



Condition Assessment Methods for Prestressed Concrete Railway Sleepers: Feasibility for South African Applications

FOR PARTIAL FULFILMENT OF THE MASTER OF ENGINEERING SPECIALIZING IN CIVIL INFRASTRUCTURE
MAINTENANCE MANAGEMENT

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Abstract

Concrete sleepers are a key component of railway systems, with estimates showing between 20 million to 35 million currently installed within the South African railway network. The condition assessment of concrete sleepers in South Africa poses a challenge for two main reasons: the scale at which condition measurements need to be conducted, and the poor access to sleepers within the ballast structure.

To assess feasibility of concrete sleeper assessment methods, the quality of technical results was reviewed to ensure the information required for long-term lifecycle needs of concrete sleepers can be produced and that the risk associated with failures of critical defects are mitigated.

The work established in the literature review was consolidated through a three-phase methodology to provide results for the assessment. This involved a Failure Mode and Effect Analysis (FMEA) that measured how well each of the methods can detect the failure modes, and then benchmarked the condition assessment methods against similar technology currently in use within the South African network. A test for defect relevance checked that the defects identified in the literature were relevant for South African applications, and allowed for further categorisation of criticality.

Longitudinal cracking and vertical cracks at the rail seat were found to be the most critical defects required to be detected by concrete sleeper condition assessment methods. Vehicle-mounted ultrasonic echo and vehicle-mounted imaging technology methods both showed good technical results from the FMEA, showing better quality information on sleeper condition than current methods in use. But only the vehicle-mounted imaging scored a residual profile value below the recommended technical threshold, and also showed to benchmark cost, lead time and operational factors in line with current methods. Consequently, vehicle-mounted imaging is proposed as the most feasible option for concrete sleeper condition assessment for South African applications.

Sleeper body abrasion cannot be well detected through any methods reviewed, and will require further study of methods before visual inspections of this defect can be improved upon. Failure modes of concrete sleepers due to prestressing steel corrosion were unclear and further testing should be done to define what early-stage cracking displays in order to accurately predict the end of the useful life of a sleeper.

Acknowledgements

“It was the best of times; it was the worst of times,” C. Dickens

As I finish this thesis, I consider the support and feedback I have had throughout the process.

Thank you to my supervisor, Prof. Hans Beushausen, whose patience, dedication to quality, and work ethic is admired, respected and the basis of what I strive to recreate.

To my favourite line manager, Solly Mahlaule, not that I’ve had many. The support, freedom and opportunities for growth provided the foundation for me completing this on time, or at all.

Thank you to my parents, Erika and Graham, for literally everything I have.

To Brian Davies, thank you for the immeasurable support.

And thank you to all my friends that let me moan then told me to get my life together.

Glossary

Crosstie

Alternative word for Sleeper.

Engine Burn Fracture

A defect on the running surface of the rail attributed to the wheels of a locomotive skidding and not rolling. Can be severe if the wheels spin in place, or progressive where only minor slips cause a progressive defect.

Field Side

The area of track on the outside of the two rails. As opposed to *Gauge Side*.

Gauge Side

The area of track between the two rails. As opposed to *Field Side*.

Gauge Widening

A track defect where the gauge, as measured at the reference point 14 mm below the crown wear of the rails, is larger than the standard and outside the allowable tolerances.

General Freight Lines

A term used for railway lines that primarily transport freight but do not meet the requirements for Heavy Haul lines. Also referred to as GFB (General Freight Business).

Heavy Haul

A descriptor used for railway lines that meet two of the three following criteria according to the International Heavy Haul Association: "Regularly operates or is contemplating the operation of unit or combined trains of at least 5,000 tonnes gross mass. Hauls or is contemplating the hauling of revenue freight of at least 20 million gross tonnes per year over a given line haul segment comprising at least 150 km in length. Regularly operates or is contemplating the operation of equipment with axle loadings of 25 tonnes or more." (International Heavy Haul Association, 1998)

Hunting

A rail/wheel interaction which induces a horizontal oscillation of the wagons while moving under certain conditions, and over time creates a sinusoidal wear pattern on the side of the gauge-side of the rail.

Mechanised Ballast Tamper

An on-track maintenance machine which uses a vibratory method to lift the sleeper to its desired location and geometric position, and then vibrates the surrounding ballast to interlock and maintain the new sleeper position.

Running surface

The area of contact between the rail and the wheel of a wagon or locomotive.

Skidmark

Common term for Engine Burn Fracture.

Tamping

The process, usually by means of using a Mechanised Ballast Tamper, in which the track geometry and ride quality of the train is maintained in a ballasted track system.

Tie

Alternative word for Sleeper.

Turnout

A track component that allows a train to divert from a set route to another route. Typically used to refer to the group of rails, sleepers, fastenings and signalling infrastructure that allows the divergence. Alternatively called a set of points , crossing, or switch.

Twin-Block Sleepers

Two reinforced concrete blocks with embedded rail fastening systems, connected by a steel rod.

TABLE OF CONTENTS

1. Introduction.....	1
1.1. Background	1
1.2. Problem Statement	2
1.3. Aim of Research	3
1.4. Objectives	3
1.5. Methodology	3
2. Literature Review and Industry Practise.....	5
2.1. Track Infrastructure Elements.....	6
2.2. Railway Sleepers and their Fuctional Requirements	7
2.2.1. Sleeper Types	9
Wooden Sleepers	10
Steel Sleepers	11
Concrete Sleepers.....	12
2.2.2. Concrete Sleeper Design	14
2.3. Damage and Deterioration of Concrete Sleepers.....	15
2.3.1. Deterioration of Concrete Systems.....	15
2.3.2. Damage Categories of Concrete Sleepers	16
2.3.3. Cracking of Concrete Sleepers	19
Map Cracking.....	19
Cracks from Fastener Down	21
Vertical Cracks at Rail Seat Base	22
Long Horizontal Cracks.....	23
Cracking due to Prestressing Steel Corrosion.....	24
Vertical Cracks at Sleeper Mid-Span.....	27
2.3.4. Abrasion of Concrete Sleepers	28
Rail Seat Deterioration.....	29
Sleeper Body Abrasion	29
2.3.5. Mechanical Damage of Concrete Sleepers.....	31
Tamping Damage (Cracking or Abrasion around Rail Seat).....	31
Derailment Damage	32
2.4. Management of Assets	33
2.4.1. Asset Management	33
2.4.2. Track Quality Through Lifecycle.....	33

2.4.3.	Maintenance Tactics	34
2.5.	Condition Assessment Methods for Concrete Sleepers	37
2.5.1.	Visual Condition Assessment of Concrete Railway Sleepers	37
2.5.2.	Non-Destructive Condition Assessment of Concrete Railway Sleepers	41
	Ultrasonic Pulse Velocity (Manual).....	41
	Ultrasonic Echo (Vehicle-Mounted).....	42
	Acoustic Emission Monitoring (Fixed Ultrasonic).....	43
	Radar	45
2.5.3.	Indirect Condition Assessment of Concrete Railway Sleepers.....	45
	Track Quality Indices.....	45
	Track Gauge Force Measurements (Gauge Widening On-Track Machine).....	47
2.6.	Summary.....	47
3.	<i>Methodology for Proposing Feasible Concrete Sleeper Condition Assessment Methods</i>	50
3.1.	Failure Mode and Effect Analysis	51
3.2.	Testing for Defect Relevance	57
3.3.	Benchmarking Feasibility Against Current Methods	58
3.4.	Summary.....	61
4.	<i>Results</i>	63
4.1.	Failure Mode and Effect Analysis	63
4.1.1.	Severity and Occurrence of Defects	63
4.1.2.	Detetction of Defects using Condition Assessment Methods	67
4.1.3.	Residual Risk of Defect after Information to Mitigate.....	71
4.2.	Results Testing for Defect Relevance	72
4.3.	Benchmarking Feasibility Against Current Methods	73
4.4.	Summary.....	75
5.	<i>Conclusions.....</i>	77
	Failure Mode and Effect Analysis	77
	Testing for Defect Relevance.....	78
	Benchmarking.....	79
	General.....	79
6.	<i>Recommendations.....</i>	80
7.	<i>References</i>	82

List of Figures

Figure 2-1: Elements of Railway Infrastructure (Li et al., 2016)	6
Figure 2-3: Track Gauge Definition (Grabe, 2017)	7
Figure 2-4: International Track Gauges (HTML, 2011)	8
Figure 2-5: Example of Sleeper Regions (Photo by Author)	10
Figure 2-6: Example of Wooden Sleepers (Theos Timber Limited, 2017)	10
Figure 2-7: Example of Steel Sleeper with Exposed Shoulder (Photo by Author)	11
Figure 2-8: P-Type Sleeper Fastening using e-clip system, Left; F-Type Sleeper Fastening, Right (Pandrol, 2024; Aveng Rail, 2017)	12
Figure 2-9: South African Open Track Sleepers (Wildenboer et al., 1989)	13
Figure 2-10: Concrete and environment: factors influencing the durability of concrete (Ballim et al., 2021)	15
Figure 2-11: Typical Sleeper Damage Adapted from sources (Thun et al., 2008)	18
Figure 2-12: Examples of ASR Map Cracking from Sleeper Manufactured in 1974 in Saldanha PPC (Photo by Author)	19
Figure 2-13: Sleeper Cracking under rail defect near East London (Picture by Author)	21
Figure 2-14: Example of a severe rail seat positive flexural crack (Zeman, 2010)	22
Figure 2-15: Long Horizontal Cracks on Sleeper in Northern Cape (Photo by Author)	23
Figure 2-16: Typical Categorization of Sleeper Cracking due to ASR and DEF (Sundaram et al., 2018)	24
Figure 2-17: Damage Deterioration Mechanism (Heckroodt, 2002)	25
Figure 2-18: Illustration of Corrosion Process in Concrete (Alexander et al., 2012)	26
Figure 2-19: Example of Centre Binding of Concrete sleepers (NTSB, 2014)	27
Figure 2-20: Sleeper Support Condition Deterioration (Remennikov & Kaewunrunen, 2007)	28
Figure 2-21: Typical Rail Seat Deterioration (RSD) (Federal Railroad Administration, 2019)	29
Figure 2-22: Sleeper Base Rounding due to abrasion near East London, Left; Localised Ballast/Sleeper abrasion and crushing near Kimberley, Right (Photos by Author)	30
Figure 2-23: Base abrasion around rail seat due to Mechanized Ballast Tamping near East London, Left;	31
Figure 2-24: Derailment Damage from Wheel Dropping on the Gauge Side (Zakeri & Rezvani, 2012)	32
Figure 2-25: Example of Track Behaviour with Different Thresholds (Zaayman, 2013)	34
Figure 2-26: Maintenance Tactics Diagram (Zaayman, 2013)	35

Figure 2-27: Preventative vs. Corrective Maintenance Costs Adapted from Douglas (2017)	35
Figure 2-28: Maintenance Cost Curve of an Under-Invested Network (RT-CAP Project, courtesy of Plasser South Africa) (Zaayman, 2013).....	36
Figure 2-29: Sishen to Saldanha ASR Cracking Axes of Identification (Grabe & Oberholster, 2000)	37
Figure 2-30: Categorization of ASR Cracks on the Sishen to Saldanha Line (Grabe & Oberholster, 2000)	38
Figure 2-31: Typical Cracking Inspection due to ASR and DEF at the Indian Railways (Sundaram, et al., 2018).	38
Figure 2-32: LuxRailer Inspection Trolley (Photo by Author).....	39
Figure 2-33: Imaging of Sleepers through Rail-Mounted Vehicles, Left; Example of data generated from vehicle-mounted inspection, Right (Federal Railroad Administration, 2018).....	40
Figure 2-34: Sleeper Testing on Latvian Railways using Ultrasonic Equipment from Riga University (Tatarinova et al., 2018).....	41
Figure 2-35: Diagram of Testing Arrangements to detect cracks in the Latvian Railway Network (Tatarinova et al., 2018).....	42
Figure 2-36: Ultrasonic Rail-Mounted Sleeper Assessment, Left; Ball-end tapper Inducing Pulse on Sleeper End, Right (Federal Railroad Administration, 2018).....	42
Figure 2-37: Raleigh Wave Sensor Response Testing for Concrete Sleepers (Federal Railroad Administration, 2018).....	43
Figure 2-38: Ultrasonic Rail Testing Vehicle and Chaser (Lennings Rail, 2020).....	44
Figure 2-39: Infrastructure Measuring Vehicle near Queenstown (TGIV) (Photo by Author).....	46
Figure 3-1: Failure Mode and Effect Analysis Process	52
Figure 3-2: Example of Class Column Symbol Diagram Adapted from Harpster (2024)	57
Figure 3-3: Illustration of FMEA Rating Scales and RPN value outcomes	61
Figure 3-4: Illustration of benchmarking rating scales for condition assessment methods.....	62
Figure 4-1: Severity and Occurrence of Failures per Concrete Sleeper Defect.....	63
Figure 4-2: Detection of Concrete Sleeper Defects using Condition Assessment Methods.....	67
Figure 4-3: Residual Risk of Concrete Sleeper Defect after Information to Mitigate.....	71
Figure 4-4: Class Column Symbol Scatter for Concrete Sleeper Defects	72
Figure 4-5: Benchmarking of Concrete Sleeper Condition Assessment Methods	75

List of Tables

Table 2-1: Standards for 1065 mm Gauge (Transnet Freight Rail, 2012).....	9
Table 2-2: Sleeper Detail General (Transnet Freight Rail, 2012).....	13
Table 2-3: Survey of Critical Sleeper Condition Components Adapted from Sources (de Souza Lima & Carneiro, 2022; Van Dyk et al., 2013).....	16
Table 2-4: Categories of Concrete Sleeper Failure Mechanisms (de Souza Lima & Carneiro, 2022)	17
Table 2-5: Categorization of ASR Cracks on the Sishen to Saldanha Line (Grebe & Oberholster, 2000)	38
Table 2-6: Summary of Literature on Concrete Sleeper Assessment Methods and the Defects Detected	48
Table 2-7: Summary of Effects of Concrete Sleeper Defects.....	49
Table 3-1: Adapted Feasibility Study Framework (McLeod, 2021).....	51
Table 3-2: Severity of Concrete Sleeper Defect (Harpster, 2024).....	53
Table 3-3: Occurrence of Concrete Sleeper Defects (Harpster, 2024)	54
Table 3-4: Detection of Defects using Concrete Sleeper Condition Assessment Methods.....	56
Table 3-5: Benchmarking Assessment Criteria Gradings.....	58
Table 3-6: Grading Criteria for Benchmarking	59
Table 4-1: Severity and Occurrence Descriptions and Ratings for Concrete Sleeper Defects.....	65
Table 4-2: Descriptions and Rating for Condition Assessment Methods Detection for Defects	69
Table 4-3: Benchmarking Descriptions and Ratings for Condition Assessment Methods.....	73
Table 4-4: Summary of Feasibility of Sleeper Condition Assessment Method.....	76

1. Introduction

As the vast networks of infrastructure developed during the 20th century continue to age, the maintenance, repair, rehabilitation, and replacement of the associated structures is a significant undertaking of the 21st century engineering workload. The South African rail network has extended its tracks over 30 000 km in the past century, with PRASA (Passenger Rail Agency South Africa) and Transnet being the major asset owners (Department of Transport South Africa, 2022). The maintenance and management of these large networks requires a dedicated and persistent effort to meet changing network demands.

Traditional ballasted railway track infrastructure is straightforward when described in theory: a superstructure comprised of rail, sleepers and ballast, and the supporting substructure of sub-ballast and subgrade (Elkhoury et al., 2018). The complexity of these components develops through their interdependent application in daily operations. The recurring use of these components over thousands of kilometres and varying conditions can present a range of potential risks if any part of their lifecycle is compromised.

The management of this large network of components requires detailed information on the condition and an understanding of how it deteriorates in order to manage the lifecycle demands, and so the data on condition and deterioration are critical. These are considered critical issues within the wider civil engineering industry as the South African Institution of Civil Engineering (2022) considers data management and condition monitoring fundamental enablers of national infrastructure networks. Failure of these large infrastructure networks in South Africa not only jeopardizes the physical safety of citizens, but also carries significant social, economic, and cultural ramifications for the nation (Bowman, 2020).

The feasibility of current condition measurement techniques will be evaluated to provide a comprehensive review of leading assessment methods, specifically focussed concrete railway sleepers.

1.1. Background

Concrete sleepers are a key component of South African railway systems, with between 20 million to 35 million currently installed as estimated by the Author. Because the primary function of a sleeper is to ensure the gauge is maintained for the passage of trains, the deviation from the standard gauge between rails is the ultimate limiting factor for end of useful life of a sleeper (Ebersohn & Grabe, 2008).

Gauge measurements are currently collected using a track geometry measurement vehicle (TGIV) or by hand measurements, and so extensive data is available for assessment. This is often the

basis for long-term planning in South Africa. The limitation is that often by the time gauge widening is measurable, either through direct measurements or statistical methods, the end life of the sleeper is imminent.

Most of the maintenance tactics for sleepers involve corrective maintenance, with no predictive or routine maintenance conducted. Relying on corrective maintenance tactics limits the rectification to replacement rather than taking preventative action to meet any extended lifecycle needs (Federal Railroad Administration, 2018). With low replacement rates of rail infrastructure over the past thirty years, detailed condition assessment is, firstly, needed to understand the actual remaining useful life of the sleepers to plan the future demand requirements, and secondly, to prioritize the replacement of current worn sleepers according to condition (Perkins, 2011).

Optimization of large infrastructure networks hinges on the quality of asset management plans. These plans outline the objectives that guide the transition from current to future network demand in accordance with the system lifecycle needs. Central to these plans is the assessment of infrastructure condition. The efficacy, reliability, and cost-effectiveness of condition assessment methods directly impact the application of the asset management principles.

A freight railway operates on four key performance metrics: price of service, reliability of delivery, volume capacity of the network, and reliability of railway infrastructure (Havenga & De Bod, 2016). All four of these metrics influence how, when and which methods can be used to assess the condition of concrete sleepers. Identifying new opportunities and improving current methods allows for enhanced decision-making to optimize time, price, volumes, and infrastructure functionality.

Despite the ongoing advancements in the field, a comprehensive examination of all current methodologies for concrete sleeper condition assessment is needed to identify opportunities for improvement and to build a more flexible, robust, and efficient network in South Africa.

1.2. Problem Statement

The condition assessment of concrete sleepers in South Africa poses a challenge for two main reasons: the scale at which measurements need to be conducted, and the poor access to sleepers within the ballast structure. An assessment of methods to conduct large-scale condition assessment of sleepers is required to understand which methods are most feasible to ensure long-term lifecycle needs can be assessed and risk associated with failures are mitigated.

1.3. Aim of Research

The aim of this research is to provide an updated, relevant perspective into the most efficient, technically advanced, and cost-effective methods for concrete sleeper condition assessment in South Africa.

1.4. Objectives

The objective of this research is to propose the most feasible methods for the condition assessment of concrete sleepers in South Africa.

This objective relies on the outcomes from several disciplines regarding the feasibility of the possible condition assessment methods in relation to how well they mitigate risks to the safety and continued operation of train service.

The specific outcomes that are required to reach the objective include:

- a) Review and consolidate the functional requirements, the typical deterioration mechanisms, and the risk of the various failure modes of concrete railway sleepers.
- b) Review concrete sleeper assessment methods.
- c) Based on the information reviewed, analyse the feasibility of the methods of concrete sleeper condition assessments.
- d) Propose a method for large-scale concrete sleeper condition assessments for the South African network.

1.5. Methodology

Two overlapping fields of literature form the basis of the topic at hand: the failure modes and deterioration mechanisms of concrete sleepers; and condition assessment methods of concrete sleepers. The literature review and industry overview establishes the consensus on these several topics to allow for evaluation of relevant sleeper condition assessment methods. This research will form the body of the information required for the assessment and will need to address questions central to the feasibility topics.

The work established in a literature review will be considered in a consolidated methodology for the assessment. This will firstly involve a Failure Mode and Effect Analysis that measures how well each of the methods can detect the failure modes, accounting for the severity and frequency of the failure mode. The system will clearly lay out a scale for each of the parameters considered, with the literature review backing up the justification for each parameter. A test for defect relevance will follow the FMEA, to classify defects as critical, routine or not relevant for large-scale assessment

requirement. Finally, the methods will be benchmarked against similar technology currently in use within the South African network.

The information reviewed in the analysis is discussed in the conclusions, with the major outcomes used to make recommendations on the feasibility of concrete sleeper condition assessment methods for South African applications.

2. Literature Review and Industry Practise

Rail freight itself is a strategic enabler for a countries' economic growth (Dedik et al., 2018). South African freight rail is losing market share to other modal choices, primarily road, despite having rail corridors that in theory have far stronger modal attributes (Havenga & De Bod, 2016). The introduction of the National White Paper on Rail Policy in March 2022 has reaffirmed that the South African government acknowledges the freight rail industry as requiring strategic intervention. While nascent in its possible renaissance, the intent to resuscitate general freight lines requires the implementation and foresight of leading engineering principles (South African Department of Transport, 2022).

Before discussing the failure modes of concrete railway sleepers and the condition assessment methods that mitigate failure risk, a broader view of all railway infrastructure will be provided. Concrete railway sleepers, or even full track structure including rails and ballast, do not exist in a vacuum and so an overview of the multi-disciplinary nature of the railway system is discussed in Section 2.1. The use of sleepers within the track structure is required because several functional demands need to be met before train operations can be declared safe. The types of sleepers and typical design will be discussed along with the functional requirements in Section 2.2.

Two intersecting areas form the bulk of the literature examined in this feasibility assessment. Section 2.3 discusses the failure modes of concrete sleepers, also their deterioration mechanisms. Section 2.5 reviews the methods used for the condition assessment of concrete sleepers. Section 2.4 will bridge the failure mode and condition assessment discussion, by reviewing the principles of asset management which are used in the industry to mitigate the associated risks.

The areas of research are informed by the global literature available on the topics, as well as the authors' industry experience that is used to apply the international literature within the South African context.

2.1. Track Infrastructure Elements

Railway infrastructure needs collaboration from multiple disciplines to ensure its continued operations (Li et al., 2016). Track, structure, power distribution and communications are the broad categories of systems that are used to describe the railway infrastructure, as shown in Figure 2-1.

