the presence of a defect in a timber sleeper. Other types of defects that can be found in timber sleepers are fungal decay, and splitting at the ends.

Figure 5-11: Timber Sleeper Failure (Hassankiadeh, 2011).

5.2.6.3 CONCRETE SLEEPERS

Concrete sleepers, which are brittle, tend to possess minimal fatigue resistance. As a result, the defects that are found in concrete sleepers tend to be severe, with one of them being concrete spalling. Concrete spalling is a process where the concrete has broken up and flaked, which occurs in the top fibre of the rail seat, and in cracks. Two types of reinforced-concrete sleepers are used in the industry: twin-block reinforced concrete sleeper and monoblock prestressed concrete sleepers.

Failure mechanisms in concrete sleepers are identified as (Hassankiadeh, 2011):

- Wet spot (which is also known as slurry spot)
- Damaged concrete bearers

- Concrete spalling
- Shear cracks
- Abrasion

5.2.7 BALLAST FAILURE AND SUB-BALLAST

Ballast is a crucial part of the substructure, because it is the only external constraint that is applied to the track, so as to restrain it (Lim, 2004). Ballast is subjected to the vertical force of the moving train, and also to the impact force of the maintenance tamping, with the forces concerned having the potential to lead to serious damage to the ballast (Selig & Waters, 1994).

Despite the fact that ballast forms part of the substructure of a track system, and constitutes a major cost in terms of track maintenance, Selig and Waters (1994) claim that, due to the properties of substructure not being standardised, the selection of maintenance best practices is problematic. Ballast deterioration is caused by repeated loading, by the intrusion of such external materials as wagon spillage, by the infiltration of inherent materials into the ballast material, and by fouling, which causes the crushing of the ballast that is in contact with the ties (Lim, 2004).

5.2.8 BRIDGES AND TUNNELS

Bridges and tunnels, which form part of the railway infrastructure, are subject to deterioration, and, thus, to failure. The deterioration of such infrastructure is mostly due to corrosion, poor maintenance management, and increased load utilisation.

5.3 RAIL TRACK FAILURE ANALYSIS

Rail track failure, which is a major cause of rail derailment, is generally caused by either internal or surface defects (Cannon *et al.*, 2003). Internal rail flaws are mostly due to the macroscopic imperfections that occur during manufacturing, and which are not picked up on, due to poor quality control. The defects concerned, when present, tend to grow, due to the cyclic vertical and horizontal loading of the rail, leading to fatigue crack growth. In contrast, surface defects are caused by wheel–rail contact stresses at the running surface of the rail. Broken rails are grouped into two categories: those that lead to derailment, and those that, on detection, are called service failures (Schafer & Barkan, 2008).

It is important to identify areas where the failures occur, as well as their causes. Therefore, comprehensive and accurate data collection is critical to be able to predict any future occurrence, so as to facilitate ongoing endeavours in terms of PM strategies. Rail failure analysis and prediction tools should always consider the following variables: rail age; rail curvature; track speed; grade; and rail weight. In addition, careful note should be taken of changes in track modulus due to the presence of such infrastructure systems as bridges and turnouts (Schafer & Barkan, 2008). Global rail track failures are discussed in the subsequent section.

The consequences of rail failures are critical, as they can amount to major train derailment, and have severe economic impact, including the following (Cannon *et al.*, 2003):

- Train delays
- The cost of broken rail derailment
- Track and equipment damage
- Clean-up costs, along with a loss of revenue and associated costs
- The need to adopt preventive methods
- The need for rail grinding, rail replacement, and track surfacing
- The need for track inspection
- The need for ultrasonic and geometric testing
- The need to apply remedial treatments
- The need to replace, or, at least, to repair, rails and welds

In South Africa, the direct costs of rail accidents in 2008–2009, as reported by the Rail Safety Regulator (RSR), amounted to R635 million for the period concerned. The costs included R575 million for Transnet Freight Rail (TFR), and R60 million for Metrorail. However, the overall sum did not take into account the indirect costs arising from service delays and cancellations. In reporting on the prevailing situation, the chief executive officer reported the fact that the failures concerned were blamed on the poor conditions of the infrastructure and the rolling stocks, but particularly highlighted poor signalling infrastructure as being the major cause of the failures (RSR, 2011). In the annual financial report for 2008 to 2009, of the 5 307 occurrences recorded, 1 202 were collisions, and 1 154 derailments. More than 90% of TFR occurrence costs are said to be directly related to derailments and collisions.

Derailments have resulted in costly delays on freight corridors, whereas the average number of trains cancelled amounts to 10 trains per day, due to accidents and other security incidents, such as the theft of copper cables. Likewise, in the USA, Illinois Rail Road Engineering reported 335 broken rail derailments from 2003 to 2006, with a total cost of $176 million. As a result, the average cost of a broken rail derailment was $525 400 (Schafer & Barkan, 2008). Hence, the impact of rail failures cannot be overlooked, and improvement and reliability strategies require periodic revision.

Schafer and Barkan (2008), consequently, derived a train delay cost as follows:

$$\mathrm{C} = \mathrm{Tx} + \sum_{\mathrm{n}=1}^{\mathrm{m}} (\mathrm{T} - \mathrm{nt})\mathrm{x} \quad \text{...} \quad (9)$$

Where:

C = total train delay cost for multiple trains
T = total delay time for service interruption

x = cost of delay per train hour
m = number of following trains delayed = T/t
t = hours per train arrival

The multivariate statistical model, as follows, and which was developed by Dick (2001) to predict service failures, is based on established applicable track and traffic data. The model is based on the following equation:

$$P_{sf2} = \frac{e^u}{(1+e^u)} \quad \text{(10)}$$

$$u = Z + 0.059A + 0.025AC - 0.00008A^2C^2 + 5.101\frac{T}{S} + 217.9\frac{W}{S} - 3861.6\frac{W^2}{S^2} + 0.897(2N-1) - 1.108\frac{P}{S} \quad \text{(11)}$$

Where:

P_{sf2} = probability that a service failure occurred during a two-year period
Z = -4.569, model-specific constant
A = rail age (in years)
C = curvature of track (in degrees)
T = annual traffic (in MGT)
S = rail weight (in pounds per yard)
W = annual number of wheel passes (in millions)
P = dynamic wheel load (in tons)
N = presence of turnout (1 if present, 0 otherwise)

Dick (2001) determined that the equation's optimal probability threshold should be 0.5 to assume whether or not the location can be seen as a failure. Schafer II's (2008) thesis modified Dick's (2001) statistical model in terms of testing for validation, with the former including factors that might affect crack growth in rails. The models concerned are useful for predicting service failure, as they can aid maintenance system engineers in improving on their maintenance strategies and detection methods.

5.3.1 FAILURE PREDICTION

Statistical methods are used for rail failure prediction, with the prediction model for failure event being based on event sequence data. As a result, the integrity of the data collection is important.

In this section Weibull distribution is used to analyse the rail failure rate and reliability. The reliability of rails can be expressed in terms of the failure mechanism of rail and the data mining of failures. Statistically, rail failure is a function of its usage in terms of million gross tonnes (MGT) for determined conditions.

Using the Weibull distribution for a sample size of less than 100, in the absence of median rank tables, the true median rank values can be approximated using Bernard's approximation, as follows:

$$\mathrm{F(t)} = \frac{(\mathrm{i}-0.3)}{(\mathrm{n}+0.4)} \quad \ldots\ldots (12)$$

Where:

i = is the ith failure
n = the total number of population

For sample sizes greater than 100, the F (t) values may be calculated from the expression of the mean ranks, as follows:

$$\mathrm{F(t)} = \frac{\mathrm{i}}{(\mathrm{n}+1.0)} \quad \ldots\ldots (13)$$

Rail failure data obtained from the Swedish rail system was used to develop the Weibull expression of reliability and failure rate (Chattopadhyay & Rahman, 2006). The usage span was 720 MGT, with 208 rail breaks. Figure 5-12 shows a plot of the accumulated number of rail breaks, versus the accumulated breakage MGT.

Simões (2008) identified that the failure rates of rail usually grow with the MGT. He also stressed that, as rail defects are mechanical in nature, failure rate grows with time. Even though the definition of a rail break and a rail defect is well established, when analysing rail reliability over time, the two have to be distinguished in the analysis undertaken.

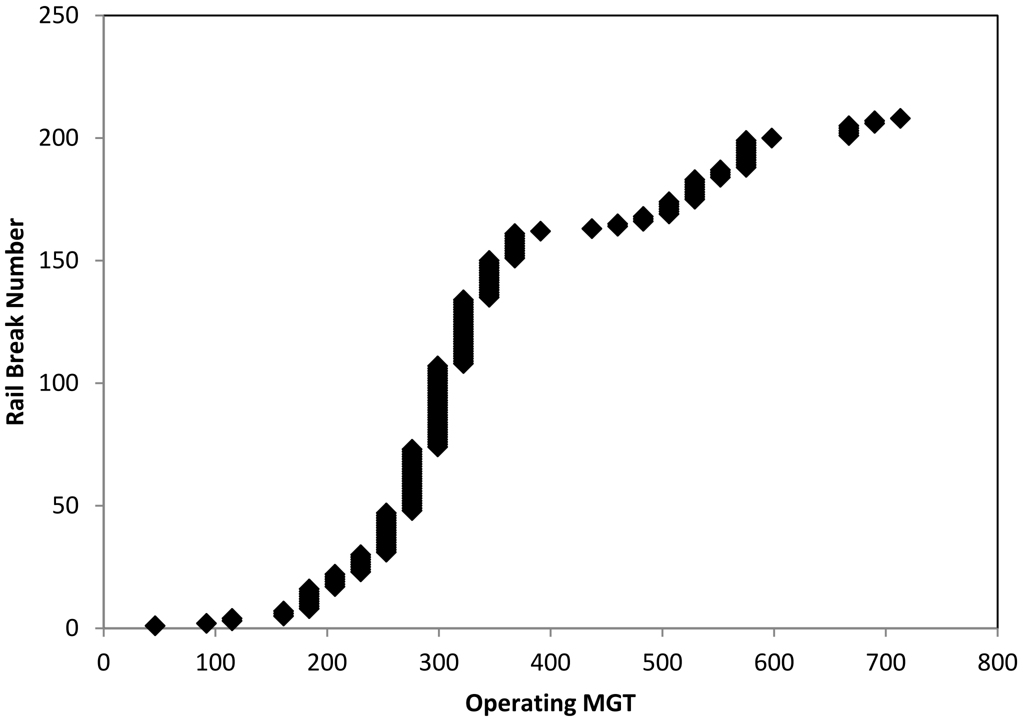


Figure 5-12: Cumulated Rail Break versus Accumulated MGT

Figure 5-13 is the Weibull plot and linear regression for the failure data. The data are from Chattopadhyay & Rahman, 2006.

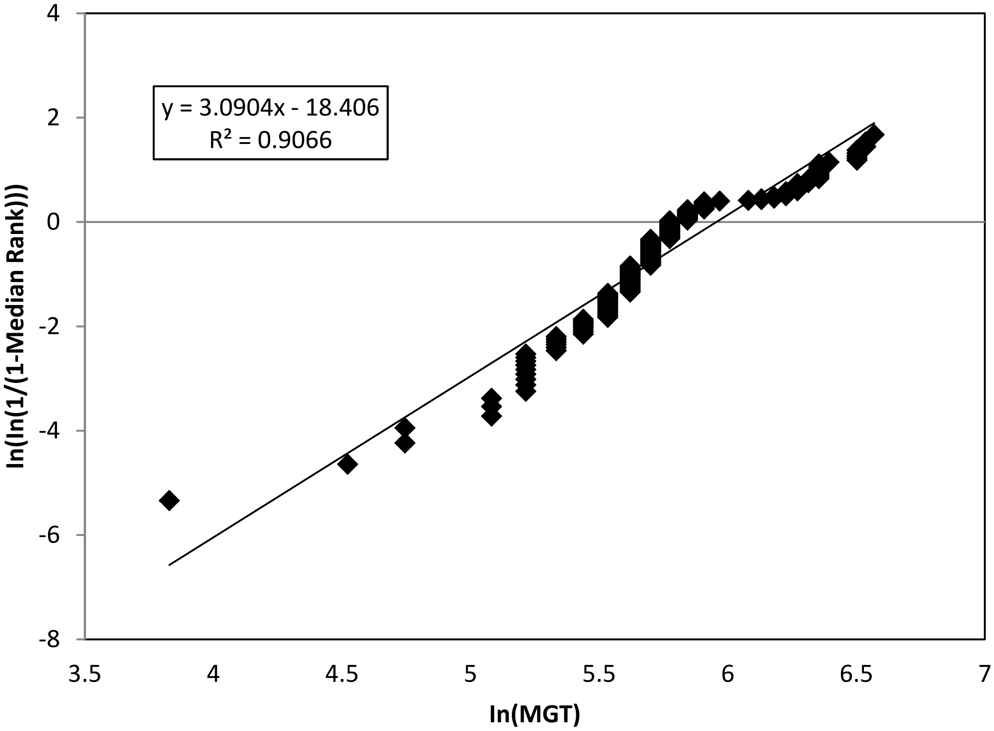


Figure 5-13: Weibull Plot and Linear Regression.

Converting the time unit t to MGT, so as to obtain the required failure rate and reliability equations, results in the following:

$$\lambda\,(\mathrm{MGT}) = \frac{\beta}{\alpha}\left(\frac{\mathrm{MGT}}{\alpha}\right)^{\beta-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ (14)$$

$$\mathrm{R(MGT)} = \exp\left[-\left(\frac{\mathrm{MGT}}{\alpha}\right)^{\beta}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (15)$$

Where:

$\beta = m\,;\ \beta = 3.0904$

m = linear regression slope

$\alpha = e^{-\left(\frac{b}{\beta}\right)}$ ……………………………………………………………………...……… (16)

Thus, $\alpha = 386$ (growth factor)

Using equation 15 and 16;

$$\lambda\ (\mathrm{MGT}) = \frac{3.0904}{386}\left(\frac{\mathrm{MGT}}{386}\right)^{2.0904}$$

$$\text{and } \mathrm{R(MGT)} = \exp\left[-\left(\frac{\mathrm{MGT}}{386}\right)^{3.0904}\right]$$

with 720 MGT usage span:

$$\lambda\ (\mathrm{MGT}) = \frac{3.0904}{386}\left(\frac{720}{386}\right)^{2.0904}$$

$$\text{and } \mathrm{R(MGT)} = \exp\left[-\left(\frac{720}{386}\right)^{3.0904}\right]$$

$\lambda\ = 294 \text{ x } 10^{-4}\text{failures/MGT and R} = 0.00104.$

Using a usage span of 30 MGT for the above example, and the same failure rate, the resulting system shows a better system reliability. The same procedure can be used for such maintenance planning as rail grinding and inspection intervals.

$$\lambda\,(\mathrm{MGT}) = \frac{3.0904}{386}\left(\frac{30}{386}\right)^{2.0904} \text{and } \mathrm{R}(\mathrm{MGT}) = \exp\left[-\left(\frac{30}{386}\right)^{3.0904}\right]$$

$$\lambda\ = 383.88 \text{ x } 10^{-7}\text{failures/MGT and}$$

$$\mathrm{R} = 0.99962$$

The above-mentioned values aid a maintenance department in undertaking a comparative analysis of rail reliability and failure rates, so as to put the effects of MGT on rail failures in perspective.

5.4 GLOBAL RAIL TRACK FAILURES DATA

The failure data from track failures around the globe are an indication of the associated trends that are witnessed in the industry. They can be used to benchmark best practices in relation to their maintenance strategies and operational philosophy. However, the performance concerned is based on different variables, such as operational conditions, train speed, axle load, rail–wheel material type, size and profile, track construction, characteristics of bogie type, MGT, curvature, traffic type, the weather, and the environment. Nevertheless, the information is still useful for obtaining insights and probability predictions.

International railway companies are analysed using data collected by Sawley and Reiff (2000). The defects were noted from 1998 and 1999 for Banverket railways. The Table 5-1 and Table 5-2 show the percentage of defects for each railway company, with the data involved indicating the relationship between rail defects and broken rails in Table 5-1 & Table 5-2. As a result, the information given can be used to investigate the risk of rail breaks, in terms of both mechanical and statistics.

Table 5-1: Causes of Defective Rails (Sawley & Reiff, 2000).

Railway	Percentages of Defective Rails by Defect Type				
SNCF (1999)	Squats 23.4%	Internal fatigue 11.5%	Shells 8.4%	Thermite welds 4.7%	-
HSPC (1999)	Thermite welds 31.5%	Wheel burns 17.2%	Horizontal split webs 13.3%	Bolt holes 11.3%	Flash weld 5.9%
Banverket (1998)	Transverse fracture 55.1%	Welded joint 32.7%	Horizontal defect 6.1%	Vertical split 2.0%	Others 2.0%
HH1 (1999)	Vertical split heads 34.7%	Thermite welds 20.3%	Detail fractures 13.1%	Bolt holes 12.2%	Flash weld 7.7%
HH2 (1999)	Transverse defects 23.6%	Thermite welds 15.5%	Wheel burns 13.2%	Shells 9.6%	Vertical split head 8.1%

Table 5-2: Broken Rails (Sawley & Reiff, 2000).

Railway	Percentage of Broken Rails				
SNCF (1999)	Thermite welds 35.3%	Internal fatigue 18.6%	Squats 8.8%	Rail manufacture 6.1%	Damage 3.3%
HH2 (1999)	Transverse defects 37.9%	Thermite welds 35.6%	Bolt holes 5.8%	Flash welds 5.6%	Broken base 4.2%

The maintenance and reliability management of broken rails and defects can be undertaken by means of risk-based assessment and rail test planning. Doing so would enable the operators to determine the optimum rail test intervals per segment of track, based on a defined level of risk for the segment concerned. Zarembski and Palese (2006) recommend the use of service defect rate-based risk definitions, which would aid in defining the maximum allowable risk for different traffic type (see Table 5-3).

Table 5-3: Broken Rail Risk Guideline (Zarembski & Palese, 2006).

Risk [service defects (rail breaks)/mile year]	Traffic Type
0.09 - 0.10	General freight route (no passenger or hazardous material)
0.07 - 0.08	Key freight line
0.06 - 0.07	Freight route with hazardous material, but no passenger traffic
0.04 - 0.06	Freight with limited passenger traffic
0.01 - 0.03	Low-speed passenger route (less than 90 mph)
0.005 - 0.01	Moderate-speed passenger route (90 mph to 125 mph)
0.001	High-speed passenger line route (125 mph and higher)

Table 5-3 can be used for improved maintenance strategy, where risks control can be planned by identifying and putting in place risk control, hence managing potential rail failures.

5.5 CHAPTER SUMMARY

In concluding this chapter, the following summary statements are made with regard to the reasons for the high increase in the number of broken rails:

- The amount of RCF has increased dramatically as a result of the introduction of bogies with higher wheel set yaw stiffness.
- The degradation of track quality has increased wheel irregularities, thus leading to the presence of increased dynamic forces.
- The axle load and traffic have increased, without a corresponding increase in the frequency of inspection and maintenance-related activity.

CHAPTER SIX

6. RELIABILITY IMPROVEMENT

Reliability, apart from being consistent over time, is measurable and can be traced with the same methodology. Therefore, the data collection and reporting procedures employed must be reproducible, dependable, and accurate. Reliability improvement should be focused on failure prevention, rather than on failure prediction. As a result, the present section is focused on the methods and the techniques employed in improving railway track reliability. Zero system break-down can be a goal, but is not attainable in a real world scenario. A plant or system design philosophy should utilise a combination of strategies to maintain system reliability, with such strategies including those relating to redundancy, PM, and CM, among other aspects.

Such statistical metrics as the reliability index, MTBF, MTTF, mean distance between failures (MDBF), MTTR, and availability are traditionally used to highlight the performance, or the reliability, of a railway infrastructure. The measures concerned usually have not been able to highlight areas of poor performance that can be used to improve the component reliability, because they are usually the averages of a region, the performance index of either a month or year, which is not consistent with the utilisation of each depot or rail segment.

Reliability improvement and, thus, the performance improvement of a railway infrastructure can be achieved by means of the use of both qualitative and quantitative methods. Therefore, the utilisation factor should be used in union to highlight the measure of reliability of a rail system.

Some of the sources of railway track unreliability that has been gathered from the literature studies, and from the railway station depot visits, are summarised as follows:

- Poor design of components and systems
- Manufacturing defects and inherent flaws (i.e. internal defects)
- Poor maintenance policies, strategies and implementations
- Organisational rigidity and complexity
- Human error
- Lack of critical skilled personnel (engineers and technicians for failures reporting, and reliability analysis).

In the current study, the reliability improvement of rail infrastructure is investigated on the basis of two concepts, namely design modification and maintenance management optimisation. The focus of the current chapter would be on reliability improvement through the latter means, but an overview of reliability improvement through the former means will also be discussed.

Figure 6-1 is the cause and effect diagram of rail unreliability. The diagram is also known as Ishikawa or Fishbone diagram. The diagram groups four possible causes that may lead to rail unreliability i.e. manufacturing, environment, design, operating conditions and maintenance.

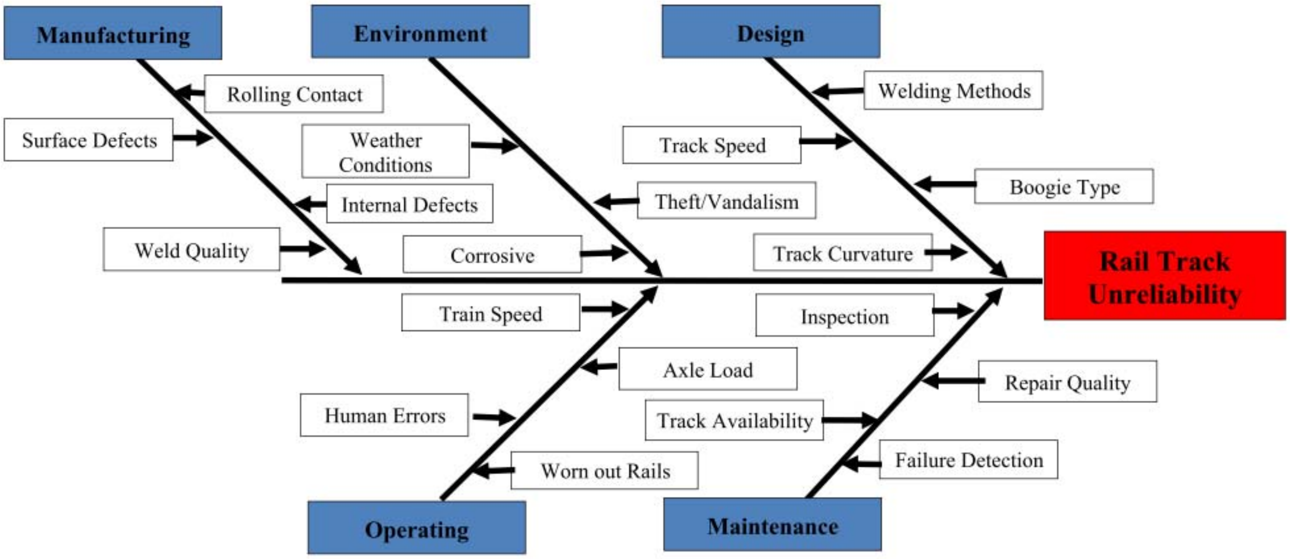


Figure 6-1: Cause and Effect of Rail Unreliability.

6.1 RELIABILITY IMPROVEMENT THROUGH DESIGN MODIFICATION

The criterion of reliability is used to measure system performance and availability. Such measurement can be achieved by setting reliability targets, as well as by means of designing system components for reliability, maintainability, and reliability modelling. Reliability forms part of the conceptual and detailed design process of system development. However, after the equipment is designed and installed, the reliability of the system becomes a quality process that is subject to continuous measurement and analysis, so as to ensure that it performs according to the reliability design intent. However, due to dynamic changes in the operation and the environment, the design reliability might not be achieved, thus the modification of design is necessary when consistent failures or defects are seen.

The reliability of rail track infrastructure can be improved by means of design, such as the following:

- The designing of rail tracks with high reliability characteristics, involving the choosing of components with good RAMS features, as well as a high MTBF, and a low MTTR
- Improved designs for rail components, such as rail pads, ballast, and turnouts
- The incorporation of online failure and smart wear detection systems
- Designing for ‘graceful degradation’ such as rail track
- Design that accommodates future expansion and loading.

The reliability of a component, or of a system, is a function of design, and not of maintenance. Hence, a system with good reliability evolves from a robust design that encompasses all possible failure and operational philosophy to which the system is likely to be subjected during its design life. Design modification, or change management, is recommended by reliability engineers when there is an increased occurrence of operational breakdown that leads to the conclusion that the system/components have an inherent flaw, or that the system could perform better with a new design, and at lower LCC. The improvement of rail infrastructure reliability can be viewed as enhancing either inherent or operational reliability.

When the inherent reliability of the system/components is faulty, the system/component modification is eminent. However, faulty operational reliability might be due to poor maintenance and personnel management, which is likely to be able to be improved with the implementation of improved maintenance management policies.

Rail tracks tend to be designed for high reliability, but when failures or defects are experienced, the repair and recoverable time that is taken up in replacing or repairing them are high, due to the non-availability of the tracks in the interim. Rail failures are generally caused by defects in the rail materials, and wear, resulting from the high demand for train transportation, the increased train speed, and the heightened axle load involved. It has become of paramount importance to improve the rail track reliability through design modifications, such as by means of railhead hardening and by improving the design for sharp bends, as well as the rail material used. Doing so should contribute to ensuring that rail track can withstand wear, load, erosion, and manufacturing defects in future.

6.2 RELIABILITY IMPROVEMENT BY MEANS OF MAINTENANCE IMPROVEMENT

Reliability improvement of railway infrastructure, in terms of both repairable and non-repairable systems, can be improved by following certain maintenance strategies that are aimed at increasing rail service life and at failure prevention.

Maintenance management is the combination of all technical and administrative actions that are intended to restore a system, or component, to a state in which it can perform its required function. Maintenance management activities that can be used to improve reliability, and thus availability, include the following, among others:

- Improved structuring and organisation of the operation and maintenance service
- Standardisation of operation and maintenance activities
- Performance measurement and cost-benefit analysis of maintenance management
- Introducing measures of redundancy in critical applications, where it is practical to implement.

The improvement of rail reliability by means of the implementation of improved maintenance policies could be achieved by way of selecting the appropriate maintenance strategy that is based on the likelihood and consequence of failure. The historical data relating to failures, and to the performance of a railway depot, can be used to improve future reliability by means of evaluating the maintenance performance and the skill levels of the maintenance personnel and operators involved. Maintenance operations are not exclusively dependent on the condition of the system or the component, as they are influenced, in some instances, by plant downtime opportunities. The influence is due to the high rate of some railway track utilisation throughout the day. As a result, much planning has to be done to schedule maintenance operations at an appropriate time, when there is either relatively little, or no, traffic.

Railway infrastructure, such as rails, consists of critical non-redundant equipment, requiring that it be maintained at 100% reliability, if the operational intent is to achieve 100% availability. In contrast, redundant equipment, such as rolling stock, is not maintained at 100% reliability, because it accumulates hours unevenly, so as to ensure that low-hour equipment is always available when it is required. Thus, for a rail to have acceptable set target reliability, a maintenance strategy must be in place to achieve the following:

- Improved spares inventory management
- Improved system reliability
- Decreased system downtime
- Decreased cost of replacing track components

6.2.1 FAILURE MODE AND EFFECTS ANALYSIS (FMEA)

FMEA is a reliability method by means of which each potential failure mode in a system is analysed to determine the results, or effects, thereof on the system, as well as to be able to categorise each potential failure mode according to its risk probability number (RPN) (IEC 60812, 2001). If the analysis is carried out to categorise each potential failure mode according to its severity and probability of occurrence, the analysis is called a failure mode, effects, and Criticality Analysis (FMECA).