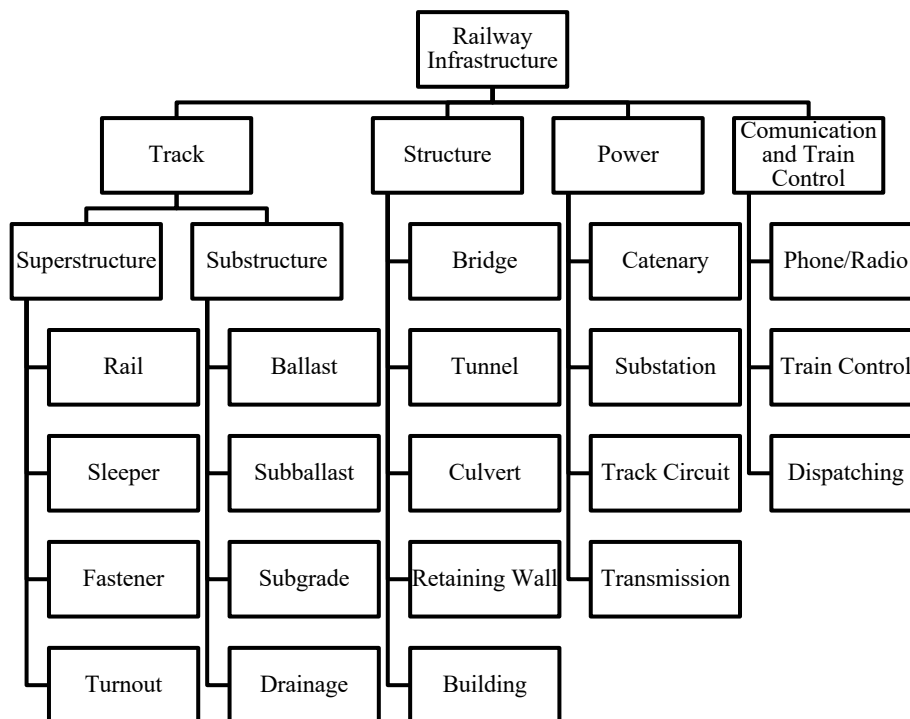


Figure 2-1: Elements of Railway Infrastructure (Li et al., 2016)

Figure 2-1 highlights that while track is considered a general term for a railway, it is also the technical term for the superstructure and the substructure of the railway infrastructure.

The superstructure is the immediate load-bearing system of components that transfers the weight of the train to the substructure components. Figure 2-2 shows a basic cross-section of the linear track components. The components such as turnouts and drainage are often discussed independently as they are discrete components and have a different assessment strategy to linear assets.

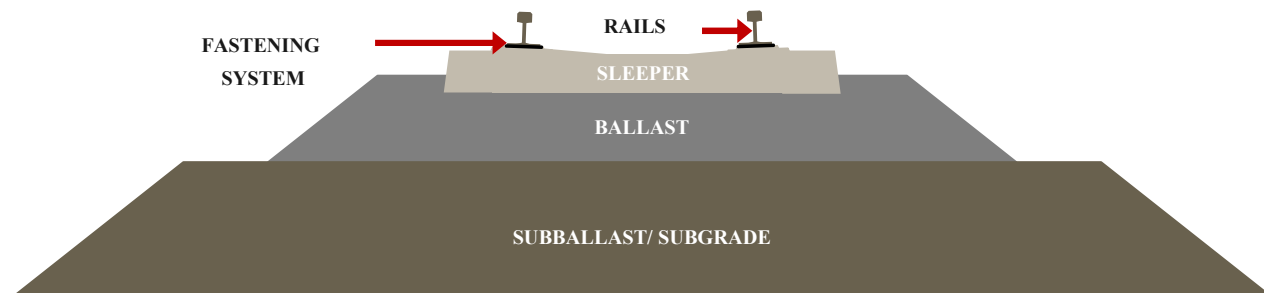


Figure 2-2: Traditional Ballasted Track Structure adapted from Selig (1994)

The technical specifications of each track component may vary due to design requirements. Rails are typically classified by their size in kg/m and then according to the metallurgical composition (Transnet Freight Rail, 2012). Rails are primarily used to guide the train wheels and transfer the load to the sleeper. Ballast is a large graded, angular, crushed rock typically from granite or basalt used primarily to support the sleeper and allow for easily maintainable track geometry (Li et al., 2016).

The bridges, tunnels, culverts and retaining walls are the discrete structures that enable the placement of the track. The power system is used to supply electricity to the electric locomotives and some infrastructure equipment. Communication and train control ensures the train can get the required authorities through telecommunications networks and signalling infrastructure.

2.2. Railway Sleepers and their Functional Requirements

Sleepers, also commonly known as railroad ties or cross-ties, are used primarily to transfer and distribute the load from the base of the rail to the ballast (Railway Technology, 2023). The evolution of system requirements has seen a transition from wooden to steel to variations of concrete sleepers (Selig, 1994).

Track gauge has always been the ultimate Go/No-Go criteria for trains, as too wide or too narrow results in the wheelset being incompatible for the movement. Gauge is defined as the point of reference measured at 14 mm below crown wear of a rail, as shown in Figure 2-3 (Transnet Freight Rail, 2012).

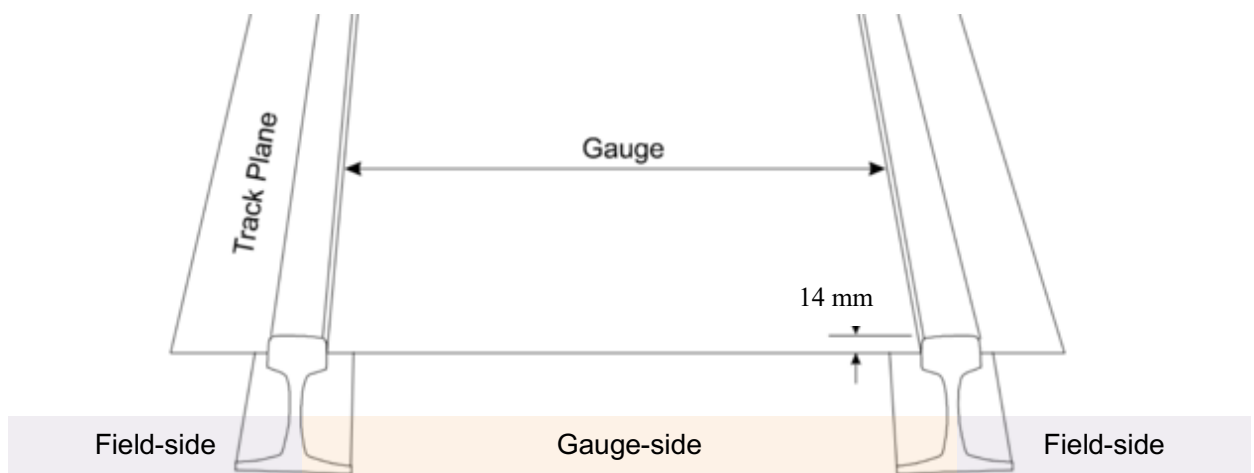


Figure 2-2: Track Gauge Definition (Grabe, 2017)

South Africa uses the Cape Gauge of 1067 mm across 64% of the lines, with 1% of the network being the Gautrain on Standard Gauge of 1435 mm and 35% on Narrow Gauge of 610 mm (Department

of Transport South Africa, 2022). Gauge-side is a common term describing the area between the two rails and field-side describes the area outside the two rails when describing any track components.

Figure 2-4 shows international track gauges, which include the typical South African gauges.

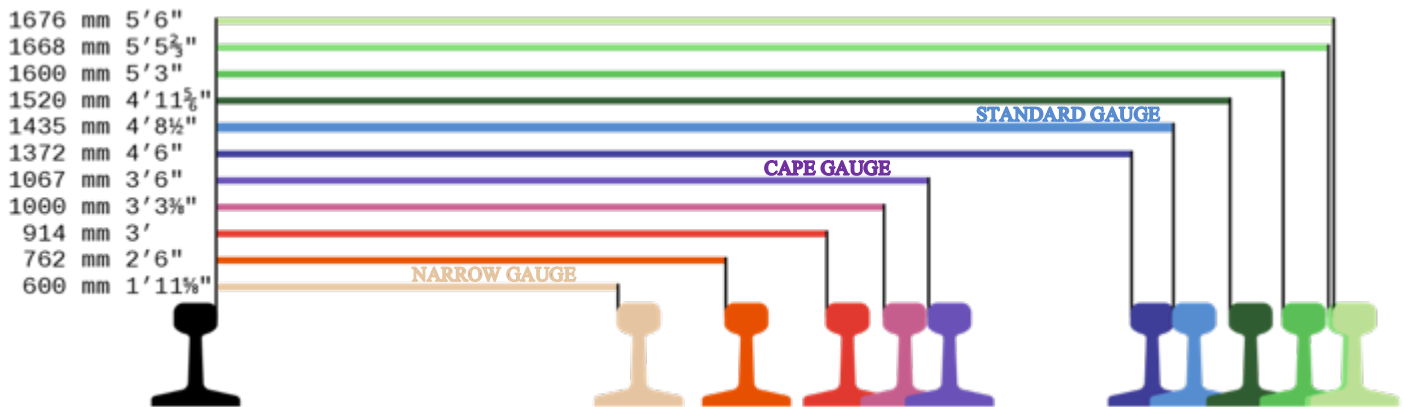


Figure 2-3: International Track Gauges (HTML, 2011)

The South African gauge is also typically described as both 1067 mm and 1065 mm, and both are considered correct as the Manual for Track Maintenance (2012) uses both depending on the type of sleeper and fastening combination.

All sleepers need to fulfil primary, secondary and serviceability functions in operational conditions over it's lifespan (Grabe, 2017).

The functions of a sleeper include to:

- maintain the track gauge,
- provide firm support to the rails,
- distribute load from rails to a large area of ballast,
- provide longitudinal, lateral horizontal resistance to applied forces,
- reduce vibration transfer to the ballast,
- align the rail and
- provide an inclination to the rail.

Wide gauge is the specific technical term that refers to when the gauge is measured and is larger than the acceptable gauge and outside the allowable tolerance standards. The narrowing of gauge is also possible, and also has a minimum threshold requirement. The South African gauge standards classifies A, B and C Standards when measuring compliance to the required gauge. Table 2-1 shows the South African gauge standards for both wide and narrow gauge.

Table 2-1: Standards for 1065 mm Gauge (Transnet Freight Rail, 2012)

Standard	Deviation from Relative Gauge (1065 mm)	
	Minimum (mm)	Maximum (mm)
A	-3	+5
B	-7	+12
C	-10	+25

The ability to maintain track gauge is the primary requirement of the sleeper. Deviation exceeding the acceptable maximum standard will result in an immediate derailment when the wheels drop down inside the two rails, while deviation below the minimum will make the wheel climb the head of the rail also causing a derailment.

The lateral, longitudinal, and vertical resistance, provided by the weight of the sleepers and the friction of the ballast/sleeper interface, is a secondary functional requirement (Grabe, 2017). The ability of the track to maintain geometric quality, i.e. smooth and level to design standards, under cyclic loading is influenced by the level of interlocking achieved between the base of the sleeper and the ballast bed beneath. Interlocking between a sleeper and ballast is a serviceability requirement of sleeper as it reduces total track settlement. The friction between the sleeper and ballast is influenced by settlement factors, and so mechanized tamping, sleeper replacement and ballast screening reduce the track stability until consolidation has occurred. Rail inclination of 20° is required to ensure a better rolling surface contact between the rail and the wheel. This inclination is achieved by creating a design incline on the rail chair of the sleeper, and as such is a secondary functional requirement.

2.2.1. Sleeper Types

Sleepers of the past were allowably made of steel and wood as their primary function was to ensure the gauge of the track was maintained under operational train loads. Increasing freight volumes and increasing axle loads extended the primary function from providing track gauge to several other key factors such as pressure distribution on the ballast, providing cant to the rails, and providing lateral, longitudinal, and vertical resistance (Ebersohn & Grabe, 2008).

Specialized sleepers, as opposed to the open track sleepers, are used when encountering turnouts, bridges, and tunnels, as they require different dimensions and loading configurations. A typical description of the sleeper regions is shown in Figure 2-5.

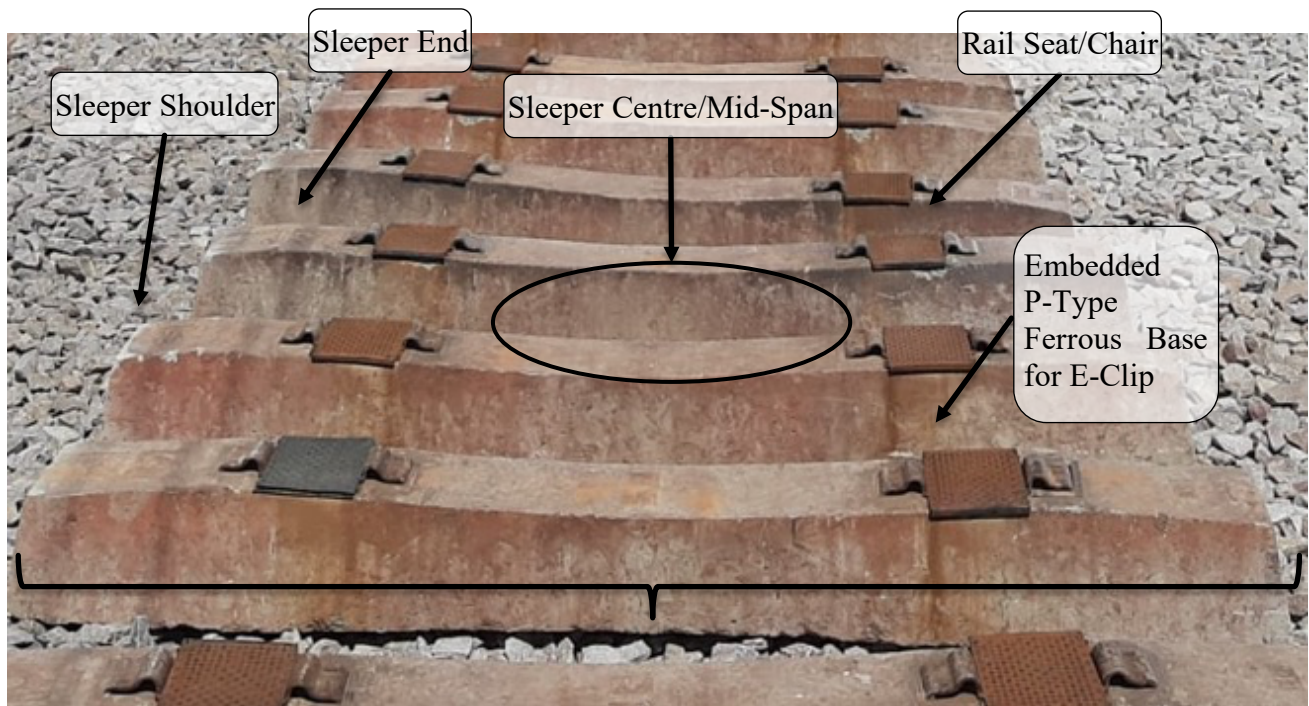


Figure 2-4: Example of Sleeper Regions (Photo by Author)

The regions shown in Figure 2-5 are typical for all sleepers, with the only specific addition item in this example being the P-type embedded ferrous E-Clip base. These sleeper types are described in further detail below.

Wooden Sleepers

Wooden sleepers are either made of a hard wood or a laminated wood and have the typical dimensions of 2100 mm x 250 mm x 195 mm (Transnet Freight Rail, 2012). Figure 2-6 shows a typical wooden sleeper.



Figure 2-5: Example of Wooden Sleepers (Theos Timber Limited, 2017)

Wooden sleepers offer the benefit of increasing system elasticity and reducing contact stresses at the sleeper/ballast interface but also see an increased vertical displacement at the sleeper centre in comparison to concrete sleepers (Grabe, 2017; Li et al., 2016). These sleepers require drilling and aligning of the rail chairs for installation using drilling templates, and this is a time-consuming process when applied to large sections. The modern cost of the high-quality treated wood for the sleepers is higher than those of concrete sleepers. No large-scale mechanized machines are available for installation or replacement and so extending past a design perspective, these are impractical for the high-demand maintenance requirements of a freight network. The condition of wooden sleepers deteriorates under poor drainage conditions, in which failure to maintain track gauge between the rails becomes a common risk. Wooden sleepers have largely been phased out in South Africa as the risks associated with modern loading, volume requirements, and maintenance requirements, outweigh the benefits.

Steel Sleepers

Steel sleepers were used for a period but are no longer manufactured for installation within the South African network. An example of steel sleepers is shown in Figure 2-7.



Figure 2-6: Example of Steel Sleeper with Exposed Shoulder (Photo by Author)

The shape of these hollow sleepers allowed the sleeper to be entrenched in the ballast and so provided a large surface area for lateral, vertical, and horizontal force resistance. Steel sleepers have similar maintenance challenges to wooden sleepers. The installation of the rail chairs is time consuming and technically challenging at a large scale. With no specialized mechanized on-track machine, the replacement rate is limited to manual installation. The use of these under electrified lines is allowed, but the requirements for insulating pads and clean ballast are more critical (Transnet Freight Rail, 2012).

Concrete Sleepers

Four main concrete sleeper types are manufactured for installation of the mainlines of South Africa (Transnet Freight Rail, 2012). They often referred to as monolithic as they are a large single-cast heavy object, but this is not a required technical descriptor for modern sleepers as the alternatives have become redundant. Historically, twin-block sleepers were widely available for installation which had two separate smaller concrete blocks joined by a steel bar.

The four types are P2, F4, PY and FY. The main differences are in their structural bearing capacity and the fastening system. The P2 and F4 have a lower bending moment resistance at the centre, where the PY and FY sleepers resist higher bending moments. The P and F denote the fastening system required for each with the P-type referring to the Pandrol Spring system and the F-type referring to the Fist Fastening System. The Pandrol systems make use of an e-clip, gauge clip and HDPE pad, as shown in Figure 2-8 (Left). The Fist system as shown in Figure 2-8 (Right) uses an insulated pin, fist clip and base plate to tension to clamp the rail to the sleeper.

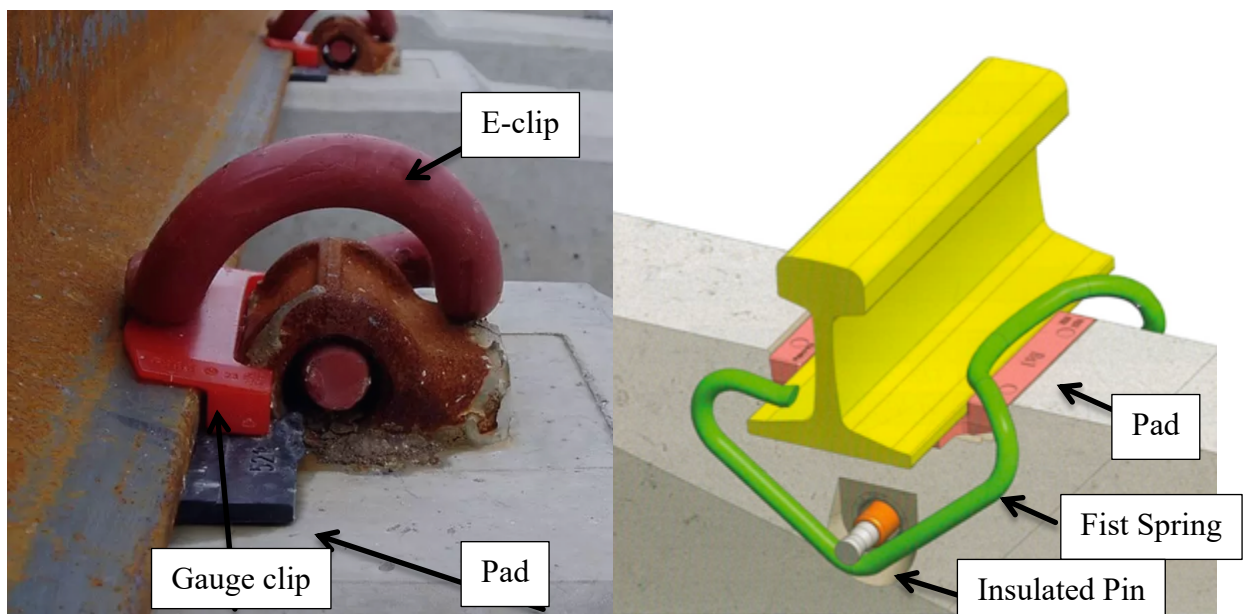


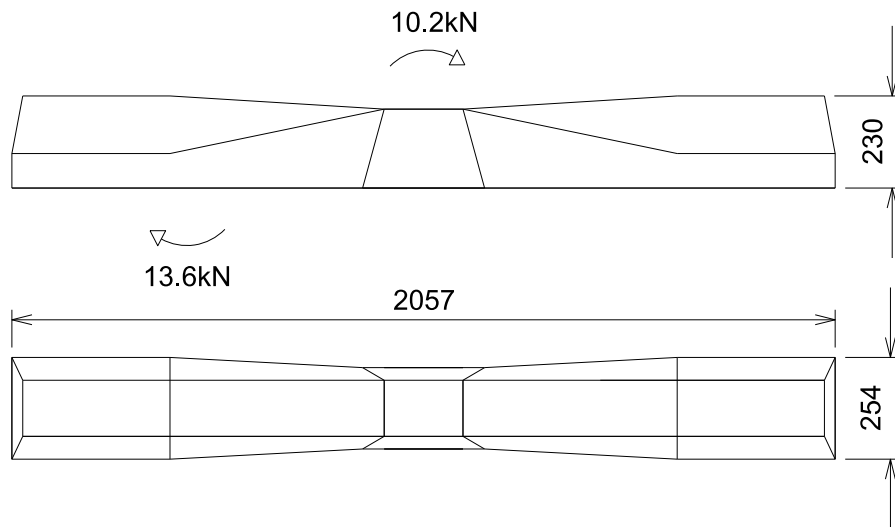
Figure 2-7: P-Type Sleeper Fastening using e-clip system, Left; F-Type Sleeper Fastening, Right (Pandrol, 2024; Aveng Rail, 2017)

The size of sleeper is the second variable for these sleepers, with each sleeper coming in a smaller (P2/F4) or larger (PY/FY) size. The change in size has two primary functions, as the larger sleepers have higher moment resistances as well as being heavier which provides higher friction between the sleeper and ballast and lateral and longitudinal resistance. An overview of the sleeper dimensions can be found in Table 2. Figure 2-9 shows the general size and moment differences between the P2/F4 and PY/FY Sleepers. The height discrepancies between Figure 2-9 and Table 2-2 are due to geometric differences of the top surface of sleepers.