FMECA is used in maintenance planning so as to monitor items whose failure modes cost more, and that take the longest to repair, as well as limiting the functionality of the system by the greatest degree. FMECA also provides for the identification of reliability critical items that are likely to require improvement.

FMEA, when performed in terms of a system, enables the identification of faults that can lead to system failure, so that they can be detected, isolated, and removed, for the preservation of system integrity. FMEA uses inductive logic in a 'bottom- up' approach, starting at the lowest level of the system hierarchy. By means of assessing the failure modes of each part of the system, the reliability engineer then traces the modes up through the system hierarchy to determine the effect that each has on the system's performance. FMEA differs, in its 'bottom-up' approach, from fault tree analysis (FTA), which utilises inferential logic in a 'top-down' approach (MIL-HDBK-338b, 1998). In FTA, the reliability engineer, assuming the nature of the system failure, and traces down through the system hierarchy to determine the event, or the series of events, that could probable cause the failure.

Whereas FMEA uses a qualitative method, FMECA uses a quantitative method. Both, however, are used extensively during the design phase for purposes of reliability improvement. Typically, quantitative measures are: the reliability index; availability; failure rates; and MTTF (Singpurwalla, 2013).

6.2.2 PURPOSE OF AN FMEA/FMECA STUDY

Below are some of the major objectives of FMEA/FMECA:

- To provide an effective method for evaluating the effect of proposed changes to the design.
- To identify failures that has unwanted effects on system performance, safety, and operations.
- To allow for improvement of the system's maintainability (by highlighting areas of risk, or nonconformity, for maintainability).
- To allow for the determination of the significance, or the criticality, of each failure mode, and its impact on the reliability, or safety, of the system.
- To allow for the development of design improvement plans geared towards mitigating failure modes.
- To support the development of an effective maintenance management, so as to mitigate, or to minimise, system failures.

6.2.3 PRINCIPLES OF FMEA/FMECA

The basis of an FMEA/FMECA study is to review a system/equipment in a series of meetings. During the meetings, a multidisciplinary team strategically analyses the system design, so as to identify all possible failure modes and causes and effects of the failures. In addition, any safeguards that are already in place can be identified at such meetings, so as to allow for the mitigation of any potential failure, through its identification and recording.

The advantage of the expert approach group is that it stimulates thought processes, and helps to ensure the input of necessary expertise. FMECA is undertaken using a risk matrix, which is employed to estimate the severity, and the probability, of each failure mode, so that it can be assigned a criticality rank. Such ranking assists the team in identifying areas, or components, that require most attention. The FMEA/FMECA team then exercises its judgement as to whether the equipment, or the system, requires modification, or further action, in terms of the risk involved, and whether any relevant recommendations should be implemented. The analysis is then recorded on the appropriate FMEA/FMECA worksheets (Singpurwalla, 2013).

The application of an FMEA/FMECA is preceded by a hierarchical decomposition of the system into its more basic elements. Such decomposition can be done with the assistance of simple block diagrams, or with the aid of existing functional diagrams, with the analysis then starting with the lowest level components. A failure mode effect at a lower level might then become a failure mode of an item in the next higher level. The analysis proceeds in a bottom-up fashion until the end effect on the system is identified. Risk is assessed in terms of RPN, which is a product of severity, occurrence, and detection (MIL-HDBK-338b, 1998).

6.3 PRASA MAINTENANCE STRATEGY

Passenger Rail Agency of South Africa (PRASA), which is a wholly state-owned company, operates the rail operation of metro commuter long-distance intercity and cross-border services. Figure 6-2 is the component of track maintenance strategy. These events are interdependent, but not necessary sequential and are used for maintenance planning and capital reinvestment.

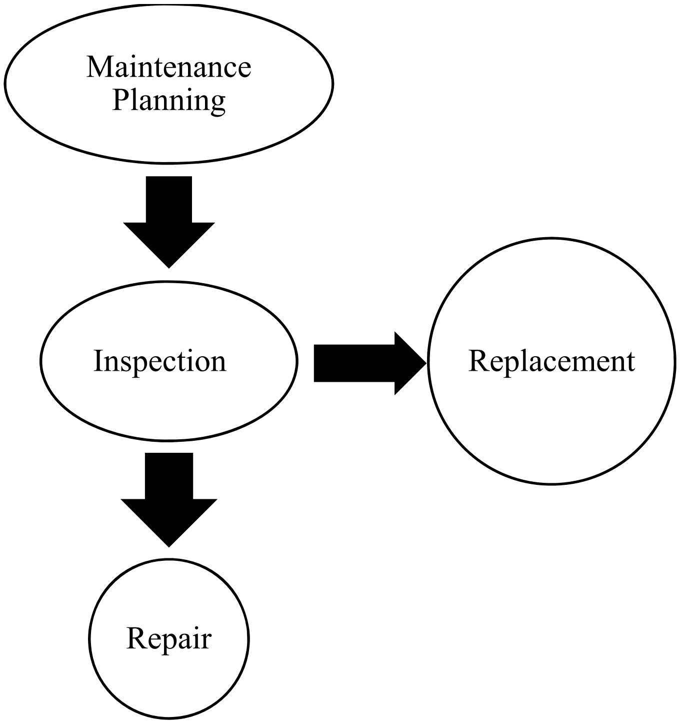


Figure 6-2: Track maintenance Chain of Events.

PRASA's Metrorail maintenance and reliability department use enterprise maintenance planning and control (EMPAC) system, in terms of which maintenance performance, planning, and the budget are documented. However, it must be borne in mind that the PRASA EMPAC system might be comprehensive, but not exhaustive, EMPAC gives only the regional and national perspective of the performance and budget.

The maintenance interval for such items as track cannot be based on the national or regional MTBF prescription, because the MTBF and the MTTR are averages that are based on constant failure rates. As a result, the Metrorail EMPAC system does not take into consideration each depot's utilisation, history, loading, and environment. Neither does it take into account the skill levels of inspectors, nor the track geometry involved. Therefore, the strategy is neither cost-effective, nor technically reliable.

PRASA Metrorail maintenance strategies of its track are presented in Table 6-1.

Table 6-1: On-Track Maintenance.

ON-TRACK MAINTENANCE		
	Work Unit	Work Frequency
PLANNED ROUTINE MAINTENANCE		
OPERATIONAL STATE ASSESSMENT		
Infrastructure measuring vehicle	Track km	4-monthly
PHYSICAL STATE ASSESSMENT		
Running lines: tangent track	Track km	48-monthly
Running lines: curved track	Track km	48-monthly
Running lines: turnouts	Unit	12-monthly
Running lines: ultrasonic rail testing	Track km	6-monthly
Running lines: rail stress assessment	Track km	12-monthly
Yard track	Track km	48-monthly
Yard turnouts	Unit	24-monthly

SAFETY INSPECTIONS		
FOOT PATROLLING		
Running lines ‘A-corridors’	Track km	Twice daily
Running lines ‘B- & C-corridors’	Track km	Weekly
Yards	Track km	Monthly
SAFETY INSPECTIONS		
TURNOUTS		
Running lines: turnouts	Unit	Monthly
Yard turnouts	Unit	6-monthly
TROLLEY INSPECTIONS		
Track inspector’s trolley	Track km	Half-monthly
Regional engineer’s trolley	Track km	2 monthly

Table 6-1 above indicates the on-track maintenance of PRASA Metrorail. The maintenance items concerned comprise planned maintenance that is undertaken in a projected financial year. The items are evaluated at the end of the year to see whether the set targets have been achieved. The frequencies are from identified failure mechanisms, as well as from the original equipment manufacturers, and from the qualitative and quantitative analysis undertaken by the PRASA technical head office. The maintenance strategy is presented to depots across the various provinces and regions for implementation.

The scheduled maintenance activities that are shown in Table 6-2, after being determined on the basis of risk analysis and maintenance best practices, are implemented across the regions.

Table 6-2: Scheduled Maintenance Activities (PRASA, 2013).

SCHEDULED MAINTENANCE ACTIVITIES		
SCHEDULED ACTIVITIES	Work Unit	Work Frequency
Tangent track and curved track		
Level crossings	Unit	Monthly
Track lubricators	Unit	Monthly
Block joints	Unit	6-monthly
Fish plated joints	track km	Yearly
Track signage	track km	Yearly

The PRASA Metrorail CM frequency (see Table 6-3) is not determined at head office, but the responsibility for the establishment of such frequency is left to the depot level. The maintenance strategy concerned seems to be executed at the depot level as a ‘run–to–failure maintenance’, by assuming which of the items are not critical to railway track availability.

Table 6-3: Corrective Maintenance (PRASA, 2013).

CORRECTIVE MAINTENANCE (DAY–TO–DAY)		
	Work Unit	Work Frequency
Track maintenance		
Repair geometry	Unit	As required
Spot rail replacement	Unit	As required
Spot sleeper replacement (turnouts)	Unit	As required

Transposition of rails	Unit	As required
Repair of UMC-detected defects	Unit	As required
Replacement of stock and switches	Unit	As required
Replacement of crossings	Unit	As required
Replacement of field block joints	Unit	As required
Load/Offload rails	Unit	As required
De-stressing of continuous welded rails	Unit	As required
De-stressing of jointed track	Unit	As required
Replacement of sleeper fastenings	Unit	As required
Offload ballast	Unit	As required
Track Welding		
Crossings	Unit	As required
Battered rail ends	Unit	As required
Skid marks	Unit	As required
Alumino thermit welding	Unit	As required
Grinding overlap	Unit	As required

If intensive and adequate condition monitoring is in place together with the principle of early detection of faults and remedial action/maintenance before the defect becomes critical, then the system cannot (Table 6-3) be considered run-to-failure.

6.4 CLUSTER MAINTENANCE STRATEGY

PRASA utilises a centralised system of maintenance strategy, where the prescribed maintenance and inspection interval for its infrastructure are documented, and roll-out to regions and depots. One of the major advantages of this strategy is the standardised procedures. However during the course of PRASA Metrorail depot visitation and consultation, it was found that the failure events and traffic utilisation are not following similar trends across train station depots. This prompt for a decentralised maintenance strategy

Cluster maintenance strategy is recommended for PRASA Metrorail. Cluster maintenance strategy for railway track infrastructure can be described as a maintenance strategy, where train station depots with similar infrastructure, critical failure events, traffic utilisation, resources and prevailing environment utilises a centralised preventive maintenance strategy for the identified cluster/s train depot stations.

6.5 CHAPTER SUMMARY

In concluding this chapter, the following summary statements are made;

- The review of PRASA's Metrorail maintenance strategy and philosophy, which uses the enterprise maintenance planning and control (EMPAC) system, in terms of which maintenance performance, planning, and the budget are documented.
- General reliability improvement was reviewed on the basis of two concepts, namely design modification and maintenance management optimisation.
- FMEA reliability improvement was introduced and the principles and objective reviewed.

CHAPTER SEVEN

7. CASE STUDY PRASA METRORAIL

PRASA Metrorail failure analysis is conducted with focus on Gauteng South. Gauteng South covers 15 train stations with total travel kilometres of 661 km. See APPENDIX A for detailed information of the train stations.

7.1 FAILURE ANALYSIS - PARETO

Pareto analysis assists the maintenance department in identifying components that have the highest contribution and impact to system failures. Pareto analysis uses the database of failures to identify where resources and research should be directed. It's a first system analysis of failures analysis. Gauteng South Track number of events, Response time and Outage time that were recorded for the year 2012 – 2013 (PRASA, 2013). The data showed that;

- Total number of failure events : 868
- Total failure response time : 578 hours
- Total failure outage time : 1680 hours

Therefore the average response time per event is 0.67 hours and average outage time per event is 1.94 hours.

Figure 7-1 is the Pareto analysis of GAUTENG SOUTH PERWAY NUMBER OF FAILURE EVENTS for the year 2012 – 2013. CALLS TO PERWAY due to railway section defects recorded the highest number of failure events (183) followed by defective rails with 172 failure events and 105 failures events for sub-standard geometry. The three frequent failure events can be attributed to mechanical degraded railway track.

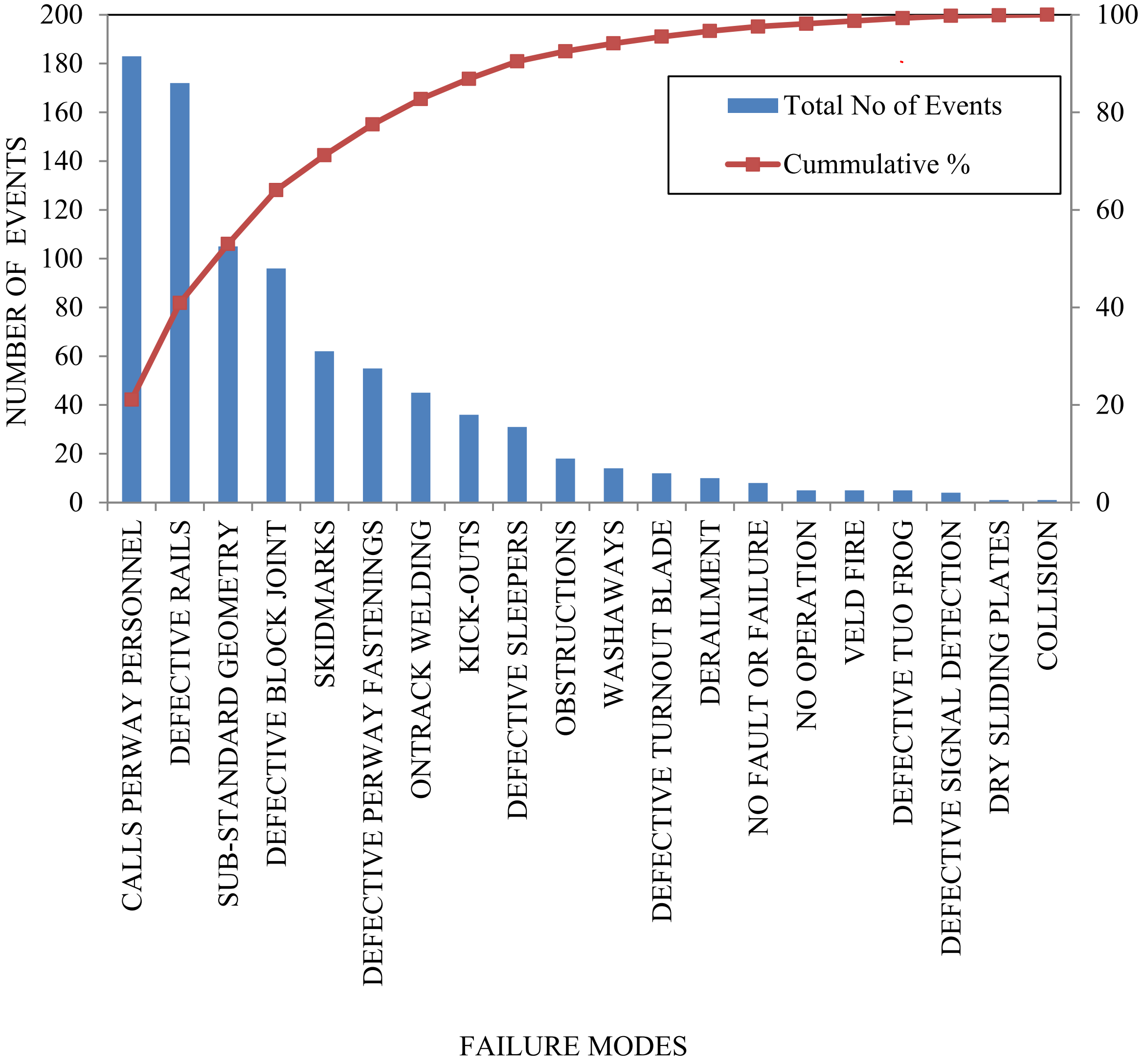


Figure 7-1: Gauteng South Perway Number of Events.

Figure 7-2 is the Pareto analysis of GAUTENG SOUTH PERWAY RESPONSE TIME. Defective rails recorded the highest response time, followed by sub-standard geometry and defective block joints in PRASA Metrorail Gauteng South Perway. These areas need improvement from PRASA maintenance department.

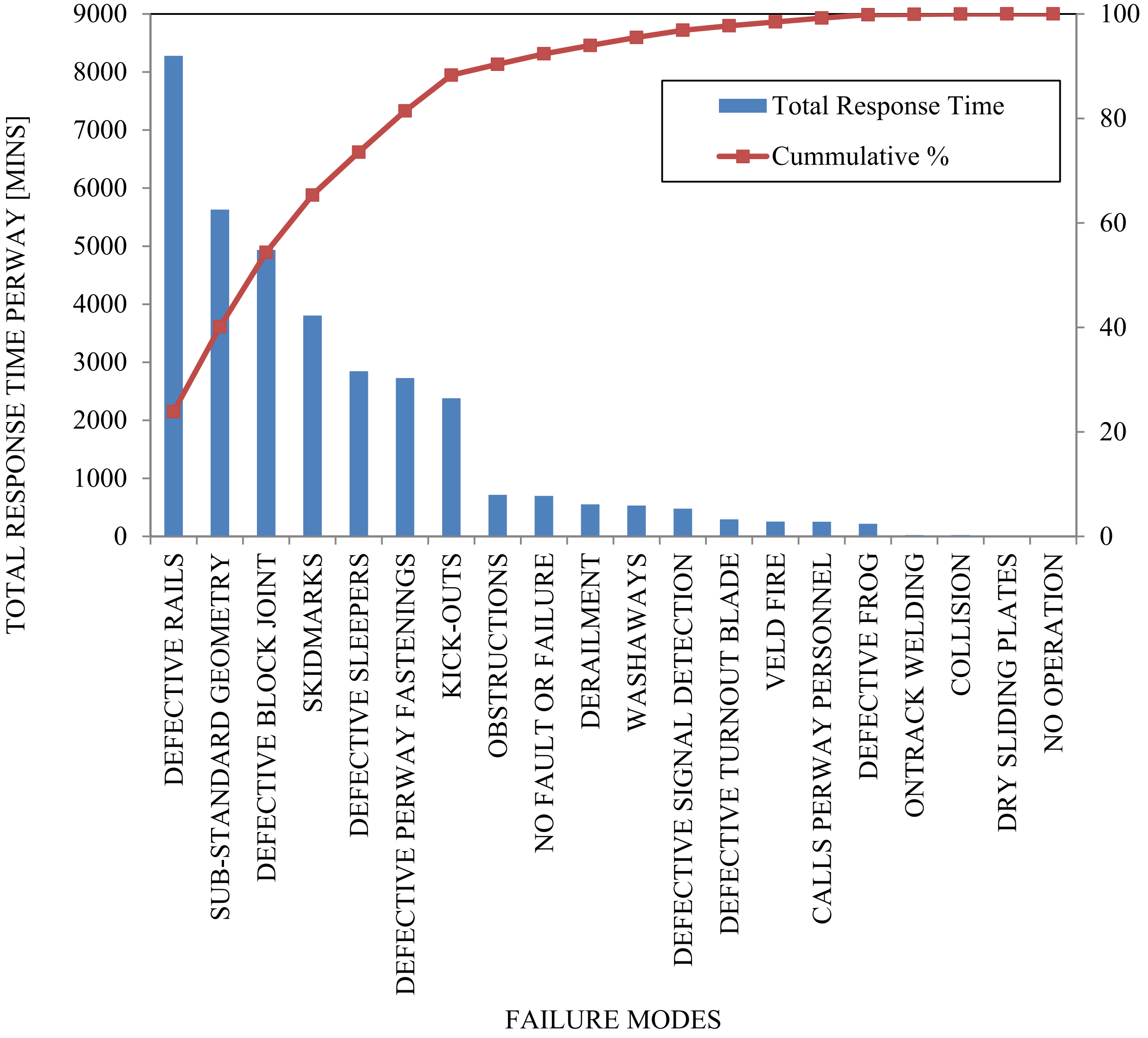


Figure 7-2: Gauteng South Total Response Time Perway.

Figure 7-3 is GAUTENG SOUTH PERWAY OUTAGE TIME. The three failure events that contributed significantly to PRASA Metrorail outage time are defective rails, skid marks and sub-standard geometry. These items require corrective replacement.

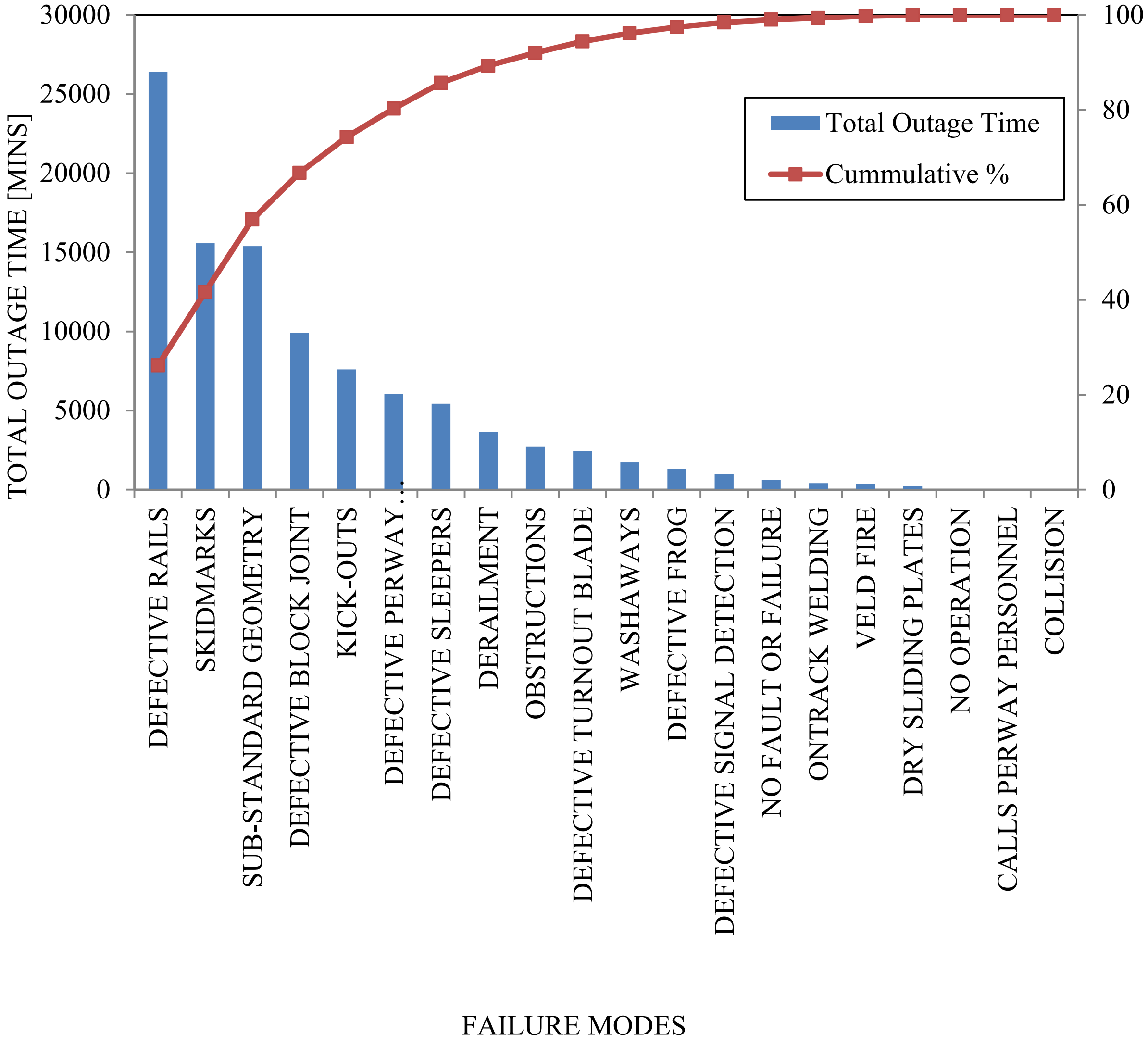


Figure 7-3: Gauteng South Total Outage Time Perway.

The summary:

- Defective rails – 154 minutes/failure events
- Skid marks – 251 minutes/failure events

- Sub-standard geometry – 60 minutes/failure events

Figure 7-4 show the frequency of defective rails in Gauteng South. The failures from Perway – Track are mostly due to rail failures that need attention from Perway personnel, which account for 21% of the failures.

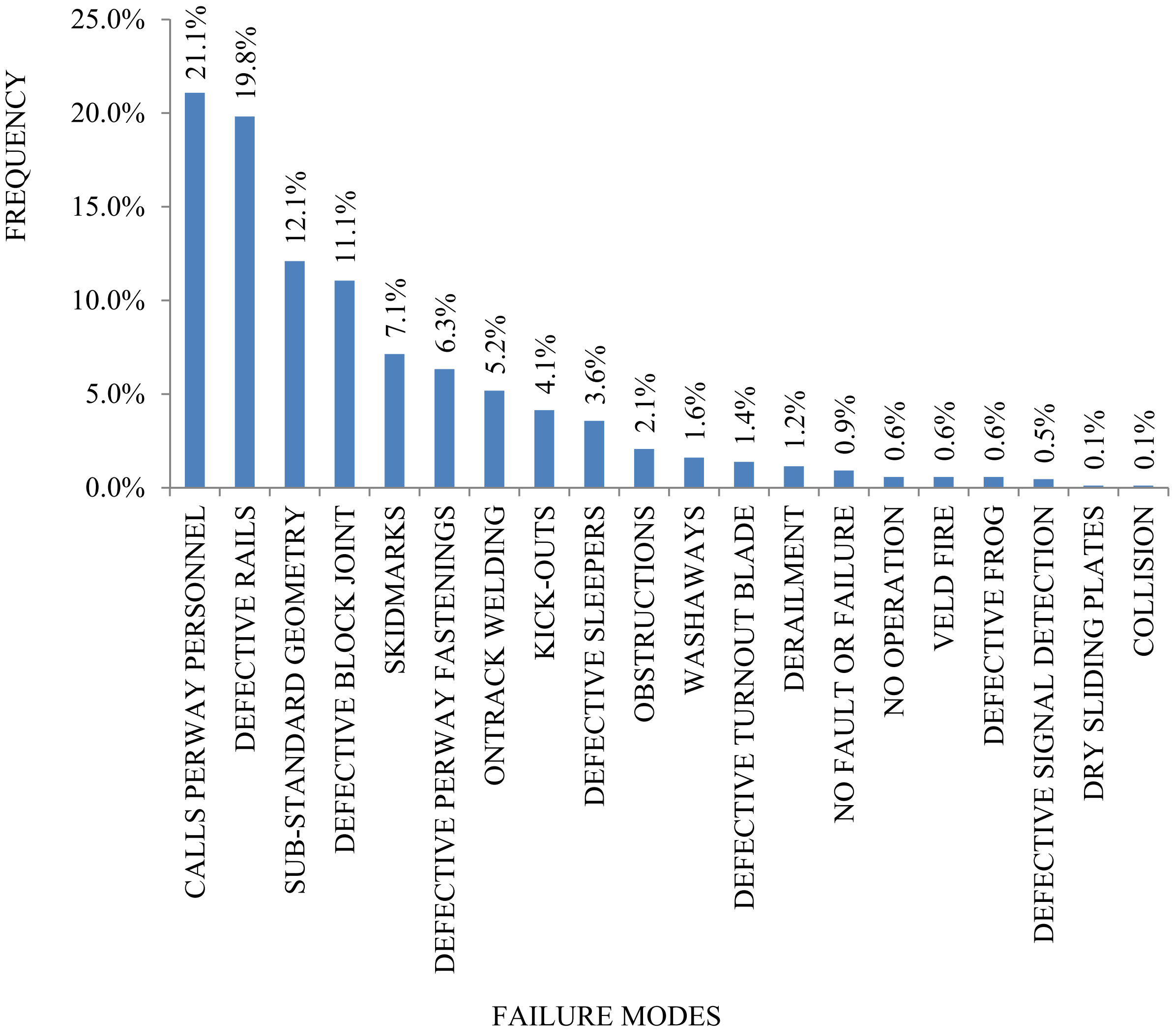


Figure 7-4: Gauteng South Failure Modes Distribution Perway 2012-2013.