Table 2-2: Sleeper Detail General (Transnet Freight Rail, 2012)

Sleeper	Length (mm)	Width (mm)	Height (mm)	Mass (kg)
P2	2057	254	230	215
PY	2200	300	232	278
F4	2057	254	244	215
FY	2200	300	258	282

P2 AND F4 (217kg)



PY AND FY (282kg)

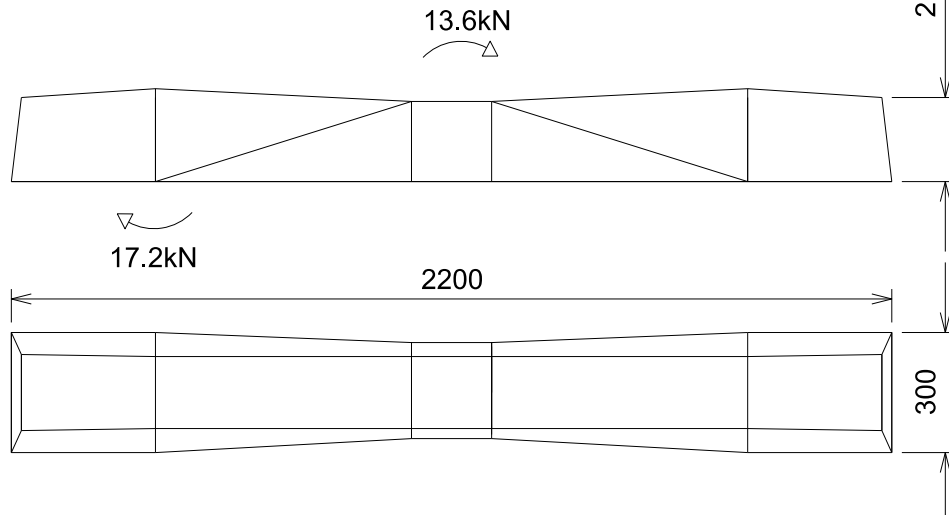


Figure 2-8: South African Open Track Sleepers (Wildenboer et al., 1989)

Mechanized replacement machines are available for both P-type and F-type sleepers allowing large-scale replacement of up to ten sleepers per minute (Lennings Rail, 2020). F-type sleepers are typically more challenging to install and maintain by hand, because to release the fist mechanism the surrounding ballast needs to be removed around the pin before it can be unfastened. This is preferred in areas where sabotage of equipment is common, as this same issue makes it more difficult to remove.

2.2.2. Concrete Sleeper Design

Design standards for concrete sleepers across America, Asia and Europe follow a similar procedure. Input requirements such as loading capacity, train profiles, and ballast parameters are used to set up the basis of any modelling technique used. The bending moments and permissible stresses are then calculated, allowing materials selection to take place. The sample manufacturing and testing process will follow before acceptance of design (Taherinezhad et al., 2013). The traditional permissible stress methods tend to underestimate material properties as well as misrepresent the dynamic load contributions, leading to a growing adoption of limit state methods as the preferred approach for updated design standards (You & Kaewunruen, 2019).

The introduction of fibres to limit crack growth has been a large focus of this, as well as investigating the use of Ultra-High-Performance Concretes (UHPC) from 150 MPa upwards to improve abrasion resistance and increase structural capacity with strain-hardening behaviour.

Typical concrete selections are in the range of C55/67 and members are reinforced with prestressed steel tendons. Tendon configurations can vary depending on the supplier as each manufacturer optimizes the sleeper result to their manufacturing methods. In the South African industry, a broad range of prestressing tendon configurations has been used historically, with a range from 3 to 20 prestressing strands observed by the Author when conducting assessments of concrete sleepers.

The design life of sleepers is typically estimated at 50 years but is dependent on the system requirements (American Railway Engineering Association, 1962). Assessing the actual design life can use fatigue methods such as the Damage Accumulation models of CEB-fip of 1990 and EN1992-2: Eurocode 2 that show good correlation of experimental and theoretical results. Typical Damage Accumulation models compare to the lower-bound results, showing suitably conservative estimations of failure. Maturation of these methods requires accurate inputs of the material properties and dynamic loads at a specific point in time to understand the prestress loss and the fatigue loading is necessary to calculate the juncture bending moment.

2.3. Damage and Deterioration of Concrete Sleepers

Concrete sleepers fail in different modes, depending on the root cause of the problem. An overview of typical concrete deterioration mechanisms will frame the more detailed discussion of how these apply to each of the failure modes of concrete sleepers.

2.3.1. Deterioration of Concrete Systems

As part of traditional concrete systems, all durability defects are possible when considering concrete sleepers. The prevalence of concrete use has created a perception that overestimates the true resilience of the material, and so understanding how concrete deteriorates allows for corrective or preventative measures to ensure the functionality is fit for purpose (Ballim et al., 2021). Figure 2-10 provides an overview of the concrete system deterioration that may arise in all concrete assets.

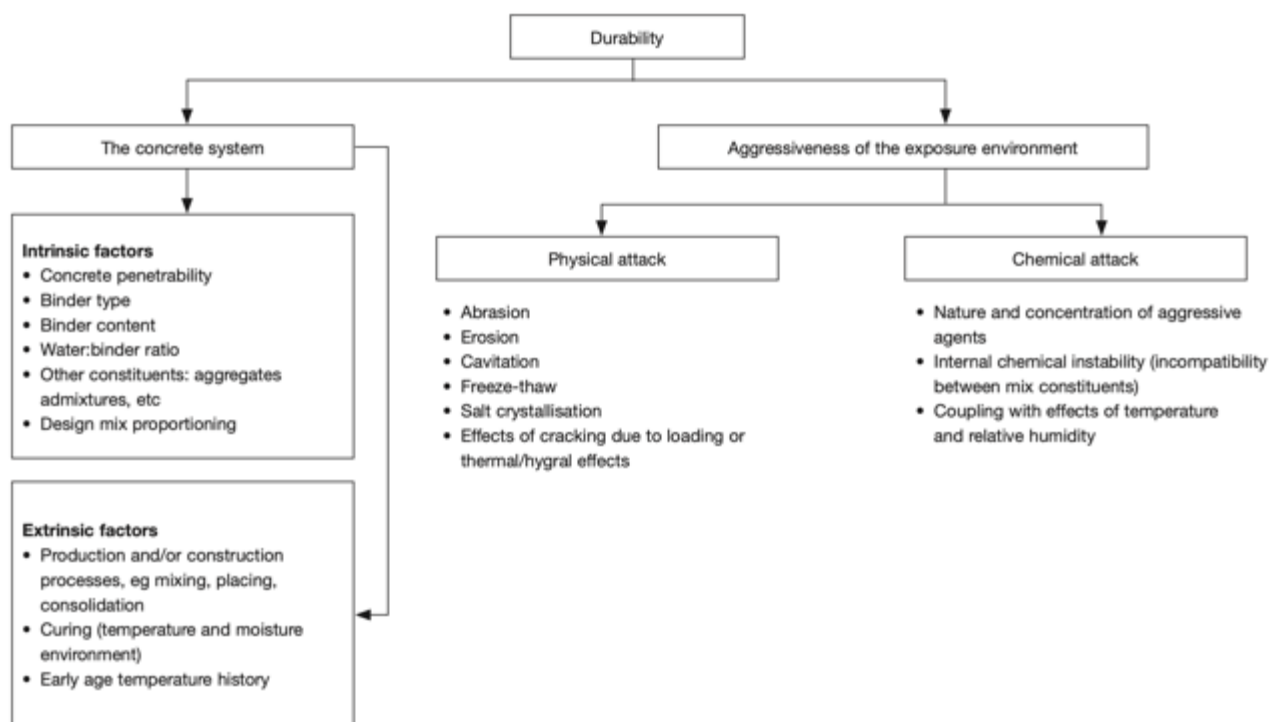


Figure 2-9: Concrete and environment: factors influencing the durability of concrete (Ballim et al., 2021)

The durability factors are, as shown in Figure 2-10, separate the concrete system durability factors to those of the exposure environment. The concrete system further splits the durability factors into intrinsic, which talk to many of the design mix components of the concrete, and the extrinsic factors that relate to the production and curing processes of the manufacturer. The environmental factors consider physical methods of deterioration that act on the concrete, or chemical methods that relate to an interaction of the concrete which causes deterioration.

2.3.2. *Damage Categories of Concrete Sleepers*

The damage of concrete sleepers has been the topic of various researchers but considered through the lens of the specific authors. Many of the sources, while using newer data available, share a handful of foundational texts that often provide structure to the newer findings. The literature for this review specifically considers the visually assessed damage of concrete sleepers and how these tie to the failure mechanisms. Understanding the defect will allow for assessing how failure occurs and the severity of the failure (Van Dyk et al., 2013).

An international concrete crosstie and fastening system survey from 2013 is a foundational reference for the literature on sleeper condition assessment. The research considered an industry survey of 46 sleeper expert individuals or organisations across the design, research, production and maintenance fields of the heavy haul or general freight industry. Participants were asked to rank the eight critical concrete sleeper/fastening problems from 1 to 8, with 8 being most critical. An average of the recorded scores was calculated for the overall ranking of importance, and shown in Table 2-3.

Table 2-3: Survey of Critical Sleeper Condition Components Adapted from Sources (de Souza Lima & Carneiro, 2022; Van Dyk et al., 2013)

Critical Concrete Sleeper/Fastening Problems	Average Rank		
	International	USA	Combined
Shoulder/Fastening wear or fatigue	5.50	6.38	5.81
Tamping Damage	6.14	4.14	5.43
Dynamic Cracking	5.21	4.83	5.07
Centre-binding Cracking	5.36	4.50	5.05
Derailment Damage	4.57	4.57	4.57
Rail-Seat Deterioration	3.15	6.43	4.32
Environmental or chemical damage	4.67	3.50	4.25
Other	4.09	3.47	3.90

The defects and failure mechanisms from Table 2-3 will be discussed in further detail in Sections 2.3.3 to 2.3.5. The findings from international survey from Table 2-3 showed a difference in the international and USA rankings when comparing the criticality of concrete sleeper defects.

Internationally, tamping damage was considered the most pressing challenge, while within the USA the rail seat deterioration was considered the most important. The combined rankings list shoulder/fastening wear as the most critical defect, followed by tamping damage. Internationally rail seat deterioration (RSD) was not given a high priority in terms of critical sleeper defects. Other important defects when looking at the combined ratings of criticality are dynamic cracking and centre-binding damage.

The research sometimes combined the visual defect, failure mode and/or failure mechanisms in the description of the sleeper/fastening problems, i.e. tamping damage or dynamic cracking, but sometimes just listed the visual damage without attributing the specific mechanism i.e. rail-seat deterioration or shoulder/fastening wear.

Researchers from Federal University of Pernambuco, in Brazil, reviewed a wide array of literature in 2022 related to the failure mechanisms of prestressed concrete sleepers and consolidated the research into two main categories; that of mechanical processes where extrinsic factors contribute to deterioration, and durability factors that form part of the intrinsic concrete system or as interaction of the concrete with the exposure conditions (de Souza Lima & Carneiro, 2022). A summary of their findings is listed in Table 2-4.

Table 2-4: Categories of Concrete Sleeper Failure Mechanisms (de Souza Lima & Carneiro, 2022)

Failure Mechanisms Category	Failure Mode
Intrinsic Factors	Cracking due to chemical deterioration – Alkali Aggregate Reactions or Delayed Ettringite Formation
	Cracking due to manufacturing defects
Extrinsic Factors	Rail Chair Abrasion
	Base Cracking Under Rail Chair
	Mid-Span Cracking/ Centre Binding
	Base Abrasion
	Freeze Thaw

The team at the Federal University of Pernambuco reference the work of Thun et al. (2008), which presented detailed information on the load carrying capacity of concrete sleepers that also looked at typical visual damage types. Figure 2-11 shows the typical damage reviewed for their analysis.

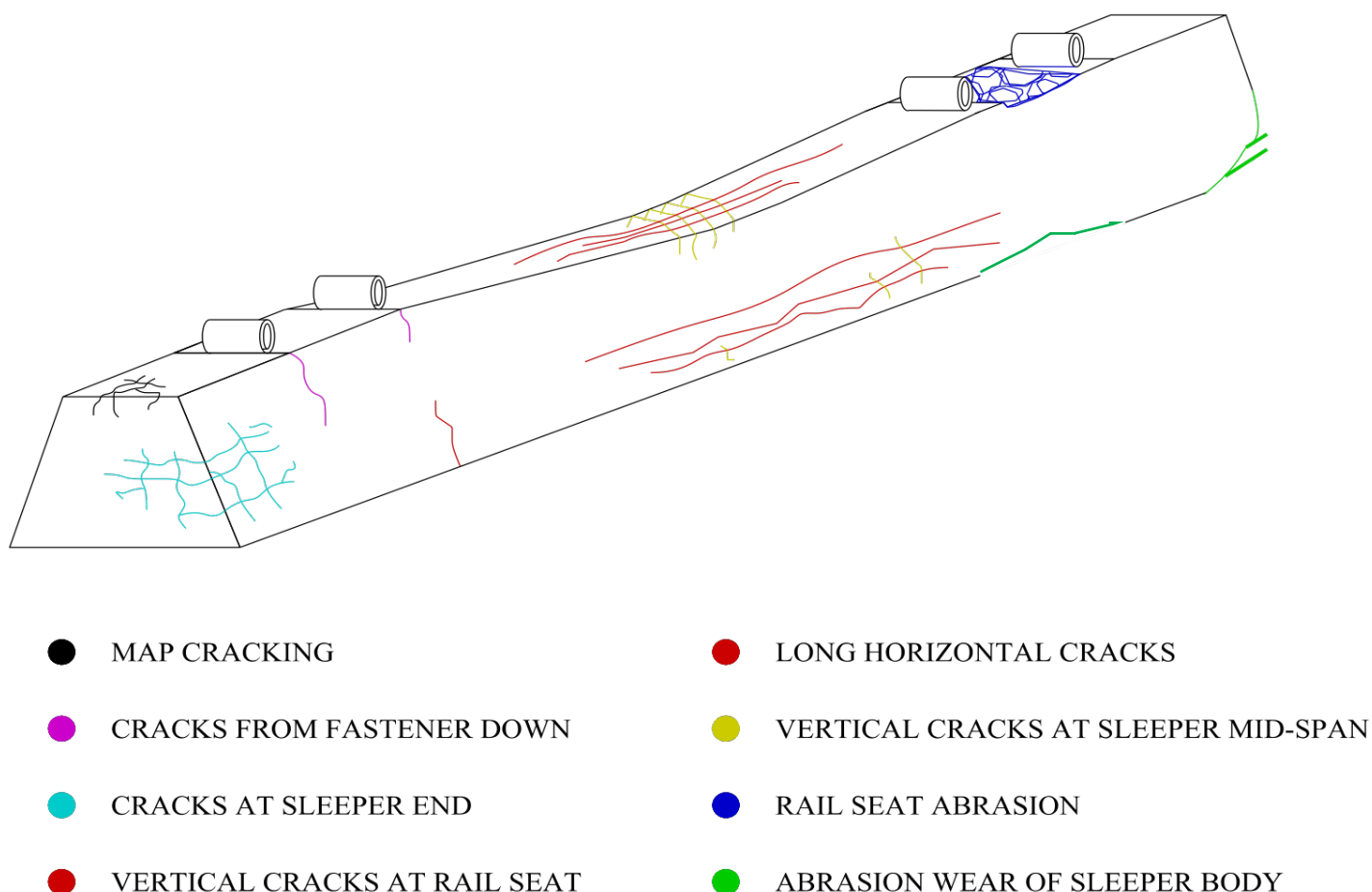


Figure 2-10: Typical Sleeper Damage Adapted from sources (Thun et al., 2008)

The visual damage as shown by Thun et al in Figure 2-11 will be used as a structure for the discussion below, combined with the research structure as set out by de Souza Lima and Carneiro (2008). The defects of concrete sleepers will be discussed in three categories: Cracking, Abrasion, and Mechanical damage.

As part of the discussion of the physical defects, the main deterioration mechanisms that lead to the visual defects and final failure modes will be discussed. While individual defects may be caused by multiple deterioration mechanisms, and similar deterioration mechanisms may lead to different damage attributes, the discussion will be structured to consider all deterioration mechanisms within a defect category. If duplication arises, reference will be made to earlier sections.

2.3.3. *Cracking of Concrete Sleepers*

Cracking is one of the prominent defects seen across the assessments of concrete sleepers (de Souza Lima & Carneiro, 2022). Failures of prestressed concrete sleepers have shown that flexural cracks will often initiate due to a failure in bending moment capacity, but final failure of the crack occurs in shear failure (Kaewunruen & Remennikov, 2007). Wire slip of the prestressed tendons is also a typical failure mode shown during testing of severely cracked concrete sleepers (Thun et al., 2008). Cracking reduces the cross section of the load-bearing member as well as allow for the ingress of unwanted particles.

The discussion on cracking will use the descriptions from Thun et al (2008) to categorise the type of damage visible. This will include map cracking, cracks from the fastener down, cracks at the sleeper ends, vertical cracks at the rail seat, long horizontal cracks, and vertical cracks at the sleeper mid-span. Reinforcement corrosion will also be discussed in this section, as cracking is both an initiator and a known defect from reinforcement corrosion of reinforced or prestressed concrete. The types of damage will then describe the failure mechanisms that contribute to the damage seen.

Map Cracking

Map cracking typically presents in a random orientation on the surface of a concrete element that is unconstrained and is a classic symptom of Alkali-silica reactions (Thomas et al., 2011). An example is shown in Figure 2-12.



Figure 2-11: Examples of ASR Map Cracking from Sleeper Manufactured in 1974 in Saldanha PPC (Photo by Author)

The resultant ASR cracking in sleepers is often seen at the ends of the sleeper in a map cracking pattern visible on the side face of the sleeper, and then propagates to the surface as longitudinal cracks when severe. The reaction between alkalis and silicates can differ depending on exact constituents of the reaction, but for the most part can be classified under the Alkali-Silica umbrella of ASR. Alkali-silica reactions in prestressed concrete sleepers have been documented internationally (Taherinezhad et al., 2013).

ASR has been documented within South Africa on the Sishen to Saldanha Iron Ore Line, sections of the Coal line from Ermelo to Richards Bay, and sections of the Manganese corridor between De Aar and Noupoort (Oberholster et al., 1992). In the research the discovery of ASR on sleepers in South Africa was first raised as a finding of longitudinal cracks on the tops of sleepers and not the typical map cracking during routine visual inspections. This is attributed to the limitations of visual inspections where the map cracking on the sleeper shoulder tends to be obscured by ballast, while the longitudinal cracks on top of the sleeper are more easily identified during visual inspections.

The Sishen to Saldanha line was constructed with an approximated 1.4 million sleepers, all manufactured in the Riebeeck Plant of PPC using local granite and Rapid Hardening Portland Cement (RHPC) (Grabe & Oberholster, 2000). The manufacturing process for the Sishen to Saldanha sleepers followed a longline process that used a heat treated curing method (Oberholster et al., 1992). This research showed approximately 70% (1 million) sleepers suffered from ASR Cracking. Visual, petrographic, and scanning electron microscope samples showed that ASR was the primary cause of cracking, although Delayed Ettringite Formation has contributed.

Laboratory tests of the South African sleeper samples with ASR show that it does not appear to influence the compressive strength of the concrete sleeper, but severely undermines the flexural strength resulting in a flexural failure mode (Oberholster, 2021). The South African track gauge of 1065 mm, a reduction of the international standard gauge of 1435 mm, could still minimize this effect of flexural due to the shorter sleeper length (Ebersohn & Grabe, 2008).

Internationally, ASR has been found in conjunction with the presence of Delayed Ettringite Formation in concrete railway sleepers (de Souza Lima & Carneiro, 2022). This is often attributed to the widespread use of steam curing methods that induce an early high temperature environment (Baingam et al., 2015).

Delayed Ettringite Formation (DEF), while presenting with similar cracking patterns to ASR during visual assessments, tend towards a stronger presentation of long horizontal cracks than map cracks in sleepers and so will be discussed under the Long Horizontal Cracks section (Sundaram, et al., 2018). Map cracking itself did not have a significant effect on the bending capacity or final failure of sleepers (Thun et al., 2008).

Cracks from Fastener Down

Cracking originating from the fastener down is attributed to increased forces, and typically induced by defects in the track or train configurations (Thun et al., 2008). Typical defects that cause these cracks are rail defects such as engine burn fractures (skidmarks), discontinuities in track joint levels, rail surface corrugation, cant defects, wheel flat defects, skew bogies on locomotives or wagons, and rail hunting are often initiators of rail chair cracking. Figure 2-13 shows a severe rail chair cracking from the fastener down due to engine burn fractures.



Figure 2-12: Sleeper Cracking under rail defect near East London (Picture by Author)

Cracks from the fastener down have the ability to impact the functionality of the fastening system (Bastos et al., 2015). Van Dyk et al. (2013) ranked defects to the fastening system overall as the most critical sleeper defects during the international study. Severe defects see the breakout of the chair from the sleeper, allowing for total clamping force loss that maintains the track gauge.

Vertical Cracks at Rail Seat Base

High-impact forces, while short in duration, create a high positive moment at the bottom of the sleeper directly below the rail seat (de Souza Lima & Carneiro, 2022; Zeman, 2010). The positive moment will induce a bending crack when the tensile strength of the concrete is exceeded, starting at the base of the sleeper and extending upwards. Figure 2-14 shows a typical crack at the base of the rail seat.