Table 7-1 is the Capital intervention for Gauteng South for the year 2012-2013. The capital interventions are planned corrective replacement and repair activities to restore component reliability.

Table 7-1: PRASA/Metrorail Capital Intervention Programme – Gauteng South.

PROJECTS	**2012/2013**		
Description	**Unit**	**Qty**	**Amount [ZAR]**
Rerail (Sections > 35m)	km rail	8.39	12,582,000
Resleeper (Sections > 35m)	km track	9.67	11,602,799
Replace turnouts 1:9	e.a.	4	3,640,000
Replace turnouts 1:12	e.a.	10	9,200,000
Replace single slips	e.a.	1	2,710,000
Replace double slips	e.a.	3	8,610,000
Replace diamond crossings	e.a.	-	-
Replace scissors crossings	e.a.	-	-
Replace major turnout components	e.a.	40	6,400,000
Replace block joints	e.a.	120	3,600,000
Replace section fencing	km	2	2,000,000
Ballast screening	km track	40	12,800,000
Replace ballast during screening operation	km track	20	1,920,000
Rail re-profiling	km track	60	9,000,000
Continuous ballast tamping operation	Km track	600	12,000,000
Rehabilitation of formation	Sum	1	1,000,000
Drainage upgrading	sum	2	2,000,000
Replace turnout sleepers (universal type)	e.a.	5	1,500,000
Rehabilitation of Service Roads	e.a.	1	1,000,000
Bridge rehabilitation	sum	2	2,000,000
PERWAY TOTAL			R 103,564,799

Continuous ballast tamping operation maintenance was planned for 91% of total travel kilometre of Gauteng South track. Ballast tamping is used to restore and align track geometry.

7.1.1 FMEA CASE STUDY

RCM is a continuous decision-making process for identifying the best-suited maintenance requirements, as well as management decisions and actions, for a system, in accordance with its LCC and safety. FMEA/FMECA is part of RCM.

Railway track failures can be grouped into two major groups:

- Deformation from Geometry: These types of failure events are caused by deformation of supporting components of the railway track such as ballast, subgrade and ties. Geometry deformation can be corrected with corrective maintenance strategy. FMEA and failure tree analysis (FTA) can address the root cause of the subsystems that contribute to the failures.
- Mechanical: These types of failure events are caused by degradation initiated by wear, loads and environmental conditions. Mechanical events in most instances in railway track cannot be corrected; hence replacements of the components are required.

Understanding the failure modes and effects would assist in determining the optimum maintenance strategy. Table 7-2 is the summary of critical failure mode and effect analysis of PRASA Metrorail track. The table shows that most of the failures can be prevented by regular inspection, maintenance and improved detection systems, therefore to improve a reliable railway track, the maintenance strategy should aim at;

- Preventive maintenance to prevent costly capital reinvestment

- Capital reinvestment to extend the life of degraded components (see APPENDIX B for the ranking of Gauteng South track components)
- Improved failure detection system so as to choose the appropriate corrective or preventive maintenance.

Table 7-2: FMEA Railway Track.

No	Description	Failure Cause	Failure Effects	Failure Detection	Maintenance Strategy
1.0	**Rail**				
1.1	Rail Corrugation	Axle loads, inconsistency traffic speeds, curve radius, rail support conditions, plastic flow of materials	Rail degradation of rail components such as rail pads, sleepers, clips, welds, bolt holes	Visual, Laser	Rail Grinding to improve profiles
1.2	Squat Defects	High dynamic load	Rail failure	Ultrasonic Inspection, Visual	Preventive rail grinding, lubrication,
1.3	Tache Ovale	Excessive hydrogen in welds and rail steel	Rail failure, increased maintenance cost	Ultrasonic Rail Inspection, eddy currents	Better quality improved manufacturing and welds
1.4	Horizontal Split Head	Metallurgical problems in manufacturing	Rail failure, maintenance cost	Ultrasonic Inspection	Grinding, Frequent inspection and replacement
1.5	Vertical Split Head	Metallurgical problems in manufacturing	Rail failure, maintenance cost	Ultrasonic Inspection	Grinding, Frequent inspection and replacement
1.6	Rolling Contact Fatigue Defects	High shear stresses, axle loads, rail geometry	Rail failures	Eddy Currents, visual & ultrasonic inspection,	Rail lubrication, Higher strength rails, rail grinding
1.7	Broken Bolt	Excessive longitudinal forces on the crossings, manufacturing defects, corrosion, improper	Derailment, rail failure, maintenance cost	Visual Inspection, radiography	Scheduled Replacement, Improved design and replacement

		torque			
1.8	Broken or Cracked Fishplate	Inadequate support to the rail sleepers, corrosion	Rail buckling, rail degradation	Visual Inspection	Scheduled Replacement, Improved design and replacement
2.0	**Sleepers**				
2.1	Concrete Sleeper				
2.1.1	Concrete Spalling	Rusted reinforcing, weather	Increased maintenance cost, Failure	Visual Inspection	Corrective repair / replacement maintenance
2.1.2	Cracks	Shear at the top, lack of concrete cover, Crack due to tamping machines, torsional load, ballast pollution, drainage problems, shocks, increased loading	Structural integrity compromised, failure, derailment	Visual Inspection	Manufacturing quality control
2.1.3	Rail Seat Deterioration (RSD)	Rail seat abrasion, hydraulic pressure cracking, chemical deterioration, fastener wear, traffic, curvature, moisture	Derailments, Increased track maintenance cost	Machine Vision	Corrective Replacement, shape recognition
2.1.4	Split Concrete Sleeper	Tamping machine, loading from non-uniform support	Structural integrity compromised, failure, derailment	Visual Inspection	Corrective Replacement
2.2	Timber Sleeper				
2.2.1	Fungal Decay	Attack from micro-organism	Structural integrity compromised, failure	Visual Inspection	Moisture control, fungicide, impregnation with synthetic chemicals

2.2.2	Termite Attacks	Termite attacks	Structural integrity compromised, failure	Visual Inspection	Treatment with chemical such as creosote, physical barriers,
2.3	Steel Sleeper				
2.3.1	Corrosion	Supporting soils agents, moisture	Sleeper failure, track geometry deficiency	Visual and Ultrasonic Inspection	Protective coating
2.3.2	Fatigue Cracking	Cyclic loading	Sleeper failure, track geometry deficiency	Visual and Ultrasonic Inspection	Corrective Replacement, increased inspection frequency
3.0	**Ballast**				
3.1	Ballast Pockets	Load induced depressions beneath the ballast layer	Structural integrity, track settlement	Visual Inspection	Corrective maintenance – draining the ballast pocket
3.2	Erosion	Water in the subgrade	Structural integrity compromised, loss of track restrain and alignment	Visual Inspection	Blanket material – preventive maintenance, frequent inspection
3.3	Ballast Fouling	Contamination by fine grained aggregate, metal rust	Deformation of ballast section, misalignment	Ground penetration radar (GPR), visual inspection	Bio remediation, Corrective replacement
3.4	Shear	Cyclic loading, high water content, fine grained subgrade	Breakage of the sharp ballast particles,	GPR, visual inspection,	Corrective replacement of Ballast

		soil	integrity compromise, derailment	automatic ballast sampling	
4.0	**Subgrade**				
4.1	Plastic Deformation	Soil compaction, cyclic loading-liquefaction	Differential track settlement, track geometry compromise	Visual Inspection, Accelerometers, Settlement probes	Preventive maintenance- subgrade replacement, geotextiles for improvement
4.2	Consolidated Settlement	Embankment weight – increased soil stress and settlement	Track geometry compromise, track settlement	Visual Inspection	Corrective maintenance-geotechnical engineering
4.3	Shear Failure	Cyclic loading, high water content, fine grained subgrade soil	Inhibits drainage, increase track maintenance	Visual Inspection, Accelerometers	Preventive maintenance- subgrade replacement, geotextiles for improvement

7.1.2 FMEA FRAMEWORK CASE STUDY

The conceptual framework presented here is comprised of FMECA failure events, occurrence evaluation, severity evaluation criteria, detection evaluation, risk priority numbers and risk assessment value. The objective is to get an improved categorisation of the most critical failure modes from the categorisation described in Figure 7-1.

Table 7-3 is the occurrence evaluation ratings used in evaluating PERWAY failures occurrence,

Table 7-4 is the severity ratings measured according to the outage time of the failure and Table 7-5 is the detection rating of the FMEA.

Table 7-3: FMEA Occurrence Evaluation (Adapted from Sameni, M.K., (2012)).

		Failures rate (Average per day in Gauteng South)	Ranking
Very high	Persistent failures	40 or more	10
		20	9
High	Frequent failures	10	8
		5	7
Moderate	Occasional failures	2	6
		1	5
Low	Relatively few failures	0.5	4
		0.2	3
Remote	Failure is unlikely	0.1	2
		0.05	1

Table 7-4: FMEA Severity Evaluation (Adapted from Sameni, M.K., (2012)).

Severity evaluation criteria	Outage Average delay minutes per incident	Ranking
Extremely disrupting	More than 160 minutes	10
Very disrupting	Up to 160 minutes	9
Very high	Up to 80 minutes	8
High	Up to 40 minutes	7
Moderate	Up to 20 minutes	6
Low	Up to 10 minutes	5
Very low	Up to 5 minutes	4
Minor	Up to 2 minutes	3
Very minor	Up to 1 minute	2
None	No discernible effect on network	1

Table 7-5: Detection Evaluation (Adapted from Sameni, M.K., (2012)).

Detection	Description	Ranking
Not detectable	The risk is not detectable by existing control mechanisms in the system	10
Almost undetectable	The risk is almost undetectable by existing control mechanisms in the system	9
Very low	There is very low chance that the risk is detected by existing control mechanisms in the system	8
Low	There is low chance that the risk is detected by existing control mechanisms in the system	7
Moderately low	There is moderately low chance that the risk is detected by existing control mechanisms in the system	6
Moderate	There is 50-50 chance that the risk is detected by existing control mechanisms in the system	5
Moderately high	There is moderately high chance that the risk is detected by existing control mechanisms in the system	4

High	There is high chance that the risk is detected by existing control mechanisms in the system	3
Very high	There is very high chance that the risk is detected by existing control mechanisms in the system	2
Definitely detectable	The risk is definitely detectable by existing control mechanisms in the system	1

Risk priority numbers (RPN) is used to prioritise components that require greater considerations. Table 7-6 is the RPN showing the ranking for PRASA Metrorail Perway failure events for the year 2012 - 2013. Defective rails score the highest RPN, followed by defective block joints, which translate to highest priority when planning for maintenance.

$$\text{Risk priority number (RPN): Occurence} \times \text{Severity} \times \text{Detection}$$

Table 7-6: Risk Priority Numbers.

Failure Events	**O**	**S**	**D**	**RPN**	**RPN Priority Ranking**
Defective Block Joint	4	9	8	288	2
Defective Perway Fastenings	2	9	8	144	7
Defective Rails	5	9	7	315	1
Derailment	1	10	7	70	8
Sub-Standard Geometry	3	9	8	216	5
No Operation	9	6	5	270	4
Skidmarks	1	10	7	70	8
Ontrack Welding	2	4	7	56	9
Calls Perway Personnel	5	6	5	150	6
Obstructions	5	8	7	280	3

RAV is focused on the ability of the system to detect failures, and manage failures. RAV is proposed due to the outage time and repair time contribution to rail unavailability.

Table 7-7 is the RAV and priority ranking. No Operation recorded the highest RAV priority followed by defective rails which had the highest RPN.

Risk assessment value (RAV): $\frac{\text{Severity} \times \text{Occurence}}{\text{Detection}}$

Table 7-7: Risk Assessment Value

Failure Events	**O**	**S**	**D**	**RPN**	**RAV Priority Ranking**
Defective Block Joint	4	9	8	288	5
Defective Perway Fastenings	2	9	8	144	7
Defective Rails	5	9	7	315	2
Derailment	1	10	7	70	8
Sub-Standard Geometry	3	9	8	216	6
No Operation	9	6	5	270	1
Skidmarks	1	10	7	70	8
Ontrack Welding	2	4	7	56	9
Calls Perway Personnel	5	6	5	150	3
Obstructions	5	8	7	280	4

7.2 CAUSES OF METRORAIL TRACK UNRELIABILITY

Even though PRASA has a maintenance plan, the causes of the failures need to be understood and eliminated. From the FMEA, the causes of failures of critical components can be attributed to;

- Age degradation due to cumulative tonnage and wear
- Budget constraints to execute planned maintenance
- Inadequate detection and monitoring systems for the railway track
- Repair and replacement occur on a reactive rather than a proactive basis
- Response time to failure events are slow

Table 7-8 is the cost component of the six critical items that contribute to track unreliability.

Table 7-8: Direct Cost of Critical Track Components (PRASA, 2013).

Description	**Unit**	**Cost [ZAR]**
Turnouts	e.a.	920,000
Single Slips	e.a.	2,710,000
Double Slips	e.a.	2,870,000
Diamonds	e.a.	710,000
Rails	km rail	1,500,000
Sleepers	km track	1,200,000

FMEA can be used to improve the reliability of rail track by identifying the sections of the railway track that have the highest (critical) and frequent failures, hence using RPN and RAV to prioritize, and determine the appropriate preventive and corrective maintenance.

RCM in railway infrastructure objective is to avoid, or to reduce, the consequences of failure, through the implementation of a PM strategy geared towards providing optimal system availability and safety, at the lowest possible cost. The FMEA conducted highlighted the following:

- Presented the severity of the potential failure modes and provide input into mitigating measures to reduce risk of the component failures.
- Provides an effective method of identifying criticality of each failure mode and the impact.
- The FMEA has shown that the failure causes are mainly due to age degradation, lack of maintenance and inadequate failure detection systems as can be seen in Table 7-6 and Table 7-7.

7.3 CHAPTER SUMMARY

In concluding this section, it is noted that we have looked at RCM Failure Mode Effects Analysis (FMEA) was used to analyze Gauteng South rail track infrastructure. RPN and RAV were used to identify areas that require improvement and attention. FMEA was able to identify points of failure and weakness in the maintenance strategy, which can be seen in the outage and response time of the component failures (see Table 7-6 and Table 7-7).

CHAPTER EIGHT

8. CONCLUSIONS AND RECOMMENDATIONS

Railway transport operation is both capital- and labour-intensive; therefore, railway managers are continuously looking for new techniques by means of which to improve the reliability of railway transport, while providing high-quality service. Their aim is to remain competitive, keeping in mind the high cost of transportation, and the inevitably deteriorating infrastructure. In line with the objective of this thesis, which has been to research methods of improving rail infrastructure reliability, it was found that railway tracks are non-redundant systems with fixed time inspection and maintenance intervals. Accordingly, most decisions regarding maintenance are taken without considering the age degradation, the utilisation, failure causes and the design life of the rail concerned.

In studying the global failures of rail track, it was found that the industry is experiencing an increased number of failures, and it is experiencing similar trends worldwide. Hence, reliability improvement techniques were evaluated to find methods that can assist in the improvement of the reliability through improved failure management. Such management is aimed at mitigating failures through the adoption of improved planning, based on the data that have become available on failures.

8.1 CONCLUSION AND CONTRIBUTIONS

It can be concluded that the research objectives have been achieved, that of:

a) A frame work for obtaining improved categorization of the most critical failure modes in railway track infrastructure has been developed. This was achieved by using RCM-

FMEA and Pareto analysis. Understanding and identifying the potential failure modes is critical in preventing their re-occurrence.

b) The collection of rail track failure data and the associated cost of preventive and corrective maintenance of critical track components. The cause and effect of railway track unreliability have also been identified.

c) The case study showed that FMEA can be employed to evaluate which RCM strategies are required; such as a preventive or corrective maintenance activity required, in the light of its ability to identify the causes, effects and mitigation of rail failure, using historical failure data.

d) It was found that rail failure is a function of its usage in terms of gross tonnage for determined conditions. In terms of such thinking, it was then observed that the MTTF and the MTBF that is traditionally used by many railway operators is not an optimised concept of measuring reliability, because such measures assume the presence of a constant failure rate. In reality, however, the failure rate is not constant, because the failure mechanisms are due to changes in the gross accumulated tonnage, and geographic-specific problems. As a result, the MTTF and the MTBF are not recommended for use in terms of the scheduling and planning maintenance intervals of rail track with dynamic changes in operation and environment.

8.2 RECOMMENDATIONS AND FURTHER WORK

8.3 RECOMMENDATIONS

In continuation of the work that has been done so far in this thesis, the following recommendations are made for future research:

a) The observation of the limited and incomplete/inaccurate database on railway failures is important, because obtaining improved data would enable the better prevention of failures, and thus lead to the betterment of maintenance planning, budgeting, and execution. Consequently, it is recommended that failure reporting be improved.

b) Cluster maintenance strategy of each depot should be applied where the interval of PM and CM is based on dynamic reliability, which takes into account the age of the system, the observed rate of service defects, and its utilisation.

c) The maintenance strategy should be dynamic, and it should not be based on either historical factors, or on the judgement of experienced personnel. This is because of the changes in rail dynamics in respect of the continuous increase of axle loads, traffic densities, and speed.

d) Reliability improvement relies on continuous evaluation that is aimed at reducing instances of failure, and thus at understanding the failure mechanisms of a system such as rail, which are vital to maintaining its integrity. Therefore, Metrorail should investigate and research new technologies with regards to rail inspection and real time condition monitoring that would not affect track availability.

8.4 FUTURE WORK

a) The cost–benefits of the preventive and CM should be implemented, so as to measure the effectiveness of the implemented maintenance strategy.

b) Further research should be conducted into the impact of the interaction of failures, as it affects the total reliability and availability of the rail track infrastructure.

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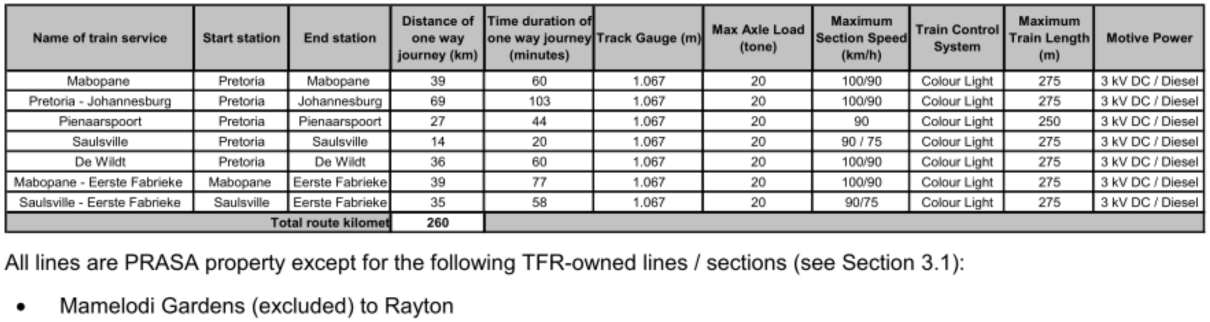
APPENDIX A

SOUTH AFRICAN TRAIN COMMUTER SERVICE

Gauteng North Commuter Service



Name of train service	Start station	End station	Distance of one way journey (km)	Time duration of one way journey (minutes)	Track Gauge (m)	Max Axle Load (tone)	Maximum Section Speed (km/h)	Train Control System	Maximum Train Length (m)	Motive Power
Mabopane	Pretoria	Mabopane	39	60	1.067	20	100/90	Colour Light	275	3 kV DC / Diesel
Pretoria - Johannesburg	Pretoria	Johannesburg	69	103	1.067	20	100/90	Colour Light	275	3 kV DC / Diesel
Pienaarspoort	Pretoria	Pienaarspoort	27	44	1.067	20	90	Colour Light	250	3 kV DC / Diesel
Saulsville	Pretoria	Saulsville	14	20	1.067	20	90 / 75	Colour Light	275	3 kV DC / Diesel
De Wildt	Pretoria	De Wildt	36	60	1.067	20	100/90	Colour Light	275	3 kV DC / Diesel
Mabopane - Eerste Fabrieke	Mabopane	Eerste Fabrieke	39	77	1.067	20	100/90	Colour Light	275	3 kV DC / Diesel
Saulsville - Eerste Fabrieke	Saulsville	Eerste Fabrieke	35	58	1.067	20	90/75	Colour Light	275	3 kV DC / Diesel
Total route kilomet			260							

All lines are PRASA property except for the following TFR-owned lines / sections (see Section 3.1):

- Mamelodi Gardens (excluded) to Rayton

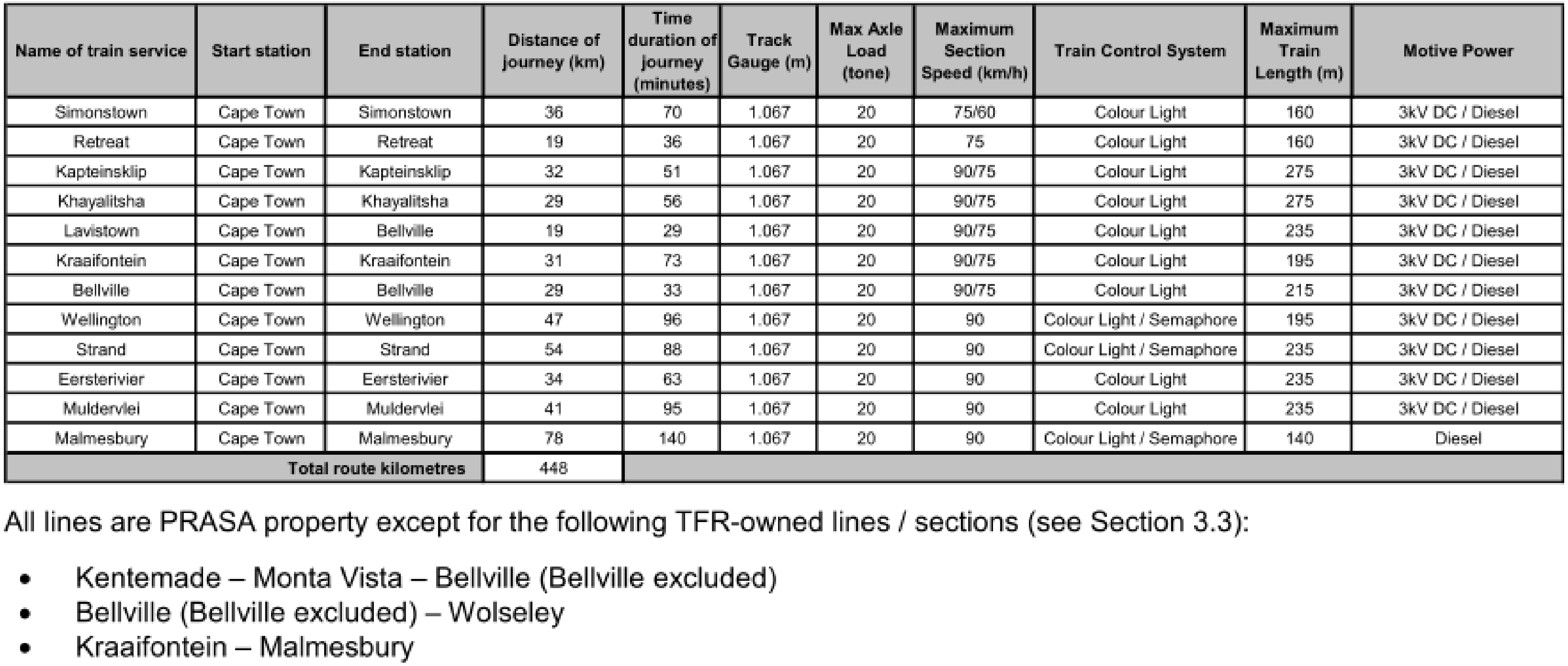
Gauteng South Commuter Service

Name of train service	Start station	End station	Distance of journey (km)	Time duration of journey (minutes)	Track Gauge (m)	Max Axle Load (tone)	Maximum Section Speed (km/h)	Train Control System	Maximum Train Length (m)	Motive Power
Naledi	Johannesburg	Naledi	28	52	1.067	20	90/60	Colour Light	275	3kV DC / Diesel
Naledi (via Crown)	George Goch	Naledi	35	54	1.067	20	90/50	Colour Light	275	3kV DC / Diesel
Leralla	Germiston	Leralla	33	46	1.067	20	100/90	Colour Light	210	3kV DC / Diesel
Daveyton	Dunswart	Daveyton	45	21	1.067	20	90	Colour Light	210	3kV DC / Diesel
Houtheuwel	George Goch	Houtheuwel	66	98	1.067	20	90/60	Colour Light / Semaphore	275	3kV DC / Diesel
Houtheuwel (via Crown)	George Goch	Houtheuwel	73	87	1.067	20	90/50	Colour Light / Semaphore	275	3kV DC / Diesel
Residensia - Vereeeniging	Residensia	Vereenigng	11	26	1.067	20	90/75	Colour Light / Semaphore	235	3kV DC / Diesel
Pretoria	Johannesburg	Pretoria	69	102	1.067	20	100/90	Colour Light	275	3kV DC / Diesel
Randfontein	Johannesburg	Randfontein	44	76	1.067	20	90/60	Colour Light	275	3kV DC / Diesel
Springs	Johannesburg	Springs	47	81	1.067	20	90/60	Colour Light	275	3kV DC / Diesel
Nigel	Springs	Nigel	24	34	1.067	20	90	Colour Light	275	3kV DC / Diesel
Kwesini	Germiston	Kwesini	21	35	1.067	20	90	Colour Light	275	3kV DC / Diesel
Germiston - Vereeniging	Germiston	Vereeniging	61	83	1.067	20	90	Colour Light	235	3kV DC / Diesel
Germiston - New Canada	Germiston	New Canada	22	37	1.067	20	90	Colour Light	275	3kV DC / Diesel
Oberholzer	Johannesburg	Oberholzer	82	96	1.067	20	90	Van Schoor / Colour Light	235	3kV DC / Diesel
Total route kilometres			661							

All lines are PRASA property except for the following TFR-owned lines / sections (see Section 3.2):

- Midway (excluded) – Bank (via Suurbekom) – Oberholdzer
- Houthewel (excluded) – Vereeniging
- Germiston (excluded) – Vereeniging
- India (excluded) – Elsburg
- Germiston West – Jupiter
- Springs (excluded) – Nigel

Western Cape Commuter Service



Name of train service	Start station	End station	Distance of journey (km)	Time duration of journey (minutes)	Track Gauge (m)	Max Axle Load (tone)	Maximum Section Speed (km/h)	Train Control System	Maximum Train Length (m)	Motive Power
Simonstown	Cape Town	Simonstown	36	70	1.067	20	75/60	Colour Light	160	3kV DC / Diesel
Retreat	Cape Town	Retreat	19	36	1.067	20	75	Colour Light	160	3kV DC / Diesel
Kapteinsklip	Cape Town	Kapteinsklip	32	51	1.067	20	90/75	Colour Light	275	3kV DC / Diesel
Khayalitsha	Cape Town	Khayalitsha	29	56	1.067	20	90/75	Colour Light	275	3kV DC / Diesel
Lavistown	Cape Town	Bellville	19	29	1.067	20	90/75	Colour Light	235	3kV DC / Diesel
Kraaifontein	Cape Town	Kraaifontein	31	73	1.067	20	90/75	Colour Light	195	3kV DC / Diesel
Bellville	Cape Town	Bellville	29	33	1.067	20	90/75	Colour Light	215	3kV DC / Diesel
Wellington	Cape Town	Wellington	47	96	1.067	20	90	Colour Light / Semaphore	195	3kV DC / Diesel
Strand	Cape Town	Strand	54	88	1.067	20	90	Colour Light / Semaphore	235	3kV DC / Diesel
Eersterivier	Cape Town	Eersterivier	34	63	1.067	20	90	Colour Light	235	3kV DC / Diesel
Muldervlei	Cape Town	Muldervlei	41	95	1.067	20	90	Colour Light	235	3kV DC / Diesel
Malmesbury	Cape Town	Malmesbury	78	140	1.067	20	90	Colour Light / Semaphore	140	Diesel
Total route kilometres			448							