Figure 2-13: Example of a severe rail seat positive flexural crack (Zeman, 2010)

The causes of these high-impact forces either relate to defects on the track or defects on the wheel or train that increase the dynamic interaction with the system (Murray & Cai, 1998). In an ideal system these are catered for during the design phase, but in reality they may far exceed the design approach used due to a combination of defects at the rail/wheel interaction increasing the dynamic loading. Hard track supports will also increase the stiffness of the system and lead to an increase in the rate of loading experienced by the sleeper (Taherinezhad et al., 2013).

When assessing these types of defects, the number of vertical cracks visible on the top of the sleeper tends to be proportional to the number of cracks seen on the bottom of sleeper (Thun et al., 2008). The research by Thun et al also showed that vertical cracks did not significantly reduce the bending moment at the mid-span or at the rail seat.

Long Horizontal Cracks

Horizontal cracks, as shown in Figure 2-15 are found either on the side of the sleeper or top in a direction perpendicular to the train movement. Long horizontal cracks appear through the sleeper due to three main causes: cracking due to Delayed Ettringite Formation, cracking due to high-impact loads induced, or manufacturing defects (de Souza Lima & Carneiro, 2022; Kaewunruen & Remennikov, 2009).



Figure 2-14: Long Horizontal Cracks on Sleeper in Northern Cape (Photo by Author)

The international research by de Souza Lima and Carneiro has shown that the presence of DEF is found internationally within prestressed concrete sleepers. The documented cases find Delayed Ettringite Formation (DEF) as a significant contributor to sleeper cracking due to the heat curing methods often used for sleeper manufacturing (Sundaram et al., 2018). Typically, Ettringite formation occurs when the concrete is wet, and can still expand. However, improper heat treatments above 70°C result in the delayed expansion of the Ettringite. This expansion later in the process results in cracking of the concrete in the already set matrix.

Figure 2-16 shows a typical crack pattern from a combination of ASR and DEF observed on Indian Railways.

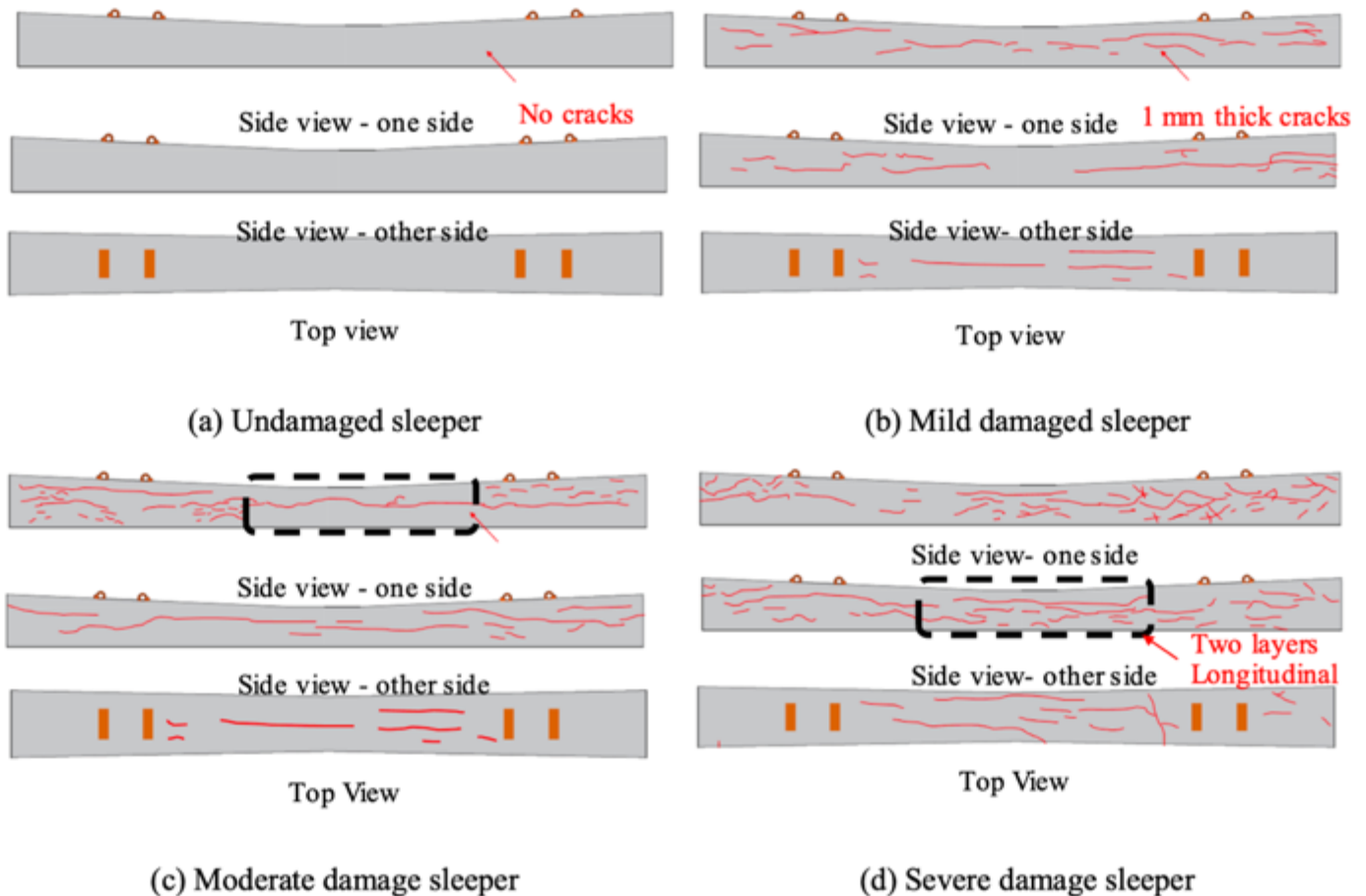


Figure 2-15: Typical Categorization of Sleeper Cracking due to ASR and DEF (Sundaram et al., 2018)

The presence of longitudinal cracks may also indicate severe loading cases (Kaewunruen & Remennikov, 2009; Taherinezhad et al., 2013). The results from the 2009 research by Kaewunruen and Remennikov show that as increasing high-impact forces are applied to the rail seat, the type of cracking changes from flexural cracks to combined flexural and longitudinal cracks at the rail seat.

No matter the cause, the presence of longitudinal cracks significantly decrease the bending moment of the mid-span and rail seat as these cracks tend to destroy the reinforcement bond and the anchorage system of the prestressed reinforcement (Thun et al., 2008).

Cracking due to Prestressing Steel Corrosion

Prestressing steel corrosion is a common deterioration mechanism for concrete assets (Alexander et al., 2012). Long before failure occurs, signs of distress will typically be visible with an increasing extent of damage. Figure 2-17 shows a schematic of the typical three damage periods during the lifespan of a structure.

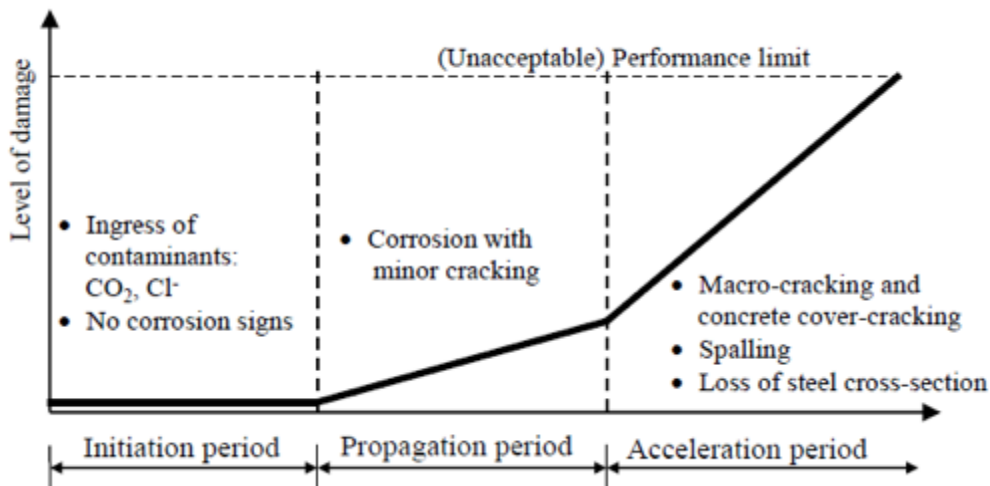


Figure 2-16: Damage Deterioration Mechanism (Heckroodt, 2002)

From the three phase damage deterioration mechanism model above, the initiation period, while still exposed to a corrosive environment, provides no physical signs of reinforcement corrosion. The inflection point between damage initiation and propagation occurs after a critical level of corrosive contaminants have built up and initiate the prestressing corrosion process. This second propagation phase will only show minor signs of cracking. The final stage of the model is when severe corrosion reinforcement is taking place and results in wide-scale cracking, spalling and loss of cross-sectional area of the steel. A structure will eventually see unacceptable damage levels, and exceed the limits of the asset.

Steel corrosion is an electrochemical process through which ion flow is created when the iron is solubilized at the cathode and then reduces the oxygen at the anode (Alexander et al., 2012). The Research Monograph No. 9 by Alexander et al. further describes the mechanisms for deterioration. The authors describe corrosion as either a microcell or macrocell corrosion effect. Typically, reinforcing or prestressing steel is embedded in concrete and the concrete will prevent this reaction as the alkaline material will passivate the steel surface and create a barrier effect with a thin ferric oxide layer. This passivation effect is known to break down when the pH of the concrete decreases due to carbonation, when chloride ingress catalyses the oxidation process of the steel, or when cracks form that remove the protective effects of the concrete.

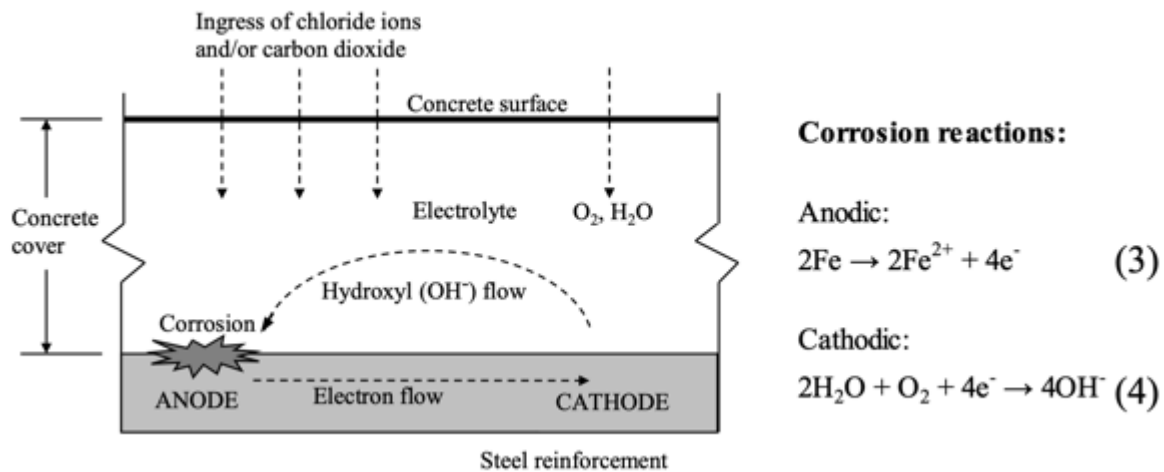


Figure 2-17: Illustration of Corrosion Process in Concrete (Alexander et al., 2012)

Despite the large body of international research on other concrete assets, prestressing steel corrosion was not noted as a major failure mechanism or damage mode for concrete sleepers in the meta-analysis of international literature or in the international industry reviews (de Souza Lima & Carneiro, 2022; Taherinezhad et al., 2013; Thun et al., 2008).

This topic was noted as a gap in the literature in 2023 by Wang et al. when the authors explored the damage of concrete railway sleepers due to prestressing steel corrosion at 10 years, 30 years and 50 years lifespan. The authors found the corrosion density, as calculated with the Butler-Volume expression, shows rapid increase in corrosion density between 10 years and 30 years but a smaller increase in corrosion density between 30 and 50 years. They find this in contrast to the damage factor showing reduction in protective coating of 10% at 30 years, while a much larger 40% reduction at 50 years. The authors recommended continued research in the field to add to the literature surrounding prestressing steel corrosion in concrete sleepers. Within the South African industry, the corrosion of prestressing steel is discussed as a design choice where exposure conditions are extreme such as the coastal areas where the chloride content is significant. The discussion suggests the width of the prestressing strands is understood to influence the corrosion but there is no literature found on the specific topic. The long-term failure modes, severity of failure and type of cracking expected from the corrosion of steel prestressing tendons is unknown at this stage.

Vertical Cracks at Sleeper Mid-Span

Cracks that form in the mid-span of the sleeper and are perpendicular to the sleeper length are often referred to as centre-binding (de Souza Lima & Carneiro, 2022). The root cause of this sleeper centre-binding is attributed to an internationally documented group of defects called ballast voiding, when ballast under a sleeper permanently displaces, leaving the sleeper in an unsupported condition (Remennikov & Kaewunrunen, 2007). The damage mechanism that leads to centre-binding cracks typically occurs when the ballast supporting the ends of the sleepers displaces due to repeated loading actions. This leaves no supporting shoulder ballast and leads to the sleeper only being supported in the centre (Zeitouni et al., 2018). Figure 2-19 shows typical Centre Binding cracks, while Figure 2-20 shows the typical loading and support configurations of sleepers due to ballast voiding conditions from international research.



Figure 2-18: Example of Centre Binding of Concrete sleepers (NTSB, 2014)

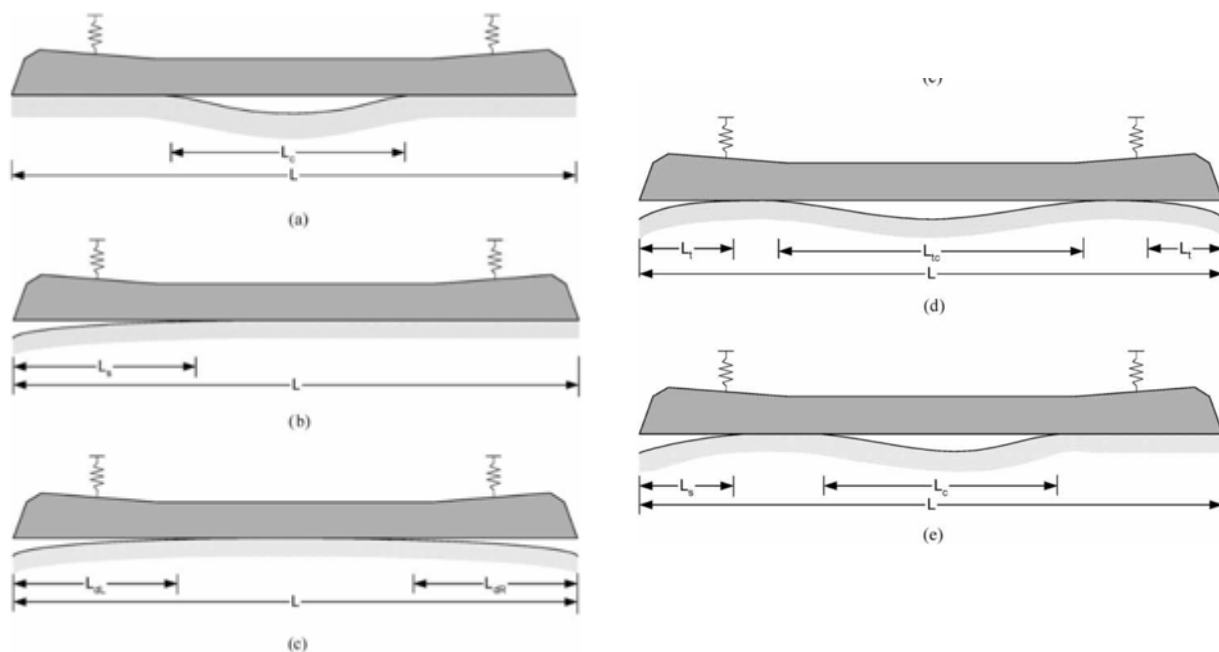


Figure 2-19: Sleeper Support Condition Deterioration (Remennikov & Kaewunrunen, 2007)

This defect was ranked overall as 5.06 out of 8 by the international study by Van Dyk et al (2013), showing a moderate criticality for corrective maintenance. This moderate ranking is attributed to the flexure that may lead to gauge widening and derailment. The research by Thun et al showed these cracks at the centre of the sleeper did not significantly reduce the bending moment at the mid-span or at the rail seat.

The unsupported conditions from Figure 2-20 provide insight as to why the South African defect from the ballast voiding mechanisms produces an abrasion defect rather than the centre-binding defect seen internationally. The South African industry more commonly sees ballast voids under the full bearing length of the sleeper, which will be discussed further below in conjunction with Sleeper Body Abrasion.

2.3.4. Abrasion of Concrete Sleepers

The environmental exposure during operations may introduce physical abrasion as a durability defect, not just to concrete sleepers but all concrete assets (Ballim et al., 2021). The abrasion on a concrete railway sleeper is seen in two typical defects: deterioration of the rail seat under the pad, and rounding of the base of the sleeper.

Rail Seat Deterioration

Rail Seat Deterioration (RSD) is described as the degradation of the concrete surface underneath the rail pad (de Souza Lima & Carneiro, 2022). This degradation leads to gauge widening because the rail is not fastened to the sleeper securely and may move under load.

RSD can arise from various deterioration mechanisms, such as: mechanical abrasion between the rail and sleeper, concrete crushing of the sleeper chair by the rail, hydraulic pressure cracking and hydro-abrasion from trapped water between the rail, pad, and sleeper. Figure 2-21 shows typical RSD.



Figure 2-20: Typical Rail Seat Deterioration (RSD) (Federal Railroad Administration, 2019)

A large body of research surrounds the topic of RSD and while it is considered an important defect to detect, it is not typically found outside North American railway lines (de Souza Lima & Carneiro, 2022; Zeman, 2010). Research that applied 3D finite element analysis to review the effects of RSD under cyclic loading concluded that it does not affect the lifespan of the sleeper (Li et al., 2022).

Sleeper Body Abrasion

The interface between the ballast and the sleeper can suffer from mechanical and hydro-abrasion of both sleeper and ballast. This base abrasion was not mentioned as a typical defect in the international meta-analysis and surveys, but is commonly seen in the South African freight industry (de Souza Lima & Carneiro, 2022; Taherinezhad et al., 2013; Thun et al., 2008). In South Africa this abrasion at the base of the sleeper is often visible in conjunction with visible localised ballast and sleeper abrasion and/or crushing, as shown in Figure 2-22.



Figure 2-21: Sleeper Base Rounding due to abrasion near East London, Left; Localised Ballast/Sleeper abrasion and crushing near Kimberley, Right (Photos by Author).

International research has described the base abrasion as soffit abrasion and discusses how it occurs either at the mid-span or under the rail seat (Li et al., 2017). A further 3D finite element analysis by Li et al. in 2022 concluded that any soffit abrasion will critically reduce the lifespan of a concrete sleeper, and when deep base abrasion is subjected to dynamic loads the lifespan is exponentially shorter.

The abrasion of the sleeper base due to loading or maintenance results in loss of sleeper angularity for ballast interlocking and increases the fines content of the ballast grading curve. The increase in fine particulate, described as ballast fouling, is often measured as the percentage of fine material passing the 4.76 mm sieve with 0% being the design measure (Li et al., 2016). Ballast fouling has a severe effect on the stiffness of the track and often results in drainage problems, track geometry defects, and subgrade failures. The authors Li et al. also attribute ballast fouling sources primarily to the mechanical or hydro-abrasion of ballast particulate, although there are external sources that may also contribute. The maintenance used to correct track geometry through adjustment of the ballast and realignment of the track is known to have drawbacks of increased fouling and possibly damaging the sleepers.

The example in Figure 2-22 was seen at a section that had historic issues with “blind slacks” that are created by sleeper voids.

2.3.5. Mechanical Damage of Concrete Sleepers

The operational conditions introduce common types of mechanical damage that should be considered during condition assessment.

Tamping Damage (Cracking or Abrasion around Rail Seat)

A mechanized ballast tamper is an important part in the maintenance of a track system used to correct the geometric profile and provide a smoother running surface for trains (Li et al., 2016). The ballast tamping machine will lift the rail and sleeper to the correct geometric alignment thereby creating a void in the ballast under the sleeper, then use vibrating metal tines to liquify then squeeze the ballast into the void (Plasser South Africa, 2024). This maintenance does come with certain trade-offs, such as ballast and sleeper deterioration over time (Selig, 1994). Typical damage is seen where the tamping tines enter the ballast, to the left and right of each rail. Figure 2-23 shows an example of this damage.



Figure 2-22: Base abrasion around rail seat due to Mechanized Ballast Tamping near East London, Left; Tamping Tine damage of sleeper near De Aar, Right. (Photos by Author)

The effect of this damage is crushing or abrasion of the sleeper base to the left and right of the rail seat as the vibration of the tamping tines abrade the sleeper or ballast. This type of damage will have the same effect as soffit abrasion, and severely impact the life-span of the sleeper (Li et al., 2017; Li et al., 2022). Any cracks created from direct impact of the tamping tines on the sleeper may create cracks with a similar effect on the to those as described above as cracking at the rail seat.

Derailment Damage

Damage to a sleeper due to a derailment is typically seen in two places; on the gauge side of the rail as a train wheel drops on the sleeper, or on the field side of the rail where the train wheel has climbed over the rail before dropping on the sleeper. The manner and severity of the derailment may result in thousands of sleepers requiring replacement (Taylor, 2010). This is seen within the South African industry, as well as globally such as the derailment in New Zealand described by Taylor (2010) where two loaded coal wagons derailed but travelled undetected for 17 km resulting in the damage of 20 000 concrete sleepers. Figure 2-24 shows an example of damage created by a wheel dropping to the gauge-side of the rail.



Figure 2-23: Derailment Damage from Wheel Dropping on the Gauge Side (Zakeri & Rezvani, 2012)

The exact location of damage on the sleeper due to a derailment may sometimes look like the damage seen due to the ballast tampers. The main distinguishers between derailment damage and tamping damage are that usually the derailment damage will be seen in a long line of sleepers and the impact damage from derailment will stretch across the width of the sleeper as opposed to cracking at the edge from the tamping tine.

2.4. Management of Assets

Railway infrastructure has a low threshold for failure. The closer the component to the rail/wheel interface, the larger the risk of failure. Broken rails, track geometry defects, rail kickouts and gauge widening were the most significant causes of derailments due to infrastructure in the United States of America from 2000 to 2014 (Liu, 2017).

2.4.1. Asset Management

Asset management plans are the overarching guidelines used to ensure the reliability of large networks of infrastructure. The history of a system is a key input when developing a maintenance plan. The current condition, expected useful life of an asset, current valuations and decay curves are all inputs to the process. Omission of any of these can lead to several risks including risking the health and safety of its users, financial risk, and societal risks.

The process of assessment requires the current condition to be assessed, the future life estimated and then compared to the expected useful life of asset. If the estimated remaining useful life does not meet the requirements, then the gap will need to be closed through intervention. This establishes the Level of Service that will be set with the corresponding performance metrics. The future demand of the asset needs to be known to review the risk of failure, and then each asset in the portfolio needs to be assessed and prioritized according to the framework that has been established. These flow down into long-term, medium term, and short-term maintenance plans.

2.4.2. Track Quality Through Lifecycle

Two factors drive the condition of the track at any point in time: construction quality and maintenance quality (Zaayman, 2013). The cost of design and construction is directly linked to the initial quality of the product received. This will have a long-standing effect on the lifecycle costs of a system, and so is a key consideration to balance cost and quality. More expensive initial outlays tend to predict a lower lifecycle cost by minimizing routine and corrective maintenance requirements.

Figure 2-25 shows an example of how setting maintenance thresholds can affect the overall pattern of track behaviour.

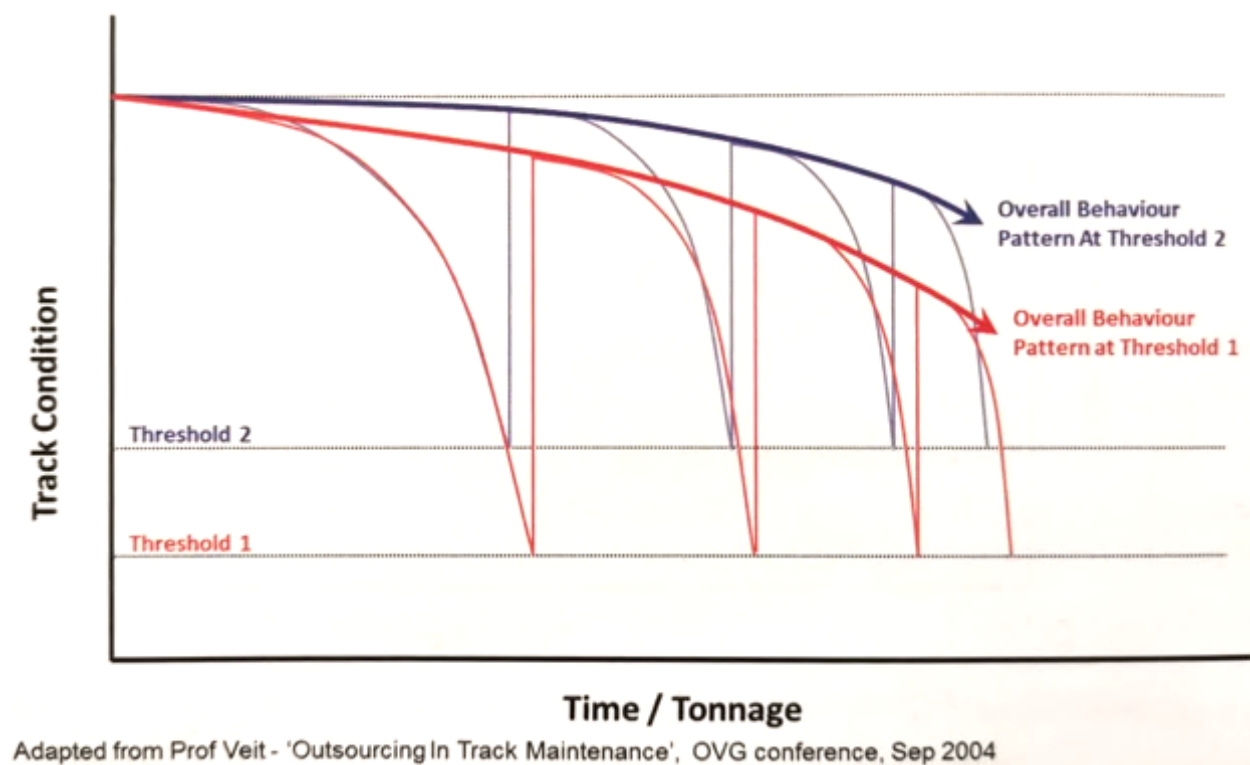


Figure 2-24: Example of Track Behaviour with Different Thresholds (Zaayman, 2013)

Once constructed, the inherent and then inherited track quality will require maintenance to keep meeting functional requirements. The setting of thresholds at which maintenance needs to be done, once again faces the challenge of balancing cost and quality. Higher thresholds come at a greater cost but can possibly extend the life of an asset as well as reducing incidents.

2.4.3. Maintenance Tactics

Sustainability guidelines govern that four major metrics drive the success of a freight corridor: price of service, time and reliability of the service, volume capacity of the network, and infrastructure resilience and efficiency (Havenga & De Bod, 2016). Maintenance tactics form part of the overarching maintenance strategy of a network operation, and so selection of the way they will be conducted is a key consideration.

Track maintenance tactics as a whole fall into two main categories: planned and unplanned maintenance. Figure 2-26 shows an overview of the structure.

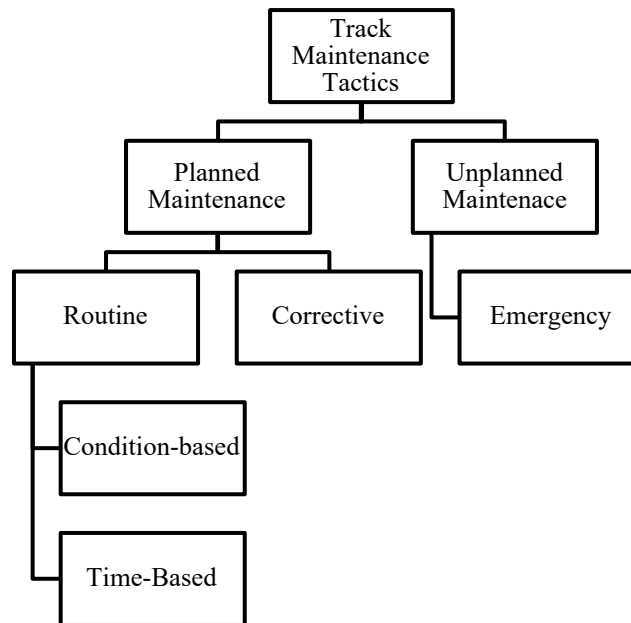


Figure 2-25: Maintenance Tactics Diagram (Zaayman, 2013)

Ideally the track system should employ a balance of planned and unplanned maintenance to optimize cost, while operating at an acceptable level of risk. Erring at either end of this spectrum will see a rise in direct or indirect cost of operations. Figure 2-27 shows how a typical track system balances routine and preventative maintenance costs.

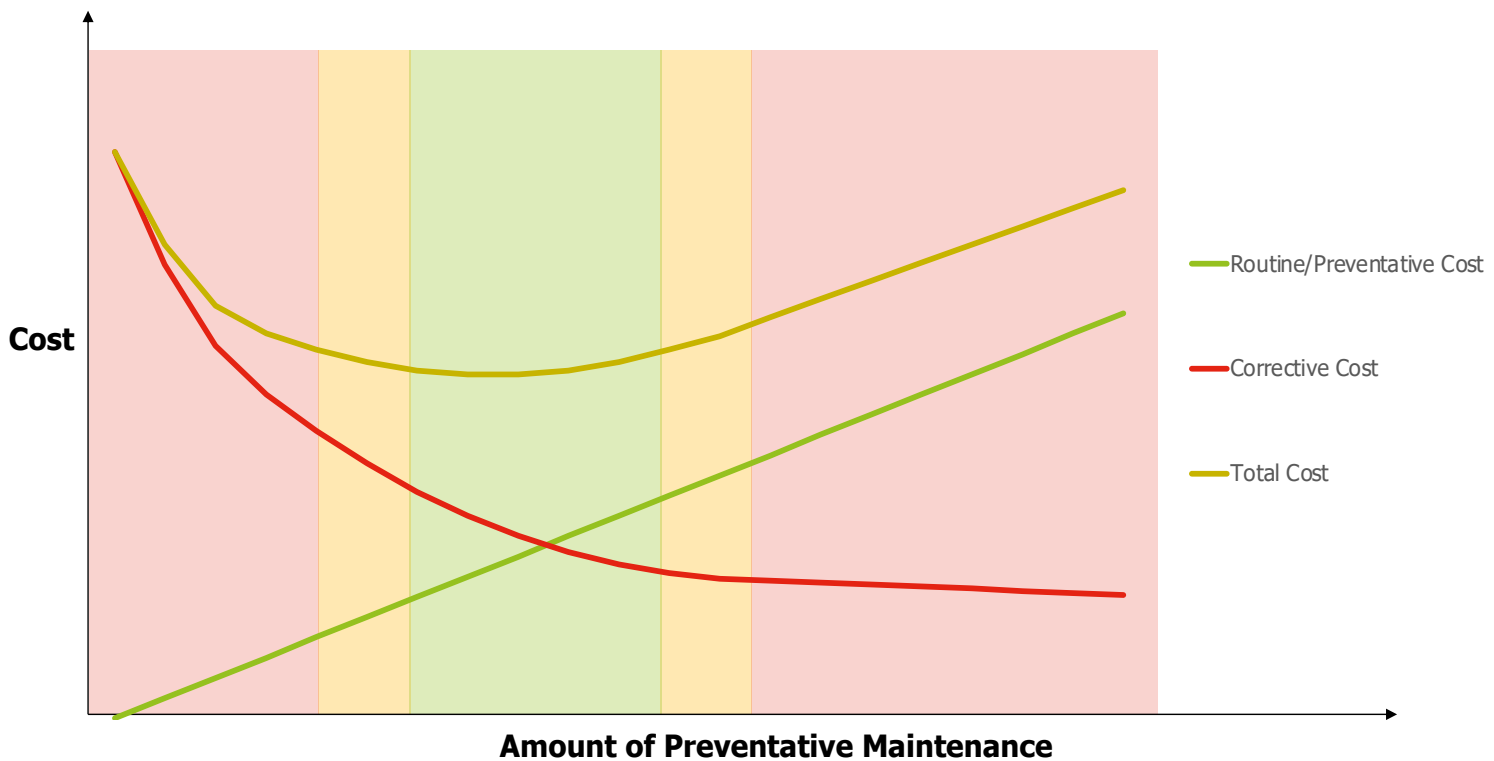


Figure 2-26: Preventative vs. Corrective Maintenance Costs Adapted from Douglas (2017)

This system example shows high corrective costs associated with low inputs of routine and preventative maintenance. The red zones indicate an inefficient or ineffective maintenance operation with an unbalanced amount of preventative to routine maintenance. Optimised maintenance strategies, as indicated by the green sections, reduce costly corrective maintenance by doing an appropriate amount of routine and preventative maintenance to mitigate major risks to the operation. The yellow zones are transition areas indicating moderate inefficiencies within a maintenance operation.

The overall cost of corrective maintenance will never be completely minimized, but operating at a higher level of routine maintenance spending will see a more predictable cost and then is better for the planning and cash-flow of the network. Each industry or system will have a unique point where the total cost to operate a system is minimised.

Figure 2-28 illustrates how an under-invested system will see an increase in speed restrictions (speed orders) and derailments, up until a point where a maintenance injection (MC2) is required to mitigate further losses.

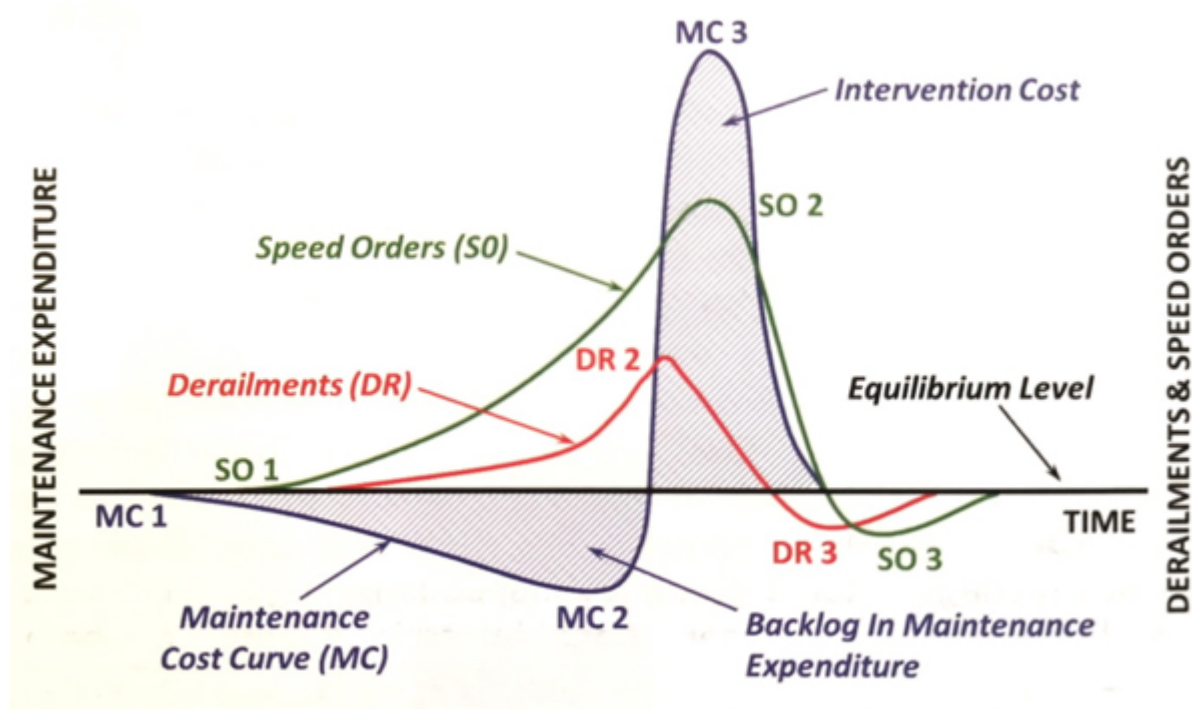


Figure 2-27: Maintenance Cost Curve of an Under-Invested Network (RT-CAP Project, courtesy of Plasser South Africa) (Zaayman, 2013)

The challenge with concrete sleepers is that while other components are frequently assessed using a combination of preventative and corrective tactics, the literature above regarding the defects typically found on concrete sleepers only refers to corrective tactics.

2.5. Condition Assessment Methods for Concrete Sleepers

The literature methods currently in use to detect defects on concrete sleepers was reviewed, with three broad categories emerging: visual assessments, non-destructive assessments, and statistical methods. Each of the methods will describe which defects are detectable and the quality of detection, as well as briefly describe how each of the assessments are conducted.

2.5.1. Visual Condition Assessment of Concrete Railway Sleepers

Visual inspections are the most rudimentary of the inspections. Physical data is collected through visible assessment of defects on the sleeper and is then transferred to a secondary system to review the information.

Walking the section to assess concrete sleeper condition provides an assessment of each sleeper but is limited to the slow speed of the inspection and the lack of visibility to the base of the sleeper unless the ballast is removed around and under the sleeper. The results from these assessments are subjective to human error. Examples of foot inspections show good insight to the specific inspection, but these are time-consuming and often expensive exercises (Sundaram et al., 2018).

Walking inspections are more suited to areas that have already been identified as concerns. The ASR cracking on the Sishen to Saldanha line used manual categorization that allowed detailed information on crack widths and location. Figures 2-29 and Table 2-5 show how this assessment used categorised the defects and their corresponding locations.

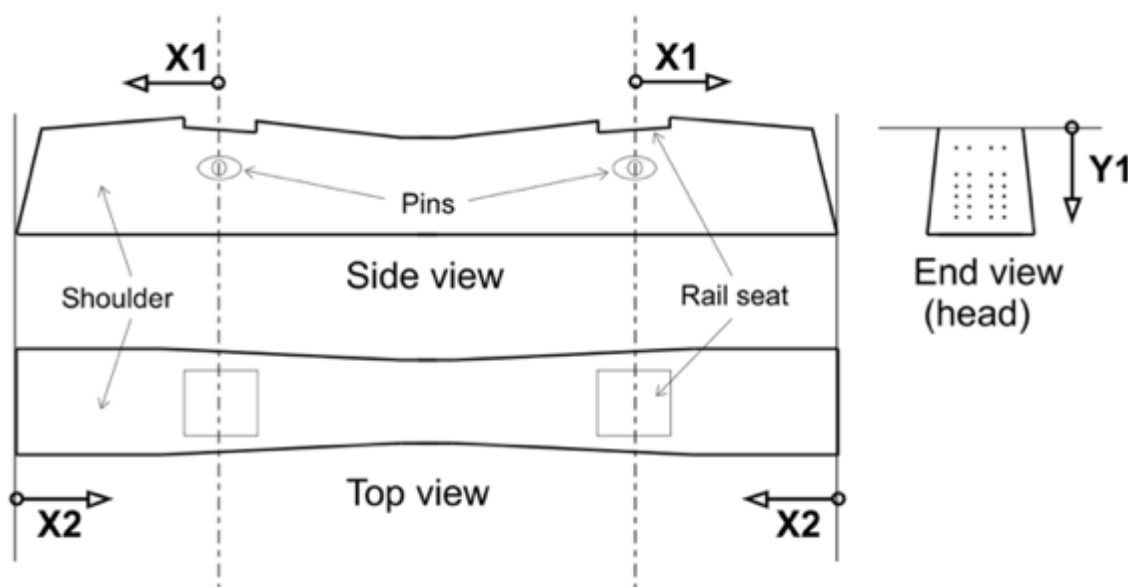


Figure 2-28: Sishen to Saldanha ASR Cracking Axes of Identification (Grabe & Oberholster, 2000)

Table 2-5: Categorization of ASR Cracks on the Sishen to Saldanha Line (Grabe & Oberholster, 2000)

Class	Crack parameter (mm)	Crack position, distribution and dimension					Cracks to pre-stressed strands
		Pin to Head		Head	Middle		
		Side, X1	Top, X2	Y1	Top	Side	
AA		No visual cracks					
A1	Length	None	<150	<100	<300	<300	None
	Width		<0.1	<0.1	<0.1	<0.1	
B1	L	None	<150	<150	<300	<300	None
	W		<0.5 at origin	<0.5 at origin	<0.1	<0.1	
B2	L	<200	<150	<200	<600	<600	None
	W	<0.1	<0.5 at origin	<0.5 at origin	<0.1	<0.1	
B3	L	Right through	<300	Right through	From pin to	From pin to	Slightly
	W	<0.1	<0.5 at origin	<0.5 at origin	<0.1	<0.1	
C1	L	Right through	Right through	Right through	From pin to	From pin to	Yes
	W	<0.1	<1 at origin	<1 at origin	<0.5 at origin	<0.5 at origin	
C2	L	Right through	Right through	Right through	From pin to	From pin to	Yes
	W	<0.5 at origin	<1.5 at origin	<1.5 at origin	<0.5	<0.5	
C3	L	Right through	Right through	Right through	From pin to	From pin to	Yes
	W	<1 at origin	<2 at origin	<2 at origin	<1 at origin	<1 at origin	
DD	L	Right through	Right through	Right through	From pin to	From pin to	Yes
	W	>1 at origin	>2 at origin	>2 at origin	>1	>1	

The example of visual assessment above provides a reference template for naming conventions of defect locations. The size of the defect at each location was categorised according to a defined class of defect, allowing separation into nine categories of defect severity.

Similar assessments, as in Figure 2-31, have been conducted manually through visual methods, such as on the Indian Railways. These have been similarly successful at categorizing small sections of track and better understanding the challenges in order to plan maintenance and corrective tactics.

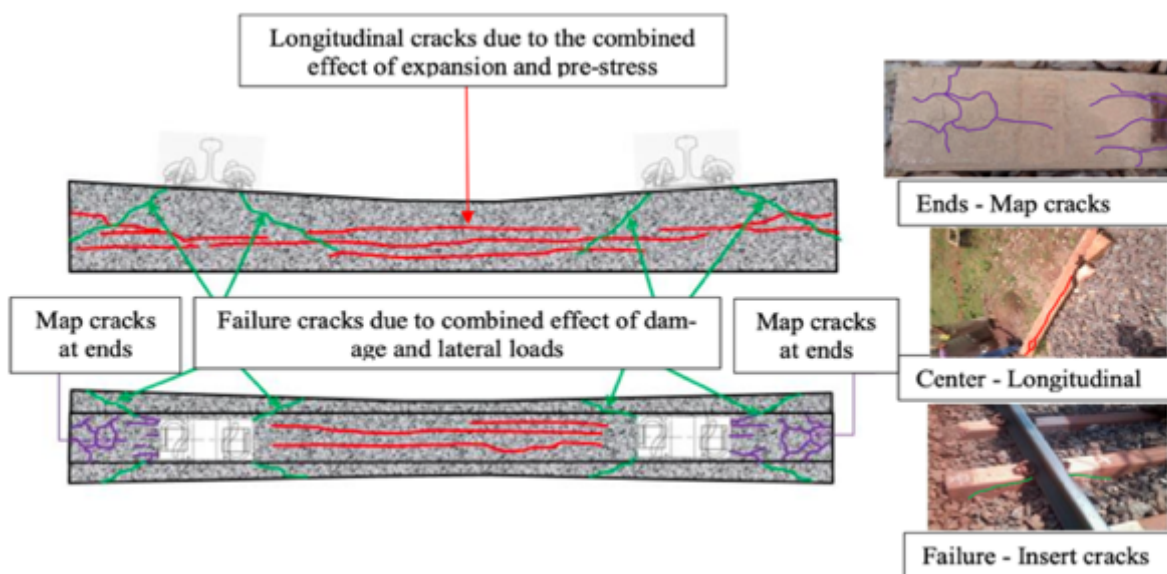


Figure 2-30: Typical Cracking Inspection due to ASR and DEF at the Indian Railways (Sundaram, et al., 2018).