All lines are PRASA property except for the following TFR-owned lines / sections (see Section 3.3):

- Kentemade – Monta Vista – Bellville (Bellville excluded)
- Bellville (Bellville excluded) – Wolseley
- Kraaifontein – Malmesbury

Durban Commuter Service

Name of train service	Start station	End station	Distance of one way journey (km)	Time duration of one way journey (minutes)	Track Gauge (m)	Max Axle Load (tone)	Maximum Section Speed (km/h)	Train Control System	Maximum Train Length (m)	Motive Power
Umlazi	Durban	Umlazi	26	47	1.067	20	90/75	Colour Light	275	3kV DC / Diesel
Kwa-Mashu	Durban	Kwa Mashu	19	33	1.067	20	75/60	Colour Light	210	3kV DC / Diesel
South Coast	Durban	Kelso	67	118	1.067	20	90	Colour Light	275	3kV DC / Diesel
North Coast	Berea Road	Stanger	77	125	1.067	20	75	Colour Light	210	3kV DC / Diesel
Pinetown	Durban	Pinetown	27	58	1.067	20	90/75	Colour Light	275	3kV DC / Diesel
Chatsworth	Durban	Crossmoor	26	45	1.067	20	90	Colour Light	230	3kV DC / Diesel
NEW LINE	Durban	Cato Ridge	71	126	1.067	20	90	Colour Light	210	3kV DC / Diesel
Bluff	Durban	Wests	20	41	1.067	20	90	Colour Light	275	3kV DC / Diesel
Total route kilometres			**333**							

All lines are PRASA property except for the following TFR-owned lines / sections (see Section 3.4):

- Rossburgh (excluded) – Cato Ridge (New main line)
- Clairwood (excluded) – Wests
- Umgeni (excluded) – Stanger

Eastern Cape Commuter Service

Name of train service	Start station	End station	Distance of one way journey (km)	Time duration of one way journey (minutes)	Track Gauge (m)	Max Axle Load (tone)	Maximum Section Speed (km/h)	Train Control System	Maximum Train Length (m)	Motive Power
Blaney	East London	Blaney	23		1.067	20	75	Colour Light	210	25kV AC / Diesel
		Total route kilometres	**23**							

All infrastructure assets are owned by TFR.

Port Elizabeth Commuter Service

Name of train service	Start station	End station	Distance of one way journey (km)	Time duration of one way journey (minutes)	Track Gauge (m)	Max Axle Load (tone)	Maximum Section Speed (km/h)	Train Control System	Maximum Train Length (m)	Motive Power
Swartkops	Port Elizabeth	Swartkops	9		1.067	20	75	Colour Light	210	25kV AC / Diesel
Uitenhage	Swartkops	Uitenhage	16		1.067	18.5	75	Semaphore	210	Diesel
		Total route kilometres	**25**							

All infrastructure assets are owned by TFR.

APPENDIX B

Turnouts	CONDITION (1=Poor, 4=Good)															
Asset number	Angle (1:6, 1:7, 1:8, 1:9, 1:12)	Direction (e.g. LH, RH, ES)	Traffic (L, M, H)	Stock & Switch Left	Stock & Switch Right	Stock & Guard Left	Stock & Guard Right	Crossing	Sleeper fastenings	Sleepers	Ballast	Formation	Alignment	Value	Score	%
CB/T52	1;12	LH	B	1	1	1	1	1	1	1	1	1	1	10	40	25
CB/T51	1;12	LH	B	1	1	1	1	1	1	1	1	1	1	10	40	25
CB/T54	1;12	LH	B	1	1	1	1	1	1	1	1	1	1	10	40	25
CB/T59	1;12	RH	B	1	1	1	1	1	1	1	1	1	1	10	40	25
BC/T25	1;12	LH	B	1	1	1	1	1	1	1	1	1	1	10	40	25
BC/T27	1;12	LH	B	1	1	1	1	1	1	1	1	1	1	10	40	25
BB/SX4	1;9	RH	B	1	1	1	1	1	1	1	1	1	1	10	40	25
AE/T113	1;9	RH	A	1	2	2	2	1	1	1	2	2	3	17	40	43
AE/T47	1;9	RH	A	1	2	2	2	1	1	1	2	2	3	17	40	43
AB/T11	1;9	LH	A	2	2	1	3	1	1	1	2	2	3	18	40	45
AE/T90	1;12	LH	A	2	2	1	1	2	2	1	2	2	3	18	40	45

AE/T94	1;12	LH	A	2	2	1	1	2	2	1	2	2	3	18	40	45
AE/T115	1;12	RH	A	2	1	2	2	2	1	1	2	2	3	18	40	45
AB/T19	1;9	RH	A	2	2	2	2	1	1	2	2	2	3	19	40	48
AB/T7	1;9	LH	A	2	2	1	1	2	2	2	2	2	3	19	40	48
AE/T48	1;9	RH	A	2	1	2	2	2	2	1	2	2	3	19	40	48
EB/T15	1;12	LH	A	3	3	2	2	1	3	2	2	2	2	22	40	55
EC/T8	1;9	RH	A	2	2	3	2	2	3	2	2	2	2	22	40	55
DC/T12	1;9	LH	A	1	1	1	1	1	1	4	4	4	4	22	40	55
EA/T28	1;12	RH	A	2	3	2	2	2	3	3	2	2	3	24	40	60
EA/T119	1;12	RH	A	2	3	2	2	2	3	3	3	3	2	25	40	63
EA/T30	1;12	LH	A	2	3	2	2	2	3	2	3	3	3	25	40	63
EA/T61	1;9	LH	A	3	2	1	2	2	3	3	3	3	3	25	40	63
EA/T76	1;12	RH	A	2	2	2	2	2	3	3	3	3	3	25	40	63
EA/T98	1;12	LH	A	2	2	2	2	2	3	3	3	3	3	25	40	63
EA/T102	1;12	RH	A	2	2	2	2	2	3	3	3	3	3	25	40	63
CC/T16	1;9	LH	A	1	1	1	1	1	4	4	4	4	4	25	40	63
EB/T7	1;12	RH	A	3	3	2	2	2	3	2	3	3	3	26	40	65
EB/T9	1;12	LH	A	2	3	2	2	2	3	3	3	3	3	26	40	65
EA/T14	1;12	LH	A	3	2	2	3	2	3	2	3	3	3	26	40	65
EA/T23	1;12	RH	A	2	3	3	2	2	3	2	3	3	3	26	40	65
EA/T29	1;12	LH	A	2	3	2	2	2	3	3	3	3	3	26	40	65
EA/T35	1;12	LH	A	2	3	2	2	2	3	3	3	3	3	26	40	65
EA/T47	1;12	LH	A	3	3	2	2	2	3	2	3	3	3	26	40	65
EA/T50	1;12	RH	A	3	3	2	2	2	3	2	3	3	3	26	40	65
EA/T87	1;12	RH	A	3	3	2	2	2	3	2	3	3	3	26	40	65
AF/T1	1;12	LH	A	2	3	3	3	3	3	2	2	3	3	27	40	68
EA/T139	1;12	LH	A	3	3	2	2	2	3	3	3	3	3	27	40	68
EA/T40	1;12	LH	A	2	2	3	3	2	3	3	3	3	3	27	40	68

EA/T92	1;12	RH	A	3	3	2	2	2	3	3	3	3	3	27	40	68
EA/T133	1;9	RH	A	3	2	3	3	2	3	3	3	3	3	28	40	70
EA/T4	1;9	LH	A	2	3	3	3	2	3	3	3	3	3	28	40	70
EA/T10	1;9	RH	A	3	2	3	3	2	3	3	3	3	3	28	40	70
EA/T71	1;12	LH	A	2	2	3	3	3	3	3	3	3	3	28	40	70
EA/T91	1;12	LH	A	2	2	3	3	3	3	3	3	3	3	28	40	70
EA/T101	1;9	RH	A	3	3	3	3	2	3	2	3	3	3	28	40	70
AG/T42	1;9	LH	B	2	3	3	3	3	3	3	2	2	4	28	40	70
FB/T2	1;9	RH	B	2	3	3	3	3	3	2	3	2	4	28	40	70
CC/T8	1;9	RH	A	4	4	1	1	1	4	4	4	1	4	28	40	70
DB/T3	1;9	LH	A	4	4	1	1	1	4	4	1	4	4	28	40	70
EA/T21	1;12	LH	A	3	3	3	3	3	3	2	3	3	3	29	40	73
EA/T100	1;9	LH	A	2	3	3	3	3	3	3	3	3	3	29	40	73
AF/T5	1;12	LH	A	2	3	3	3	3	4	4	3	3	2	30	40	75
DC/T27	1;12	RH	A	4	4	1	1	1	4	4	4	4	4	31	40	78
CD/T20	1;12	RH	A	4	4	4	4	4	1	1	4	1	4	31	40	78
EA/T6	1;12	RH	A	3	1	4	4	3	4	4	3	3	3	32	40	80
FB/T3	1;9	LH	B	4	2	4	4	4	4	2	3	2	4	33	40	83
FA/T14	1;9	RH	B	4	4	4	4	4	4	2	3	2	3	34	40	85
AH/T16	1;9	RH	B	4	4	4	4	4	4	2	3	2	3	34	40	85
AH/T51	1;12	RH	B	4	4	4	4	4	4	2	3	2	3	34	40	85
AB/T35	1;9	RH	B	1	1	4	4	4	4	4	4	4	4	34	40	85
AB/T33	1;12	RH	B	1	1	4	4	4	4	4	4	4	4	34	40	85
DC/T25	1;12	RH	A	4	4	4	4	1	4	4	4	1	4	34	40	85
AG/T59	1;9	LH	B	4	2	4	4	4	4	4	3	2	4	35	40	88
FA/T19	1;9	RH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
FA/T10	1;9	LH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
FA/T13	1;9	RH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
FB/T1	1;9	RH	B	4	4	4	4	4	4	2	3	2	4	35	40	88

FB/T4	1;9	LH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
AH/T3	1;9	RH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
AH/T5	1;12	RH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
AH/T9	1;12	RH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
AH/T10	1;9	LH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
AH/T17	1;9	RH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
AH/T37	1;12	RH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
AH/T38	1;12	RH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
AH/T39	1;12	RH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
AH/T52	1;12	RH	B	4	4	4	4	4	4	2	3	2	4	35	40	88
FA/T5	1;9	LH	B	4	2	4	4	4	4	4	3	2	4	35	40	88
FA/T6	1;9	RH	B	2	4	4	4	4	4	4	3	2	4	35	40	88
AD/T13	1;12	LH	B	4	4	4	4	1	4	4	4	4	4	37	40	93
AC/T60	1;12	RH	B	4	1	4	4	4	4	4	4	4	4	37	40	93
AC/T55	1;12	LH	B	4	4	4	4	1	4	4	4	4	4	37	40	93
AD/T22	1;9	RH	B	4	1	4	4	4	4	4	4	4	4	37	40	93
AD/T23	1;12	LH	B	4	1	4	4	4	4	4	4	4	4	37	40	93
AC/T36	1;12	LH	B	4	1	4	4	4	4	4	4	4	4	37	40	93
AC/T37	1;12	LH	B	1	4	4	4	4	4	4	4	4	4	37	40	93
AC/T4	1;9	LH	B	4	4	4	4	1	4	4	4	4	4	37	40	93
AC/T55	1;9	LH	B	4	4	4	4	1	4	4	4	4	4	37	40	93
BA/T8	1;9	LH	B	4	4	4	4	1	4	4	4	4	4	37	40	93
BA/T1	1;9	LH	B	4	4	4	4	1	4	4	4	4	4	37	40	93
DC/T51	1;12	RH	A	4	4	4	4	4	4	4	4	4	1	37	40	93
DC/T24	1;12	LH	A	4	4	4	4	1	4	4	4	4	4	37	40	93
CC/T15	1;9	LH	A	1	4	4	4	4	4	4	4	4	4	37	40	93

S/Slips	CONDITION (1=Poor, 4=Good)																							
Asset number	**Angle (1:7, 1:8, 1:9)**	**Traffic (L, M, H)**	**Stock & Switch Left/Left Outer**	**Stock & Switch Right / Left Inner**	**Stock & Switch Right/Right Inner**	**Stock & Switch Left/Right Outer**	**Obtuse-Left**	**Obtuse-Right**	**Acute-Right Hand**	**Acute-Left Hand**	**Inner Slip Rail**	**Outer Slip Rail**	**Stock & Guard Outer-Left**	**Closure Rail Assembly Left**	**Closure Rail Assembly Right**	**Rail fastenings**	**Stock & Guard Outer-Right**	**Sleeper fastenings**	**Sleepers**	**Ballast**	**Formation**	**Alignment**	**Value**	**Score**	**%**
EA/SS1	1;7	A	3	3	3	3	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	56	80	70
AB/SS1	1;6	B	1	4	4	4	1	1	1	1	4	4	4	4	4	4	4	4	4	4	4	4	65	80	81