Visual inspections can be done more quickly using a rail-mounted vehicle instead of walking. An example of a rail-mounted inspection vehicle is seen in Figure 2-32.



Figure 2-31: LuxRailer Inspection Trolley (Photo by Author)

The speed of inspection can be increased with the vehicle but often at the loss of information resolution. These are also subject to human error, both in the initial inspection then again in the data processing and recording aspects from the inspection sheets. Inspections that are done by foot and set detailed inspection criteria allow for detection of all types of damage and deterioration, but routine foot inspections do not set out to collect detailed information at scale due to resource constraints. And so faster methods such visual inspections, with the use of an inspection trolleys, forfeit the quality of information in favour for scale of assessment. Inspection trolleys are likely only able to detect the more severe defects visible from the top of the sleeper, such as the cracks that form on the top of the sleeper and mechanical damage on the top of the sleeper. Defects such as abrasion, some types of tamping damage, cracks at the seat of the rail base, and possible map cracking may be overlooked when inspection visual inspections are not done by foot.

Imaging of sleepers through rail-mounted vehicles provides detail on defects visible from the top of the sleeper (Federal Railroad Administration, 2018). Figure 2-33 (Left) shows the vehicle used, while Figure 2-33 (Right) shows an example of the data collected.

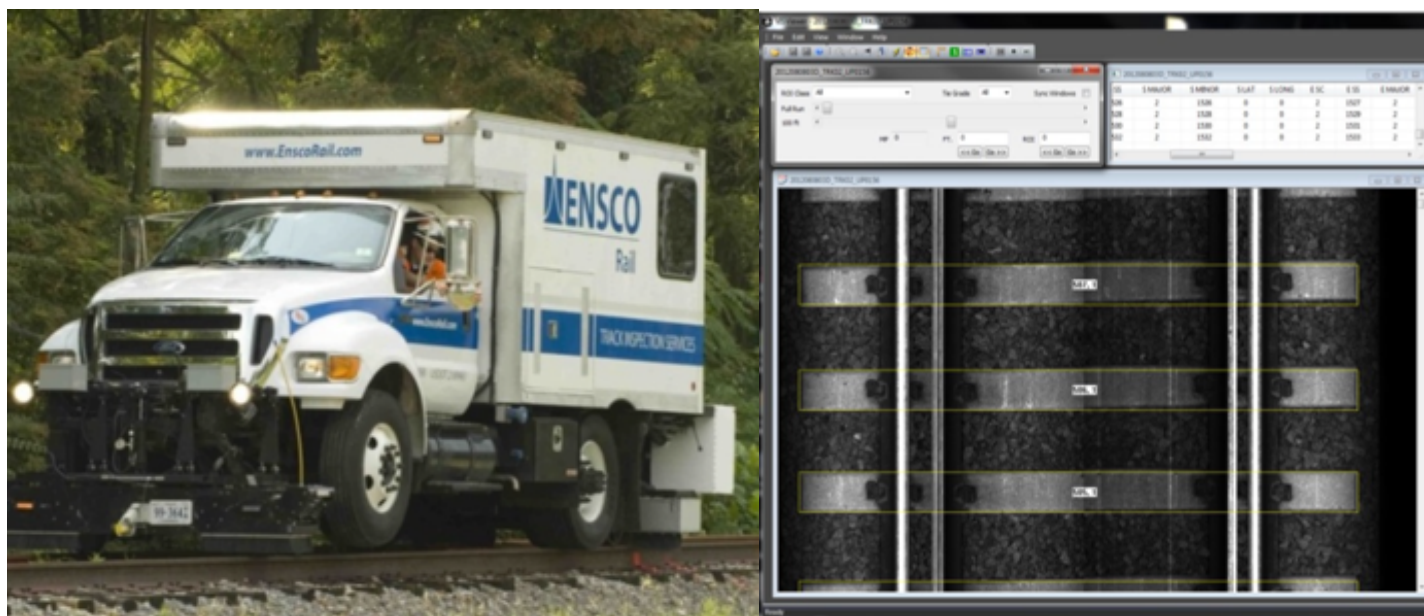


Figure 2-32: Imaging of Sleepers through Rail-Mounted Vehicles, Left; Example of data generated from vehicle-mounted inspection, Right (Federal Railroad Administration, 2018)

The high-railer-mounted monochrome imaging system used by the North American railroad operates at between 30 km/hr. to 40 km/hr. and can operate in both day and night conditions. The images are processed using a machine vision algorithm and can classify defects in five categories from Class 1 showing no material deformities to Class 5 showing ineffective to function.

Because the measurement campaigns occur at different time periods, a time-based crack propagation estimate can be produced. This provides insight into the most severe degradation of concrete sleepers and can be used to track manufacturer quality. The limitations are that it does not do well with assessing abrasion and small chipping as the pattern recognition software struggles to separate small defects from small manufacturing irregularities that are within tolerance. As with visual inspections by trolley some types of tamping damage, cracks at the seat of the rail base, rail seat deterioration (RSD), base abrasion and possible map cracking may be overlooked. As such it is in line with the other visual methods in that it is useful to assess where corrective maintenance is required, but the scale and quality of information also allows for predictive or preventative maintenance planning.

2.5.2. *Non-Destructive Condition Assessment of Concrete Railway Sleepers*

The importance of continued serviceability of a structure during assessments has provided focus on methods of non-destructive technology. Non-destructive methods are concerned with the interaction of energy, and thus apply energy and measure the response. The defining categories include mechanical, electromagnetic, electrochemical, magnetic and spectroscopical. The scope of these can be used to assess cover depths to reinforcement, reinforcement corrosion severity, concrete quality, crack depth and position, and to locate reinforcement (Beushausen & Louw, 2021).

Deterioration of monolith concrete sleepers predominantly manifests as cracking and abrasion, and so non-destructive methods focus on this rather than the measuring the strength or reinforcement condition properties of the concrete.

Ultrasonic Pulse Velocity (Manual)

Ultrasonic testing is an acoustic impedance method, and so cannot penetrate through air. Couplants are needed with some transducers or specialized dry-contact transducers, to ensure this method is effective. Ultrasonic testing has long been in use within the industry but not for sleepers, rather focusing on the testing of rail condition and monitoring of defects. Ultrasonic rail detection uses angled probes to find internal defects within the head and web of the rail (Zaayman, 2013).

Singular testing methods are possible using classic concrete testing, such as the crack mapping shown in Figure 2-34 and illustrated in Figure 2-35.



Figure 2-33: Sleeper Testing on Latvian Railways using Ultrasonic Equipment from Riga University (Tatarinova et al., 2018)

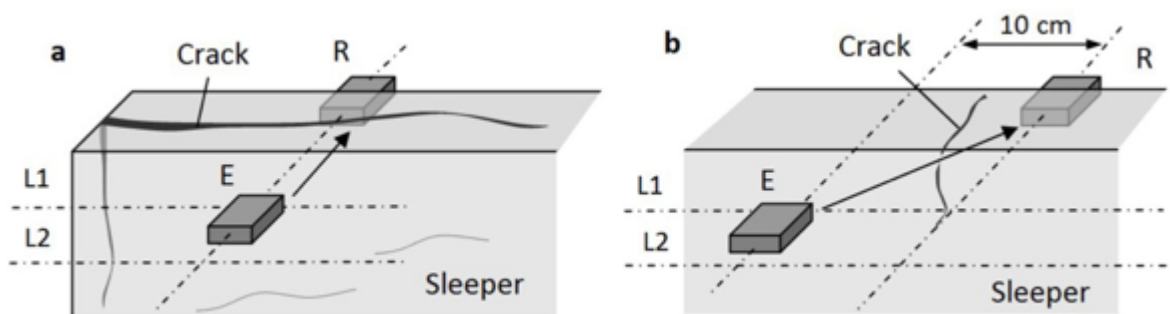


Figure 2-34: Diagram of Testing Arrangements to detect cracks in the Latvian Railway Network (Tatarinova et al., 2018)

The results can provide insight into crack depths and widths, but are limited to a small sample size of tests that can be conducted (Tatarinova, et al., 2018). The manual ultrasonic results were found to detect longitudinal and transverse cracks, centre binding, cracks at the base of the rail seat and some cracks around the fastener, and then allows them to be classified in up to four categories.

Ultrasonic Echo (Vehicle-Mounted)

The American Railroad Federation has put forward a railroad vehicle-mounted ultrasonic configuration that uses a ball-end tapper to induce a pulse and then measures Raleigh waves to identify cracks in the sleeper. Raleigh waves are tested within a range of 20 kHz, and this method shows optimum results at 17 kHz using a -58 DBV/microbar. Figure 2-36 shows the prototype of the fully mounted device, with the ball end tapper shown closer in the image on the right.



Figure 2-35: Ultrasonic Rail-Mounted Sleeper Assessment, Left; Ball-end tapper Inducing Pulse on Sleeper End, Right (Federal Railroad Administration, 2018)

Testing of sensors and impact methods is underway to assess the best configurations for application. An example of data in Figure 2-37 shows a contact and microphone sensor to detect the response.

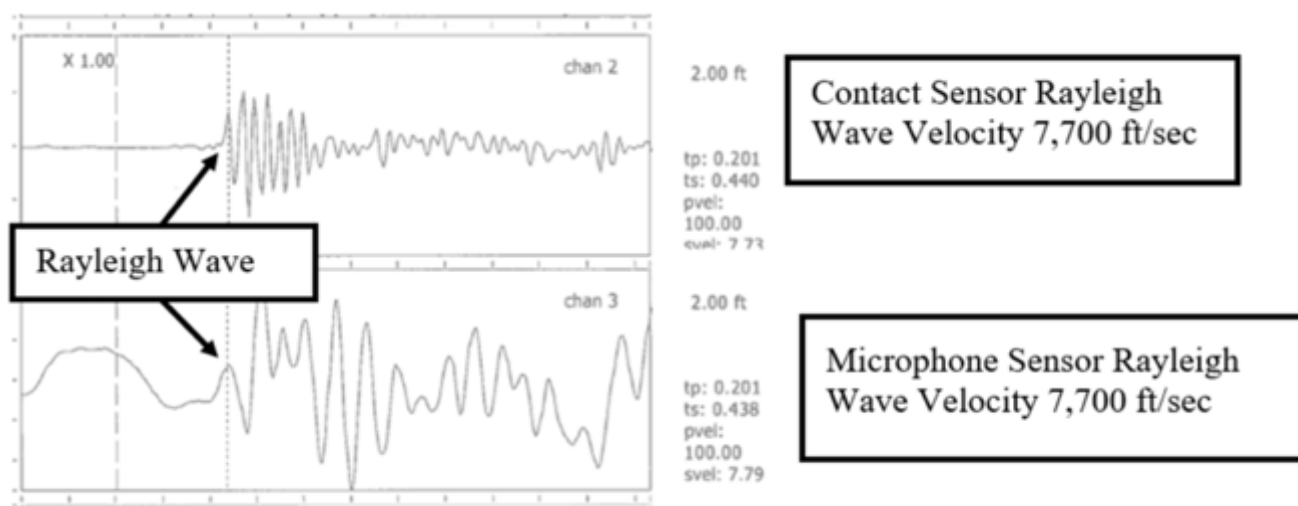


Figure 2-36: Raleigh Wave Sensor Response Testing for Concrete Sleepers (Federal Railroad Administration, 2018)

This has shown to adequately identify cracks both visible from the surface and hidden within the ballast layer. This means it will detect all types of cracking defects, but no abrasion defects and not all mechanical defects. The cracks identified can be used to classify the sleeper condition within five condition-based categories. The limitations to current technology include that of testing speeds being 30 km/h to 40 km/h, which is similar to the testing speed for the current rail ultrasonic testing machine in the South African industry, but higher speeds will need to be developed internationally to meet the requirements of the high-speed rail industry (Federal Railroad Administration, 2018; Aveng Rail, n.d.).

Acoustic Emission Monitoring (Fixed Ultrasonic)

Ultrasonic methods can be applied through passive methods such as Acoustic Emissions (AE) testing. These methods do not induce a signal, but rather wait for events that induce measurable emissions. The Kaiser Effect is a known limitation of this method, in which the time of installation is the reference template against which the condition is measured. This means the condition tracking only occurs once the system has exceeded the historic maximum stress level, and in relation to the starting deterioration template.

Monitoring systems have been tested at sites, such as the Hammersmith flyover in London, that attach a permanent acoustic emissions sensor to the sleeper (Clark et al, 2017). These discrete systems have shown promising results to track the crack propagation within concrete sleepers. This may provide information on all types of cracking defects, but does not indicate any mechanical or abrasion

related defects. High-risk areas benefit from this system as they allow for continuous monitoring and assessing the progress of cracks through the sleeper. This method will not be included in the analysis as based on industry experience it is not suited for large-scale implementation within the South African networks due to theft, maintenance constraints of attaching technology to a sleeper, and electricity supply in remote and unelectrified sections.

Ultrasonic methods are already in use within the South African network, as shown in Figure 2-38, but to measure the integrity of the rail. The management of continuously welded rails is a continuous and rigorous maintenance activity within the rail network. The use of ultrasonic technology mounted on high-railers has provided continuous sets of data to the network on the condition of the rail, allowing prevention of costly rail breaks during operation.



Figure 2-37: Ultrasonic Rail Testing Vehicle and Chaser (Lennings Rail, 2020)

This system uses the RFAS 2100 Ultrasonic rail flaw detection system, which measures up to speeds of 38 km/hr. While slower than the running speed of most freight lines, the accuracy of the data improves with slower campaigns and so is testing mostly at below 30 km/hr.

Limitations of the system include the lack of detection possible in the foot of the rail, as well as flaw shielding in sections of rail with rolling contact fatigue.

Radar

Radar techniques involve the generation of electromagnetic impulses and then the recording of their reflections at layer boundaries and objects (Taffe, 2008). Deviation from the expected transit time indicates integrity of the concrete, and if material proportions are known then thickness of members can be measured. The changes in permittivity measured have a significant impact on measurement of steel members, which creates a total reflection of the signal thereby inhibiting measurement beyond steel. Radar uses for concrete sleepers are limited at this stage, primarily due to the spacing of the reinforcement being closer than the 7 cm recommended limit.

This method, while having limited application within the concrete sleeper industry to date, may still be feasible for some concrete sleeper condition assessments.

2.5.3. Indirect Condition Assessment of Concrete Railway Sleepers

The challenges of the condition assessment of railway track infrastructure often arise when the performance of linear assets need to be assessed. The direct measurement through vehicle-mounted systems can be applied in a statistical manner to derive conclusions about the state of the track.

Track Quality Indices

Models are used to tie condition assessment data together and draw conclusions about the health of a system. Often track condition is summarized under the Track Quality Index (TQI), which focusses on the statistical roughness of track geometry over a specified length (Qing Li1, 2019). Sleeper condition as an independent input and output is not considered. Often outcomes of these variables still require further condition assessments to understand the root causes and plan interventions. South African rail networks have been measuring track geometry with the use of infrastructure measuring vehicles since 2000, when the original “IM2000” machine was commissioned by Plasser South Africa (Zaayman, 2013). This has since been replaced by more updated machinery, but the principle measurement requirements remain. Figure 2-39 shows the measuring vehicle.

Five track geometric parameters are measured by the South African machine: profile, alignment, gauge, twist and superelevation. The absolute gauge measurements are converted to a relative parameter then used to calculate a standard deviation over a 200 meter track length and called SD Gauge.



Figure 2-38: Infrastructure Measuring Vehicle near Queenstown (TGIV) (Photo by Author)

This SD Gauge value is used within the industry to indicate the condition of the sleeper, using a threshold value to indicate failure. This metric allows basic forecasting of the long-term planning requirements but due to limitations of using a statistical method this bears a moderate amount of uncertainty. When measuring sections that have critical gauge values the uncertainty of this value is lower, and so this SD Gauge metric is acceptable to assess the critical condition sections. This uncertainty is not currently a problem due to the limited replacement capacity of mechanised methods so only the most critical get replaced, which is a more certain result of this SD Gauge. But finer determinations between average and good condition are not possible using the SD Gauge as a metric.

There is no direct correlation between detection of defects discussed in Section 2.3 and this method of assessment, but as it measures gauge it may indicate damage to the rail seat and centre-binding as these defects result in deviation from the gauge standards. The TGIV also measures rail inclination as a parameter that can be used to indicate Rail Seat Deterioration as it measures rail inclination.

The measuring speed of the machine can be up to 80 km/hr and so runs freely through all sections within the network.

Track Gauge Force Measurements (Gauge Widening On-Track Machine)

The translation of track gauge information is often used to assess the immediate risks of derailment. Specialized track measurement vehicles have been used to apply vertical and horizontal loads to the track and measure the responding gauge. These will then be processed with a gauge-widening equation and result in a Gauge Widening Ratio (GWR) or Gauge Widening Projection (GWP) that is used to assess the risk (Federal Railroad Administration, 2006). Simplified results from the TGIV provides a direct track gauge measurement result that can be used to assess discrete defects. These are also used within the Track Quality Index calculations to review overall ride quality.

The South African industry used a similar method in the early 2000's on sections with wooden sleepers to assess their condition. This was not adopted as the test sections created severe damage to the sleeper through use, which created immediate corrective maintenance requirements.

2.6. Summary

The literature review was focussed on two main areas of research: the defects and deterioration mechanisms of concrete sleepers, and the condition assessment methods used for concrete sleepers. These topics were framed by a review of the physical, social and economic environment in which railway infrastructure, particularly concrete sleepers, operates.

The defects related to concrete sleepers were discussed in Section 2.3, and the methods used to assess the defects were discussed in Section 2.5. Some methods of condition assessment provided evidence of detecting some of the identified defects, while having limited to no assessment evidence for assessing other defects. The summary considers the condition assessment methods and if they have documented use for each concrete sleeper defect. This literature review has consolidated the results in an original summary table, shown in Table 2-6.

The methods were categorised by the Author into three groups to show how the literature documented the detection of each defect using the method. A method that showed documented use of the defect (●), showed examples of how the method was used to assess the condition of concrete sleepers. A method with partial evidence (○), described the defect possibly being measured with the method or a similar defect being detected in other concrete assets. A method that was not documented, represented with a “-”, did not make any reference to the method in relation to the defect.

Table 2-6: Summary of Literature on Concrete Sleeper Assessment Methods and the Defects Detected

	Cracks from Fastener Down	Derailment Damage	Longitudinal Cracking	Map Cracking	Rail Seat Deterioration (RSD)	Sleeper Body Abrasion	Tamping Damage	Vertical Cracking at Mid-Span	Vertical Cracks at Rail Seat Base
Gauge Widening (On-Track Machine)	●	○	-	-	●	-	○	-	○
Radar (Manual)	-	●	●	●	-	-	●	-	-
Track Quality Indices	○	○	○	○	●	○	○	-	○
Ultrasonic Echo (Acoustic Impedance Vehicle-Mounted)	●	-	●	●	●	○	-	●	●
Vehicle-Mounted Imaging Assessments	●	●	●	●	-	-	-	●	●
Visual Inspection	●	●	●	●	○	●	○	●	●

Description of Symbols:

- Documented use of method for defect
- Partial evidence of defect detection
- Method not documented for defect

The functional requirements of concrete sleepers and the defects related to concrete sleepers were discussed in Sections 2.2 and 2.4. A concrete sleeper defect can influence a range of functions that a sleeper is required to perform. The most important defects relate to the loss of a primary function of a sleeper, while a reduction of a primary function or loss of a secondary function is less important. Serviceability functions do not create immediate risks but may create long-term reliability risks to the network. The literature was consolidated to provide the original Table 2-7, in which the effects on the performance of concrete sleepers are summarised.

Table 2-7: Summary of Effects of Concrete Sleeper Defects

Concrete Sleeper Defect	Effect of Concrete Sleeper Performance
Cracks from Fastener Down	Loss of primary function with immediate risk to network.
Derailment Damage	Reduction of primary function.
Longitudinal Cracking	Loss of primary function with immediate risk to network.
Map Cracking	Loss of secondary function or serviceability.
Rail Seat Deterioration (RSD)	Reduction of primary function.
Sleeper Body Abrasion	Loss of secondary function or serviceability.
Tamping Damage	Reduction of secondary function or serviceability.
Vertical Cracking at Mid-Span	Loss of secondary function or serviceability.
Vertical Cracks at Rail Seat Base	Loss of secondary function or serviceability.

The maintenance of railway infrastructure, with concrete sleepers as a focus was discussed in Section 2.4. The full maintenance strategy was discussed to highlight the condition information required for sleepers at different levels. On the most immediate maintenance level, the sleepers require detection of defects that pose a risk to the safety of continued network operations.

For a long-term forecasting of network requirements, nascent defects or defects that affect the serviceability or impair functional requirements need to be identified. The literature review and industry practise, as a whole, discussed the framework and required inputs to effectively manage the life cycle of concrete sleepers.

3. Methodology for Proposing Feasible Concrete Sleeper Condition Assessment Methods

A typical feasibility study is interested in determining the best outcome of a series of possible choices (McLeod, 2021). The related body of research spans various fields, exploring the different applications to assess feasibility. The use of any example without adapted methodology creates an oversimplification or misrepresentation of the results, and so a broader framework from McLeod (2021) at the University of Western Australia will be applied as it is intended for more novel or complex reviews such as this.

The condition assessment method recommended must be able to provide better information than current assessment methods to mitigate critical network risks and plan for life-cycle costs. This will require an understanding of which failures are the most critical to detect, and how well the method will detect those failures. This includes an exploration of the viable methods, developing an informed basis for selecting a proposal, then reviewing if the minimum requirements are met to recommend an option.