D/Slips			CONDITION (1=Poor, 4=Good)																								
Asset number	Angle (1:7, 1:8, 1:9)	Corridor	Stock & Switch Left / Left Outer Front	Stock & Switch Right / Left Inner Front	Stock & Switch Left / Right Inner Front	Stock & Switch Right / Right Outer Front	Stock & Switch Left / Left Outer Back	Stock & Switch Right / Left Inner Back	Stock & Switch Left / Right Inner Back	Stock & Switch Right / Right Outer Back	Obtuse-Left	Obtuse-Right	Acute-Front	Acute-Back	Stock & Guard Assembly Outer-Left Front	Stock & Guard Assembly Outer Right Front	Stock & Guard Assembly Outer-Left Back	Stock & Guard Assembly Outer Right Back	Rail fastenings	Sleeper fastenings	Sleepers	Ballast	Formation	Alignment	Value	Score	%
CB/DS9	1;7	B	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	22	88	25
CB/DS10	1;7	B	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	22	88	25
CB/DS11	1;7	B	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	22	88	25
CB/DS7	1;7	B	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	22	88	25
CB/DS6	1;7	B	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	22	88	25
AB/DS9	1;7	A	2	1	2	1	2	2	1	1	2	2	1	1	2	2	2	2	2	1	1	1	1	2	34	88	39
AB/DS2	1;7	A	2	2	2	2	1	1	1	1	2	2	2	2	2	2	2	2	2	1	1	1	1	2	36	88	41

AB/DS1	1;7	A	2	2	2	2	1	1	2	2	2	1	2	2	2	2	2	2	2	1	1	1	1	2	37	88	42
AF/DS1	1;7	A	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	44	88	50
AF/DS2	1;7	A	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	44	88	50
AF/DS3	1;7	A	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	44	88	50
CC/DS1	1;7	A	4	4	4	4	4	4	4	4	1	1	4	4	4	4	4	4	4	1	1	4	1	4	73	88	83
CC/DS2	1;7	A	4	4	4	4	4	4	4	4	4	1	4	4	4	4	4	4	4	4	4	4	4	4	85	88	97

Diamonds	CONDITION (1=Poor, 4=Good)																	
Asset number	**Angle (1:4,5, 1:6, 1:7, 1:8, 1:9)**	**Traffic (L, M, H)**	**Obtuse-Left**	**Obtuse-Right**	**Acute-Front**	**Acute-Back**	**Stock & Guard Outer-Left Front**	**Stock & Guard Outer-Right Front**	**Stock & Guard Outer-Left Back**	**Stock & Guard Outer-Right Back**	**Rail fastenings**	**Sleeper fastenings**	**Sleepers**	**Ballast**	**Formation**	**Alignment**	**Value**	**Score**	**%**
AB/DX2	1;4,5	A	1	1	2	2	1	2	2	2	2	2	2	1	1	2	23	56	41
AB/DX4	1;9	A	1	2	2	1	2	2	2	2	2	2	2	1	1	2	24	56	43
CB/DX1	1;8	B	1	1	1	1	4	4	4	4	1	1	1	1	1	1	26	56	46
AF/DX3	1;7	A	2	2	2	2	3	3	3	3	3	3	3	3	3	3	38	56	68

AF/DX1	1;7	A	3	3	2	2	3	3	3	3	3	3	2	3	3	3	39	56	70
AF/DX2	1;7	A	3	3	2	2	3	3	3	3	3	3	2	3	3	3	39	56	70
AF/DX5	1;7	A	3	2	2	3	3	3	3	3	3	3	3	3	3	3	40	56	71
GA/DX1	1;7	B	3	3	3	3	3	3	3	3	3	3	3	2	2	3	40	56	71
EA/DX1	1;7	A	3	3	3	3	3	3	3	3	3	3	3	3	3	3	42	56	75
EA/DX2	1;7	A	3	3	3	3	3	3	3	3	3	3	3	3	3	3	42	56	75
EA/DX3	1;8	A	3	3	3	3	3	3	3	3	3	3	3	3	3	3	42	56	75
AF/DX4	1;7	A	3	3	3	3	3	3	3	3	3	3	3	3	3	3	42	56	75
GA/DX2	1;7	B	3	3	3	3	3	3	3	3	3	3	3	3	3	3	42	56	75
AG/DX1	1;7	B	3	3	3	3	3	3	3	3	3	3	3	3	3	3	42	56	75

Rails

Asset number	**48/57 kg/m**	**Section**	**Km start**	**Km end**	**Length**	**Traffic (L, M, H)**	**Side wear**	**Crown wear**	**36m rails**	**Value**	**Score**	**%**
EC/C7	48KG	Limindela	29.780	27.925	62	A	20	4	52	20	13	-54
EC/C6	48KG	Limindela	27.944	29.785	102	A	14	4	51	14	13	-8
EC/C8	48KG	Limindela	30.680	29.920	42	A	14	3	21	14	13	-8
EC/C9	48KG	Limindela	29.910	30.696	42	A	13	2	22	13	13	0
CB/C13	48KG	Booysens	14.305	14.124	11	B	Skid mark Fatigue		5	0	13	0
AC/C48	57KG	Roodepoort	33.002	33.242	12	B	Skid mark Fatigue		7	0	18	0
CB/C15	48KG	Booysens	14.143	14.365	13	B	Skid mark Fatigue		6	0	13	0
AD/C11	57KG	Westrand	47.588	48.348	14	B	Skid mark Fatigue		21	0	18	0

AD/C12	57KG	Robinson	51.599	51.928	19	B	Skid mark Fatigue		9	0	18	0
AC/C47	57KG	Roodepoort	32.924	33.216	40	B	Skid mark Fatigue		8	0	18	0
AF/C33	57KG	Driehoek	2.640	2.266	20	A	17	0	10	17	18	6
EA/C26	48KG	Ravensklip	5.083	5.215	8	A	10	4	4	10	13	23
AH/C9	48KG	Benoni	15.894	16.352	26	B	10	0	13	10	13	23
GB/C25	48KG	Elsburg	5.769	6.425	36	B	10	0	18	10	13	23
AF/C40	57KG	Geldenhuis	3.231	2.958	16	A	13	2	8	13	18	28
AF/C38	57KG	Geldenhuis	2.882	3.140	20	A	13	1	7	13	18	28
AF/C39	57KG	Geldenhuis	2.886	3.146	14	A	13	0	7	13	18	28
AF/C31	57KG	Driehoek	1.858	2.002	20	A	13	0	4	13	18	28
CD/C1	48KG	Ikwezi	31.883	33.254	77	B	9	4	38	9	13	31
EA/S50	48KG	Ravensklip	4.881	5.083	12	A	9	3	6	9	13	31
AE/C38	48KG	Ellispark	12.153	12.622	25	A	8	3	13	8	13	38
EA/C37	48KG	Elandsfontein	6.439	6.705	16	A	8	2	7	8	13	38
AF/C9	57KG	Germiston	0.455	0.749	16	A	11	3	8	11	18	39
AF/C20	57KG	President	1.070	0.951	38	A	10	5	3	10	18	44
AF/C48	57KG	Geldenhuis	3.675	4.077	22	A	10	4	11	10	18	44
AF/C80	57KG	Denver	7.975	8.364	22	A	10	4	11	10	18	44
AF/C81	57KG	Denver	8.962	8.618	18	A	10	4	10	10	18	44
EA/C36	57KG	Elandsfontein	6.430	6.709	16	A	10	3	8	10	18	44
AF/C49	57KG	Geldenhuis	4.060	3.797	14	A	9	6	7	9	18	50
AE/C86	48KG	Johannesburg	13.897	14.035	7	A	6	4	4	6	13	54
EA/C116	57KG	Birchleigh	21.795	22.389	32	A	8	3	16	8	18	56
AB/C20	57 KG	Mayfair	17.160	17.102	3	A	8	2	2	8	18	56
AB/C43	57KG	Crosvenor	18.356	18.677	16	A	7	3	9	7	18	61

Sleepers											
Asset number	**Timber/concrete**	**Section**	**Km start**	**Km end**	**Length**	**Traffic (L, M, H)**	**Dry/wet rot or rounded base**	**Shoulder damage/chair imprint/broken screws**	**Value**	**Score**	**%**
CB/S97	Timber	Riverlea	20.931	20.179	1074	B	1	1	2	8	25
CB/C75	Timber	Riverlea	21.019	20.931	126	B	1	1	2	8	25
CB/A38	Timber	Riverlea	21.025	21.019	8	B	1	1	2	8	25
CB/C77	Timber	Riverlea	21.110	21.025	121	B	1	1	2	8	25
CB/S108	Timber	Riverlea	22.110	21.110	1429	B	1	1	2	8	25
CB/S112	Timber	Riverlea	22.831	22.110	1030	B	1	1	2	8	25
CB/C79	Timber	Riverlea	23.105	22.831	391	B	1	1	2	8	25
CB/S114	Timber	Riverlea	23.350	23.105	350	B	1	1	2	8	25
DC/CS7	Timber	Lenz	43.299	43.397	140	A	1	1	2	8	25
DC/C56	Timber	Residensia	70.626	69.873	1076	A	1	1	2	8	25
DC/S109	Timber	Eatonside	70.637	71.402	1093	A	1	1	2	8	25

DC/C110	Timber	Eatonside	71.421	70.626	1136	A	1	1	2	8	25
DC/C58	Timber	Eatonside	71.402	71.617	307	A	1	1	2	8	25
DC/C59	Timber	Eatonside	71.607	71.421	266	A	1	1	2	8	25
DC/S111	Timber	Eatonside	71.617	72.068	644	A	1	1	2	8	25
DC/S112	Timber	Eatonside	72.060	71.607	647	A	1	1	2	8	25
DC/C60	Timber	Eatonside	72.068	72.720	931	A	1	1	2	8	25
DC/C61	Timber	Eatonside	72.706	72.060	923	A	1	1	2	8	25
DC/S119	Timber	Kwaggastroom	75.332	76.332	1428	A	1	1	2	8	25
DC/S121	Timber	Kwaggastroom	76.332	76.820	697	A	1	1	2	8	25
AC/S100	Concert	Lanwen	43.306	43.591	408	B	1	1	2	8	25
AC/C83	Concert	Lanwen	43.192	43.192	163	B	1	1	2	8	25
AC/A44	Concert	Lanwen	43.186	43.192	9	B	1	1	2	8	25
AC/C81	Concert	Lanwen	43.186	43.096	129	B	1	1	2	8	25
AD/S20	Timber	Millsite	50.360	51.360	1429	B	2	2	4	8	50
AD/S19	Timber	Millsite	49.348	50.348	1429	B	2	2	4	8	50
AD/S22	Timber	Millsite	51.360	51.599	342	B	2	2	4	8	50
AD/S21	Timber	Millsite	50.348	51.348	1429	B	2	2	4	8	50
AD/C12	Timber	Millsite	51.928	51.928	470	B	2	2	4	8	50
AD/S23	Timber	Millsite	51.348	51.593	350	B	2	2	4	8	50
AD/C13	Timber	Millsite	51.593	51.910	453	B	2	2	4	8	50
AJ/S1	Timber	Springs	33.272	33.482	475	B	3	3	6	8	75
AH/A37	Timber	Springs	33.671	33.680	30	B	3	3	6	8	75
AH/C35	Timber	Springs	33.671	33.735	125	B	3	3	6	8	75

AH/C36	Timber	Springs	33.724	33.857	95	B	3	3	6	8	75
AH/S39	Timber	Apex	19.276	19.522	150	B	3	3	6	8	75
AH/S40	Timber	Apex	19.302	19.557	104	B	3	3	6	8	75
AH/S4	Timber	Dunswart	12.331	12.355	65	B	3	3	6	8	75
AH/S8	Timber	Dunswart	12.474	12.519	65	B	3	3	6	8	75
AH/S10	Timber	Dunswart	12.527	12.599	130	B	3	3	6	8	75
AH/A3	Timber	Dunswart	12.561	12.574	62	B	3	3	6	8	75
AG/A27	Timber	Boksburg-oos	9.679	9.691	40	B	3	3	6	8	75
AG/A25	Timber	Boksburg-oos	9.619	9.652	20	B	3	3	6	8	75
AG/S73	Timber	Boksburg-oos	10.590	10.644	40	B	3	3	6	8	75
AG/A31	Timber	Boksburg-oos	10.665	10.696	50	B	3	3	6	8	75
EA/S81	Timber	Elandsfontein	7.416	7.506	129	A	3	3	6	8	75
EA/C49	Timber	Elandsfontein	7.361	7.506	207	A	3	3	6	8	75
EA/C48	Timber	Elandsfontein	7.315	7.430	164	A	3	3	6	8	75
EA/S80	Timber	Elandsfontein	7.317	7.340	161	A	3	3	6	8	75
EA/C44	Timber	Elandsfontein	7.219	7.297	111	A	3	3	6	8	75
EA/C45	Timber	Elandsfontein	7.229	7.317	126	A	3	3	6	8	75
EA/S75	Timber	Elandsfontein	7.029	7.229	286	A	3	3	6	8	75
EA/S70	Timber	Elandsfontein	6.805	6.826	30	A	3	3	6	8	75
AF/S80	Timber	George Goch	8.364	8.620	366	A	3	3	6	8	75
AF/A6	Timber	Germiston	0.316	0.356	57	A	3	3	6	8	75
AF/A21	Timber	President	1.601	1.642	58	A	3	3	6	8	75
AF/A23	Timber	President	1.674	1.717	61	A	3	3	6	8	75
AF/A28	Timber	Driehoek	1.835	1.800	50	A	3	3	6	8	75

AF/A39	Timber	Geldenhuis	5.008	4.968	57	A	3	3	6	8	75
AF/S61	Timber	Cleveland	4.972	5.010	54	A	3	3	6	8	75
AF/A50	Timber	Cleveland	5.765	5.806	58	A	3	3	6	8	75
AF/A48	Timber	Cleveland	5.785	5.798	18	A	3	3	6	8	75
EA/S25	Timber	Germiston	0.619	0.655	51	A	3	3	6	8	75
EA/A15	Timber	Germiston	0.639	0.645	8	A	3	3	6	8	75
EA/A17	Timber	Germiston	0.666	0.701	50	A	3	3	6	8	75

PRASA Reliability Methodology Example

PERWAY RELIABILITY(MTBF) (hours)		**2013/14 - YTD**
	Target	35.1
	National	95.1
	Gauteng	32.2
	Durban	408.0
	Cape Town	32.0
PERWAY AVAILIBILITY (%)	MTBF/(MTBF+MTTR)	2013/14 - YTD
	Target	95.9
	National	96.2
	Gauteng	92.7
	Durban	98.8
	Cape Town	85.5