McLeod (2021) uses six research questions to cover the questions that need to be answered for a feasibility assessment. The “capability to plan, deliver and operate” asks if the proposed solution is in line with what is already being done within the industry. This first feasibility question is reworked for this assessment to relate to the impact a solution will have on the network operations and ask if the method is possible to implement given the South African network demands. The second question relates to acceptability of the solution and asks if it should be done. This can be related to the relevance of the implemented solution, and in this case can be rephrased to assess if there are current unmitigated risks to the network that this solution will detect. This question ensures there is a demand for the solution. The third question considers the long term and lifecycle of a solution and asks if this solution will remain relevant in the future. The application of this question for this research will discuss the limitations for the reviewed foundational. The fourth question looks at technical feasibility, asking if this can be done. The technical solution must evaluate how well a method can provide information on the condition of the concrete sleepers. The fifth and sixth questions relate to the cost and time-related implementation of the solution, which were adapted to ask if the solution will fall within a reasonable price range and delivery timeline.

These categories for feasibility will be the basis for making an informed proposal. Table 3-1 shows a summary of the adapted research areas and questions that will be answered through this methodology, using research presented in the literature review and industry perspectives of Chapter 2.

Table 3-1: Adapted Feasibility Study Framework (McLeod, 2021)

Feasibility Area	Types of Research Questions	Method
Impact on Operations	Is this method possible to implement given the South African network demands?	Benchmarking
Acceptability	Is there a current unmitigated risk to the network that this method detects?	Failure Mode and Effect Analysis
Long term/ Life-cycle	Are all the limitations to the defects and assessment methods discussed that may result in future risk?	Literature Review
Technical	How well can a method provide us with technical information to assess the condition of a sleeper?	Failure Mode and Effect Analysis
Cost	Are the costs related to a method within an acceptable range?	Benchmarking
Time	How long will it take to implement a method?	Benchmarking

Table 3-1 shows the six feasibility areas that will be reviewed for this analysis. The research questions will require the use of two assessment methods to evaluate feasibility: a Failure Mode and Effect Analysis (FMEA) and benchmarking. The FMEA will answer the risk-related questions concerned with the quality and relevance of technical information each assessment method provides. The benchmarking assessment will consider the feasibility from a business standpoint, as it considers the impact on operations, cost and lead times of each assessment method. The literature review will inform both the FMEA and the benchmarking, as well as answer the outstanding feasibility questions.

3.1. Failure Mode and Effect Analysis

The method used to explore the technically viable methods for condition assessment of concrete sleepers will follow that of the well-established Failure Mode and Effect Analysis (FMEA). This method was methodically documented in the 1995 book of the same title by Stamatis. The method has since been used in the engineering field using adapted processes to suit industry needs (Zeman, 2010; Nadaf & Chanmanwar, 2020; Pattnaik & Mahendra, 2020; Lange et al., 2001). An overview of the steps in the FMEA process is shown in Figure 3-1.

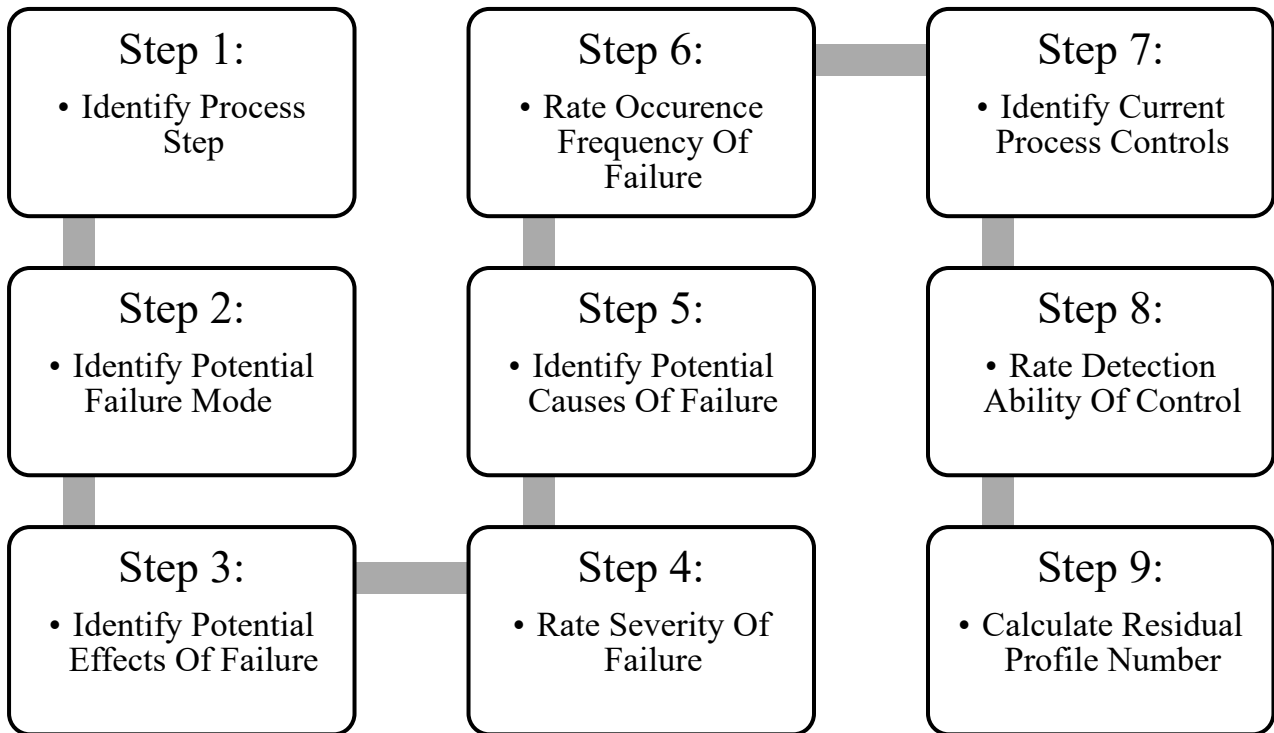


Figure 3-1: Failure Mode and Effect Analysis Process

FMEA uses a Residual Profile Number (RPN) to assess the severity of each defect, the failure rate of the defect, and then identifies how well the control measure will identify and mitigate the risk of the defect as shown in Equation 1.

$$RPN = S \times O \times D$$

Equation 1

Where:

S = Severity of Failure

O = Occurrence Frequency of Failure

D = Detection ability of Failure

The values for S, O and D are derived from a scale of 1 to 10. The ratings used for each scale require review and adjustment based on the unique analysis requirements, but within typical format so that the method produces comparable results (Lange et al., 2001).

A maximum RPN of a thousand is achievable and represents a severe defect that happens regularly but has no control in place to mitigate the severity or occurrence frequency. An acceptable RPN value is below 100, and for this assessment this number will also be used to deem a method adequate in mitigating risk to the network (Lange et al., 2001; Harpster, 2024).

The determination of the scales required for evaluation will be based on the work done by Harpster (2024) which provides an overview of what each scale is required to represent in order to achieve the comparable RPN results.

For Severity of Failure, the ratings will be considered in three categories: Safety/Legal Zone, Return/No Buy Zone and Conditioned Response Zone (Harpster, 2024). These criteria appear with relevant variations in other literature reviewed, but these guidelines were used for this methodology as they provide a closer link to the three practical severity categories that industry in asset maintenance management of Section 2.4 described of routine, corrective and unplanned maintenance.

These criteria are reviewed using industry experience and information from the literature review and adapted to produce rating criteria are shown in Table 3-2.

Table 3-2: Severity of Concrete Sleeper Defect (Harpster, 2024)

Rating	Severity of Defect
1	No measurable defect.
2	Deviation from standard requirements but not commonly noticeable.
3	Deviation from standard requirements noticeable but does not marked as defect.
4	Deviation from standard requirements noticeable but not primary, secondary or serviceability.
5	Reduction of secondary function or serviceability.
6	Loss of secondary function or serviceability.
7	Reduction of primary function.
8	Loss of primary function.
9	Critical to safety of continued operations with warning.
10	Critical to safety of continued operations issue with no warning.

The Safety/Legal zone represents the greatest risk to the continued operations of a company, and ratings will be either 9 or 10. The risk can be financial, social, health and safety, environmental or compliance risks that cannot be negated once they occur. These defects require significant corrective maintenance or full replacement of the asset.

The Return/No Buy Zone represents ratings from 4 to 8 where the defect is related to a serviceability or functional issue but does not result in a catastrophic failure. The differentiation of this category is based on if the defect results in a loss or reduction of a primary functional requirement, or loss or reduction of a secondary or serviceability function. The descending values will be attributed to the priority of the defects, with defects which impair the primary function being rated an 8 and defects which reduce a serviceability function a 4. The infrastructure assets in this zone require corrective maintenance to repair lost functionality.

The Conditioned Response Zone is indicated with ratings from 1 to 3 where there is a defect, but the outcome does not raise immediate repair issues from serviceability or ultimate states. It is a zone when the defect is accepted as normal and does not have an effect on the operations or infrastructure. These assets may still require routine maintenance to remain fully functional.

The severity of the defect will be rated using the information from the literature review related to the function which compromises the mode of failure. For example, if the failure mode is gauge width consistency due to flexure, this reduces a primary function and will score a 7 according to the rating scale.

For the occurrence of failure scale, failure data is often unavailable or requires subjective rankings. This is not considered an issue necessarily, if the ranking is done consistently from 1 to 10 (Wegscheid, 2000). The frequency failure due to the defects are shown in Table 3-3.

Table 3-3: Occurrence of Concrete Sleeper Defects (Harpster, 2024)

Rating	Occurrence of Failure due to Defect
1	Failure unlikely due to defect.
2	Relatively few failures occur due to defect.
3	
4	
5	Moderate number of failures due to defect.
6	
7	High number of failures due to defect.
8	
9	Failure will occur in the presence of defect.
10	

The occurrence failure ratings from Harpco Systems will be used as per the standard method. A rank of 1 relates to failures that are unlikely, or the change of failure is remote. Ratings from 2 to 4 are considered when relatively few failures occur. Values 5 to 6 represent a moderate number of failures, or failures that occur occasionally. Values of 7 to 8 represent a high probability of failure, or repeated failures. Instances of 9 or 10 represent failures that will almost certainly occur.

The outcome for an occurrence rating needs to establish how often the expected failure occurs due to the specific defect. This failure occurrence does not take into account the prevalence of the defect, just the number of failures that occur due to the defect. The way this occurrence will be rated is by using the international rankings for importance of defects, and then adjusted if required by considering the amount of international research available on the topic as well as the industry perspective from South Africa.

The detection evaluation criteria set out by Wegscheid (2000) range from 1, which represents the best detection of failure, to 10, which represents the poorest detection of failure. This rating is typically used in the context of the decisive action that mitigates the risk, which in this case would often require the replacement of the damaged sleepers. For this assessment, however, it will rate the quality of information the method will produce on the condition of the concrete sleepers. This adaption is more reasonable for this use-case as the gap in understanding the defect is the first step to mitigating the associated risk of failure.

Values of 1 and 2 describe defects that are detected in time to be planned for with routine maintenance. Values of 3 and 4 describe defects that occur but are able to be detected early enough to plan for correction within required timelines. Values of 5 and 6 reflect the defects that lead to failure that are detected but require immediate unscheduled maintenance for correction. Values of 7 and 8 relate to defects that are not detected until failure occurs and require immediate maintenance. Values of 9 and 10 relate to defects that are not immediately detected after failure, and additional damage occurs before the failure is detected.

The rating of a detection method for a specific method will require the Authors' judgement to rate the method. This risk related to the Authors' judgement is reasonably mitigated by the setting of clear rating categories. The quality information provided by each assessment method does not always correlate with the quantity of information provided by the method. The use of the rating scale will still require a qualitative assessment to consider how the quality and quantity of information will inform the maintenance requirements. The detection of defect rating is summarised in Table 3-4.

Table 3-4: Detection of Defects using Concrete Sleeper Condition Assessment Methods

Rating	Detection of Defect
1	Detection of defects allows for planned routine maintenance.
2	
3	Detection of defects allows for planned corrective maintenance.
4	
5	Detection of defects allows for unplanned corrective maintenance.
6	
7	Detection does not occur until after failure, requiring immediate unplanned maintenance.
8	
9	No detection, defect will only be detected after further damage occurs.
10	

The detection of the defect ideally should sit at 1, to allow for planned routine maintenance of the network and facilitate the long-term planning schedules. If not possible, the defects that occur often and are severe in nature need to have the best detection.

The limitations of using these rating styles must be highlighted. The Author has taken care to objectively use the rating criteria to classify the input conditions, but there is still a certain inherent perception of the Author required for the categorisation.

3.2. Testing for Defect Relevance

The Failure Mode and Effect Analysis should further test for relevance of defects to ensure only defects which have tangible effects on network operations are included for review. Harpster (2024) recommended the use of a Class Column Symbol Table to account for defects that can be removed from consideration if they are both low in frequency and low in severity, as illustrated in Figure 3-2.

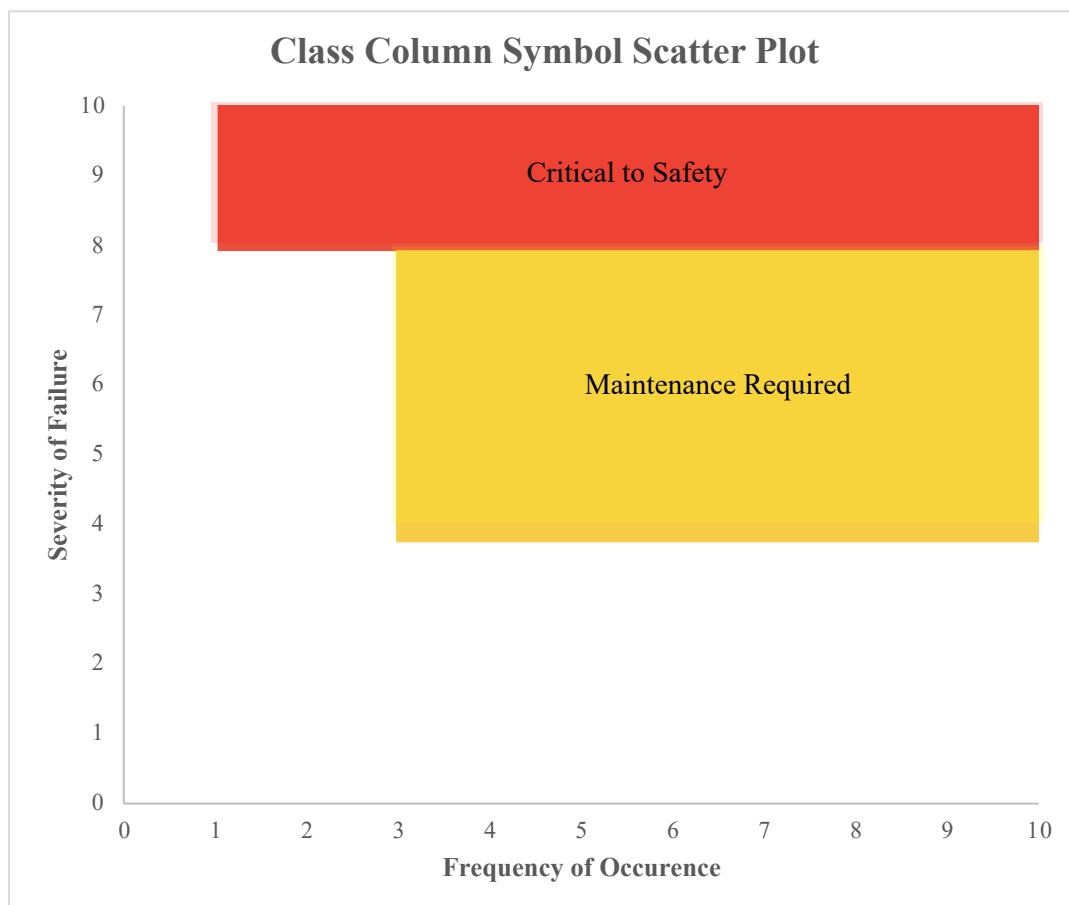


Figure 3-2: Example of Class Column Symbol Diagram Adapted from Harpster (2024)

The S or red zone refers to defects categorised as critical to safety, while the M or yellow zone refers to defects that will require maintenance. The test from Figure 3-2 will indicate if there are any defects worth considering negligible to large-scale assessments.

As per the definitions above for the categories, defects with a severity between 1 and 3 are considered negligible for the assessment because they do not require any planned or unplanned intervention for correction of the ultimate state or serviceability defects. The occurrence definitions provide a stepwise increase for consideration depending on the severity of occurrence. Only defects

that are unlikely to occur are considered negligible when the severity indicates a defect that will compromise a safety or legal condition on the track.

The severity of defects must be considered from a maintenance perspective, where the actions required will change depending on the severity of the defect. If there are then relatively few failures occurring from less severe defects, then they are considered negligible to the importance of a condition assessment for both short-term and long-term planning perspectives.

A defect on the threshold of two categories will be qualitatively assessed by the Author to determine the final relevance outcome.

3.3. Benchmarking Feasibility Against Current Methods

The boundaries to application should be considered in the selection of preferred concrete sleeper condition assessment methods. The best business case to motivate for any changes or additions to the assessment regime will be based on solutions that not only provide high-quality information for defect detection but are at least as economically and as operationally feasible as current methods.

Benchmarking is used as a formalised approach to enable the comparative assessment of solutions in reference to a baseline (Passos & Haddad, 2013). The comparisons can be scored by translating qualitative descriptions to a rating system or directly through quantitative metrics.

The maintenance and scheduling which is relevant for the requirements of the South African industry will mostly be based on the authors' experience.

To standardize the benchmarking, each category will be classified into five distinct categories. The scale in Table 3-5 will be used to create categories for each of the criteria.

Table 3-5: Benchmarking Assessment Criteria Gradings

Value	Quantitative Description	Qualitative Description
-2	Minimum	Large Decline from Control/Current
-1	25 th Percentile	Moderate Decline from Control/Current
0	Median	Control/Current
1	75 th Percentile	Moderate Improvement to Control/Current
2	Maximum	Large Improvement to Control/Current

To assess the feasibility of implementation, a metric will apply a qualitative description relevant to the feasibility category related to the main benchmarking criteria. The assessment uses a five-point scale in which a large return value will represent high feasibility and a low number will represent a less feasible solution. Solutions with a negative score are considered unfeasible. Table 3-6 shows an overview of the gradings for the three categories of assessment. The justifications for the criteria choices are discussed further below.

Table 3-6: Grading Criteria for Benchmarking

Rating	Cost	Lead Time	Effect on Operations
2	Reducing Demand on Current Staff Schedules and Reduction of Other Services	Immediately Possible at scale	No disruption to running of trains
1	Reducing Demand on Current Staff Schedules or Reduction of Other Services	Possible to Implement from Initiation to Assessment within 1 Year at scale	Requires single +2 hour occupation per 100km per year for section.
0	No Additional Cost or Breakeven	Possible to Implement from Initiation to Assessment within 3 Years at scale	Requires +10 occupations per year per 100 km section for +2 Hours
-1	Additional Staffing or Service Provider	Possible to Implement from Initiation to Assessment within 5 Years at scale	Requires +30 occupations per year per 100 km section for +2 hours daily
-2	Additional Staffing and Additional Service Provider	Solution not Viable at Scale	Requires 10 Days train “shutdown” conditions

The cost of these methods will be considered qualitatively due to constraints of market-related pricing. The two factors that cost will be based on is related to the internal and external requirements of implementation. No change to internal or external resource demands is the midpoint of the scale, as this considers the current methods as included within the control. The use of internal or external

resources for this will be used to benchmark resources. An improvement or decline in either of these will move the grading scale in the direction of the increase or decrease. The most cost-effective solutions will save on current internal and external resources, allowing for redirection of those resources to other areas. The most expensive solutions will require an increase in staffing to implement the solution, as well as the cost of appointing an external service provider.

Different solutions will have different lead times for implementation. The most feasible solutions are possible to immediately implement. The midpoint of the scale relates to current industry practises within the national freight network, which is around 3 years from initiation. These 3 years are currently used as an expected timeframe for large on-track machines. This includes 18 months for internal processes, such as developing the specifications, allocation and motivation for funding based on estimates, procurement processes and final award of the tenders. Another 18 months is often allocated for the winning bid to manufacture, import, test and commission the on-track machine. This is considered the control as this is in line with the current condition assessment procurement timelines.

Solutions which improve on this process may see a reduced commissioning time, which may see implementation within a year. This reduction in time is possible either due to improved internal processes that can be fast-tracked as they already have budget allocation and specifications in place. These solutions can also be implemented sooner if the solutions allow for retrofitting of existing infrastructure. The ultimate benefit if a solution is immediately implementable, which can be due to modification of existing solutions or assessment methods currently in place.

Some solutions will take longer than three years to implement. These solutions may extend the process by requiring further technology development at scale, either by requesting more information from the market or developing a useful specification. Some solutions, that while offer promising methodology, are not at this stage remotely applicable for large-scale assessments and no timeframe can be estimated. These will be rated lowest on the lead-time scale.

The upper and lower boundaries for the effect on operations relate to the current maximum and minimum time the industry will allocate within a year for infrastructure maintenance requirements. The effect on operations is bound by the maximum time allowed of a 10-day maintenance shutdown. These maintenance shutdowns typically occur once per year and are staggered across all major freight routes to allow for resources to be focussed on all times (Weekly, 2023). If a method required ten full days for the assessment to be done it will only offer one opportunity per year, which is not good for industry requirements due to an inflexible test window. The minimum effect to operations will be when train schedules are not affected at all due to a maintenance block in the train plan. Between these two extremes, maintenance blocks are scheduled during maintenance occupation times. These occupation times for the daily maintenance blocks are coordinated between the rail network infrastructure teams

and the train scheduling teams. A common maintenance block within the industry is considered between two to three hours per day. The number of these blocks will differ, and the more blocks needed then the larger the effect the proposed solution will have on operations. Currently, condition assessment methods differ according to their requirements, but the best methods that require a maintenance block are currently the on-track condition assessment methods such as the track geometry vehicle. The on-track methods require one to two maintenance blocks per year per 100 km section, depending on the assessment requirements according to the line classification. The slowest on-track condition assessment machine, the Ultrasonic Measurement Car (UMC), will be used as the mid-point for the benchmark as it is accepted by industry as good quality information for the measuring speed. This machine typically requires ten maintenance slots per 100 km of track length per year. This estimate is based on the frequencies for the general freight lines, as the heavy haul freight lines see increased testing frequencies to mitigate and manage the critical rail defects.

The outcome of these three criteria will show a comparative view of the condition assessment methods for concrete sleepers, including the methods already in use.

3.4. Summary

The feasibility of condition assessment methods for concrete sleepers in the South African network will be assessed with a FMEA, benchmarking assessment, and a test for defect relevance.

The outcome of the FMEA will be a Residual Profile Number (RPN). This RPN is a product of three rating scales: severity of occurrence, frequency of occurrence, and the ability of a method to detect a defect. Figure 3-3 shows an original illustration of how the rating factors combine to provide a RPN value.

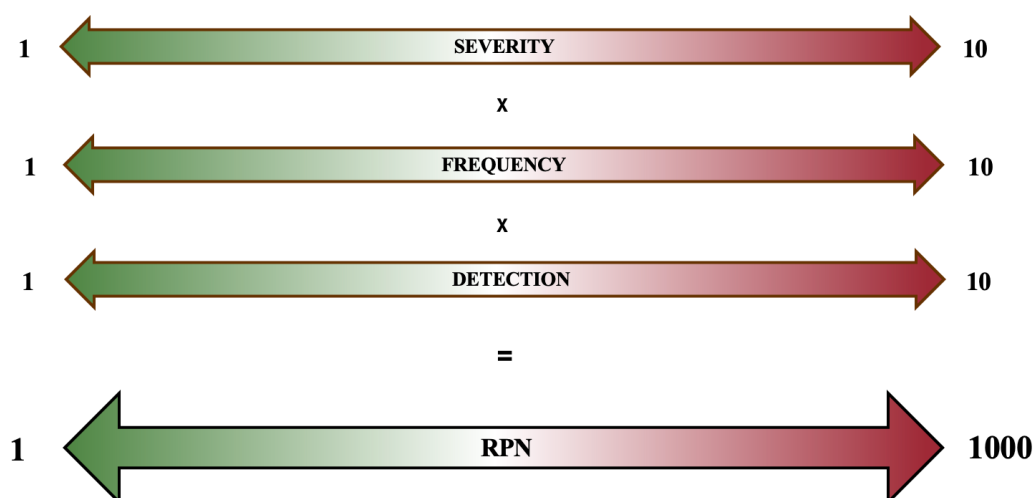


Figure 3-3: Illustration of FMEA Rating Scales and RPN value outcomes

The best RPN score is below one hundred as this means that despite high severity and frequency scores of the defect, a method to detect this defect is excellent for risk mitigation. If a specific defect does not have any assessment methods resulting in an RPN below one hundred, then technically feasible methods must at least provide a lower RPN than methods currently in use. If neither of these statements are true, then there is currently no feasible method to detect a specific defect.

The test for defect relevance will follow the FMEA. Testing for defect relevance considers only the severity and frequency of occurrence of the defect. Defects are categorised on a scatter plot to review how important they are to planning and risk mitigation of the continued network. This is required for this assessment as methods that fail to meet the two conditions for a technically feasible RPN score may still be feasible for the most important methods, even if they do not provide sufficient information to all defects.

The benchmarking assessment will consider three feasibility areas of each method: impact on operations, the cost of implementation, and the lead time for procurement of method. Figure 3-4 summarises how the three scales are rated from -2 to 2, and then results then summed to provide a value from -6 to 6.

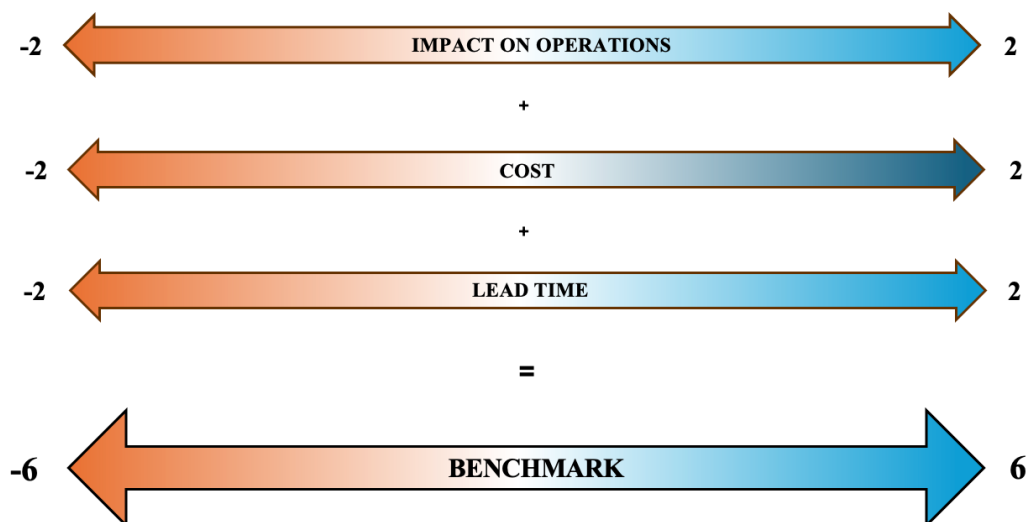


Figure 3-4: Illustration of benchmarking rating scales for condition assessment methods

The scores for benchmarking were set by considering best (+2) and worse case (-2) scenarios for each item, with the mid-point (0) of the scale representing the current industry practise. Benchmarking results require a method to be at least as feasible as the current industry methods, and so final scores of zero through six were considered feasible. Comparatively, the larger the number the more feasible the assessment method in terms of impact on operations, cost and lead time. But ultimately values of zero and above show feasible methods.

4. Results

The feasibility of methods selected to assess the condition of railway concrete sleepers needs to address the questions discussed in Section 3, specifically described in Table 3-1. This is done through the use of two methods. This will, firstly, use a Failure Mode and Effect Analysis (FMEA) to review the severity and frequency of defects and review how the associated risks can be mitigated through the use of condition assessment methods; and, secondly, Benchmarking of proposed methods against current methods to assess if the methods are, at a minimum, as implementable as current methods. A further test will be done to check if each defect is relevant for the South African network.

4.1. Failure Mode and Effect Analysis

The FMEA results will be discussed in two parts by first reviewing the impact of the defects through the rating or severity and frequency, and then assessing the condition assessment methods and how well it can provide information to mitigate the impact of the defect. Only the most severe failure mode is considered for each of the defects, as while there may be multiple failure modes possible the most severe case and its corresponding frequency is needed for assessment.

4.1.1. Severity and Occurrence of Defects

By reviewing the severity and frequency of failures due to the identified defects, an understanding of the risk of each defect can be quantitatively compared. Figure 4-1 shows the ratings out of ten for each defect, rated in line with the rating outlines from Table 3-2 and 3-3. A detailed justification of each rating is provided in Table 4-1.

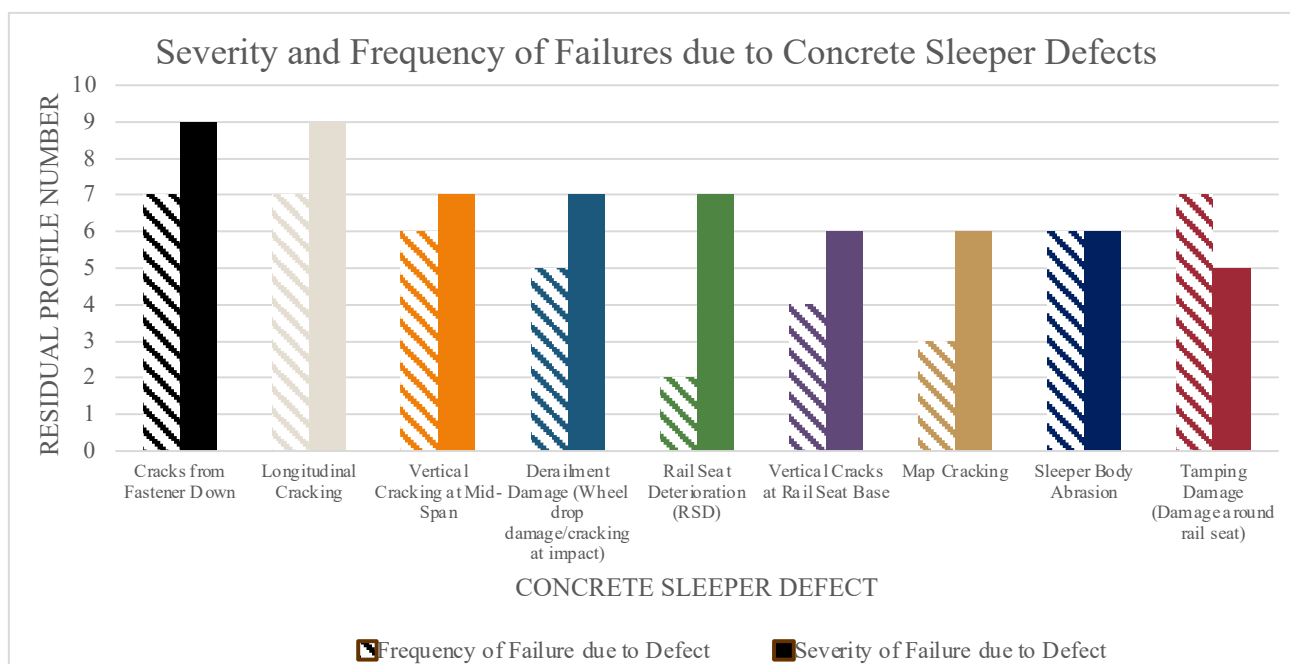


Figure 4-1: Severity and Occurrence of Failures per Concrete Sleeper Defect

The results of Figure 4-1 were filtered to show decreasing severity of failures. Descriptions of the failure mode of each defect, as well as the corresponding literature that informs the severity and occurrence frequencies is shown in Table 4-1.

The results show that cracks from the fastener down, and longitudinal cracks create the most severe failure outcomes as they create a condition which imposes an unsafe condition on the track. Vertical cracking at mid-span, derailment damage, and rail seat deterioration shared the next most severe failure outcomes that indicate a reduction in the primary function of sleepers, i.e. the maintenance of track gauge. The remaining defects show severity ratings that indicate a loss or reduction of secondary functions. None of the defects reviewed were rated in the Conditioned Response Zone, and so all had an effect on primary, secondary or serviceability functions of the concrete railway sleepers.

The occurrence frequency of a defect bears no relationship to the severity of outcome of the defect. The frequency of occurrence of a defect was highest rated for cracks from the fastener down, longitudinal cracking and tamping damage, which align with a high number of failures due to the defect. Vertical cracking at mid-span and sleeper body abrasion were found, as referenced in Table 4-1, to occur in the literature a moderate number of times, followed by derailment damage and vertical cracks at the rail seat base. Map cracking and rail seat deterioration occurred relatively infrequently in the literature and are not widely experienced across the South African rail network.

The ratings in Table 4-1 include the Authors' perspective of the South African industry where relevant and considered common knowledge in the South African Rail Network. The final Severity/Occurrence Value is shown in the last column in descending order. This order represents which defects are most critical to mitigate as they occur often and severely enough to have a high impact on network availability.

Table 4-1: Severity and Occurrence Descriptions and Ratings for Concrete Sleeper Defects

Defect	Potential Failure Mode	Description of Frequency Failure Research	Frequency of Failure	Potential Cause of Failure	Description of Severity for Failure	Severity of Failure	Severity/ Occurrence Value
Tamping Damage (Damage around rail seat)	Loss of angularity and cross section under rail seat	Mentioned in international study as second critical defect (Van Dyk et al., 2013) , Noted in SA industry.	7	Tamping Damage	Reduction of interlocking reduces steady load transfer	5	35
Derailment Damage (Wheel drop damage/cracking at impact)	Loss of prestress reinforcement bond to concrete, loss of cross section around rail seat base.	Mentioned in international study as moderately critical defect (Van Dyk et al., 2013) Noted in SA industry.	5	Derailment Damage	Cracking of sleeper top, possibly affecting fastenings.	7	35
Vertical Cracks at Rail Seat Base	Reduction of bending moment at mid-span, final failure in shear.	Not referenced directly in international study (Van Dyk et al., 2013), Noted in research studies for investigation (de Souza Lima & Carneiro, 2022).	4	High-Impact Loads from rail/wheel interface defects	Reduction in flexural strength	6	24
Map Cracking	Reduction of flexural strength, final failure in shear	Not mentioned in international study (Van Dyk et al., 2013), Meta study with ASR research (de Souza Lima & Carneiro, 2022), Localised in SA Industry (Oberholster et al., 1992).	3	ASR	Reduction in flexural strength	6	18
Rail Seat Deterioration (RSD)	Gauge widening	Not seen in SA Industry, International research shows it's not common internationally only in America (Van Dyk et al., 2013).	2	Fastenings not secure and move under load.	Loses gauge consistency to do overturning of rail	7	14
Cracks from Fastener Down	Total loss of fastening clamping force	Top ranked reason in international study (Van Dyk et al., 2013), Mentioned in international meta-study (de Souza Lima & Carneiro, 2022). Noted in SA Industry.	7	Defects at Rail/Wheel interface	Sudden Gauge Widening (Loss of Primary Function causing defects	9	63
Longitudinal Cracking	Loss of prestress reinforcement bond to concrete.	Mentioned in SA as reason for investigation of ASR (Oberholster et al., 1992),	7	DEF or severe loading cases.	Sudden loss in bearing capacity when cracks are severe	9	63

Defect	Potential Failure Mode	Description of Frequency Failure Research	Frequency of Failure	Potential Cause of Failure	Description of Severity for Failure	Severity of Failure	Severity/ Occurrence Value
		<p>Showed in research studies specifically as cause of final failure (Kaewunruen & Remennikov, 2009),</p> <p>Shown in DEF studies (de Souza Lima & Carneiro, 2022).</p>					
Vertical Cracking at Mid-Span	Gauge Widening due to flexure	<p>Showed in research studies as cause of failure (Kaewunruen & Remennikov, 2007) (Zeitouni et al., 2018).</p> <p>Derailment with cracking (NTSB, 2014)</p> <p>Mentioned in international research as 5/8 (Van Dyk et al., 2013).</p>	6	Flexure at midspan due to unsupported ballast condition	Loses gauge consistency to do flexure	7	42
Sleeper Body Abrasion	Loss of angularity and cross section of base	<p>Not mentioned in international study, but commonly seen effects within SA industry.</p> <p>Issue of voided track is common in research; defect is usually framed in reference to ballast concerns but prevalent (Kaewunruen & Remennikov, 2007).</p>	6	Increased loading or maintenance.	Loss of interlocking reduces steady load transfer	6	36

4.1.2. *Detetction of Defects using Condition Assessment Methods*

Each method considered for the condition assessment of concrete railway sleepers was assessed as to how well it was able to detect each concrete sleeper defects. Ratings were awarded based on the criteria shown in Table 3-4, in which a ten reflects a defect that is not at all able to be detected with the method, and one representing methods which provide full information of the defect to allow for planned preventative maintenance on the sleeper. Thus, the higher the total sum of detection, the worse the method is at being able to provide detailed condition information on the array of defects. Figure 4-2 shows a total of the detection of the defects, with the subtotals for each defect also reflected.

The values assigned for each rating were based on the discussion in Chapter 2, where it was established how a method measures a defect. Information on each method, which was referenced in Chapter 2, provides a basis for the justification of these ratings but where no explicit information was available the Author would provide judgement on the rating within the bounds of the rating system.

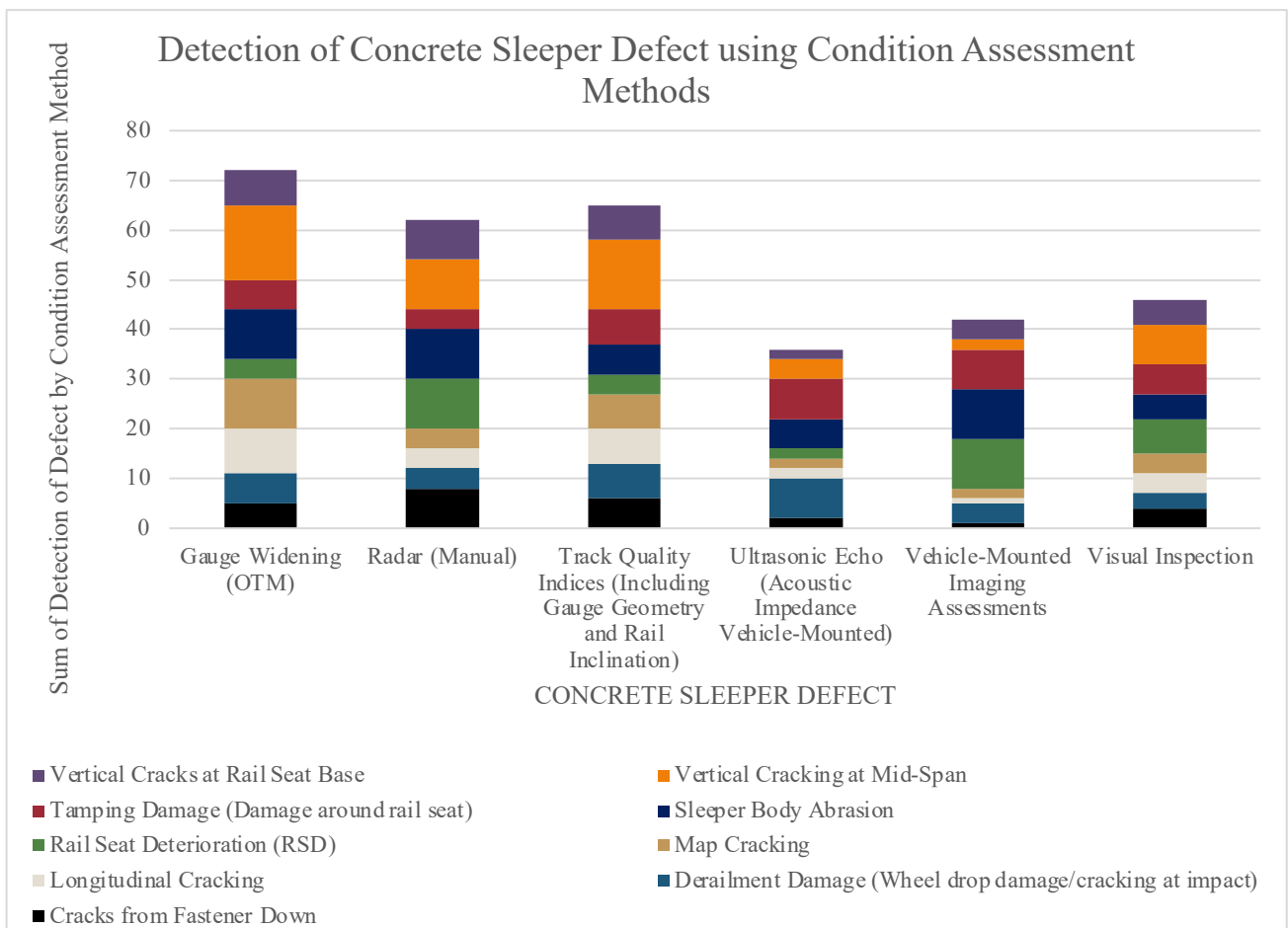


Figure 4-2: Detection of Concrete Sleeper Defects using Condition Assessment Methods

Defects were rated based on the criteria established in Chapter 2 and discussed in more detail in Table 4-1. The gauge widening, manual radar and track quality indices methods provide the worst total levels of detection across all of the methods assessed. The detection of the condition of concrete sleepers using the gauge widening OTM was the poorest rated method as this method is focussed only on defects with potential fastening or rail inclination issues. The method using manual radar methods is only feasible for limited applications and does not provide good information on defects that extend further than the reinforcement layers or are near the fastening anchors of the P-type sleepers. Track quality indices methods do not provide direct data on condition with the exception of the rail seat inclination measurement used to detect the RSD defects and to some extent the cracks around the rail seat that cause gauge widening.

The ultrasonic echo, vehicle-mounted imaging and visual inspection methods provide better assessments of the defects on concrete sleepers. The ultrasonic echo method showed the best overall assessment of the array of defects, but there are still some limitations if the contact required for assessment is not achieved. Vehicle-mounted imaging assessments provide detailed insight to defects that are visible from the surface and can be used to track defects over time, but if the defect is at the base of the sleeper, then it will not be detected. Visual inspection provides good information for most condition assessment methods but are limited to scale of application and therefore often do not provide information required for long-term planning of preventative maintenance.

The Table 4-3 shows the description and rating of how each assessment method is able to meet the requirements for detection of each concrete sleeper defect. The ratings were applied based on the discussion formed in Chapter 2.

Table 4-2: Descriptions and Rating for Condition Assessment Methods Detection for Defects

Defect	Visual Inspections		Gauge Widening (OTM)		Radar (Manual)		Track Quality Indices (Including Gauge Geometry and Rail Inclination)		Ultrasonic Echo (Acoustic Impedance Vehicle-Mounted)		Vehicle-Mounted Imaging Assessments	
	Vertical Cracking at Mid-Span	Visible once cracked	4	Only detected after failure occurs.	7	Can possibly detect but only in specific use cases.	5	Possibly indicate through statistical methods but only after failure requiring unplanned maintenance.	7	Can detect cracks in up to 5 categories, not demonstrated crack progression techniques.	2	Visible cracks for demonstrated time-based assessments of crack progression.
Map Cracking	Visible once cracked	4	Only detected after failure occurs and further damage.	10	Can possibly detect but only in specific use cases.	4	Possibly indicate through statistical methods but only after failure requiring unplanned maintenance.	7	Can detect cracks in up to 5 categories.	2	Visible cracks for time-based assessments of crack progression but if on side then not early stage defects.	2
Cracks from Fastener Down	Visible once cracked	4	Will detect gauge widening that already requires immediate maintenance as primary function has failed.	5	Cannot Detect near fastening reinforcement.	8	Detects defects from direct measurement but requires unplanned maintenance.	6	Can detect cracks in up to 5 categories.	2	Visible cracks for time-based assessments of crack progression.	1
Vertical Cracks at Rail Seat Base	Not Visible, but commonly seen with corresponding cracks on top.	5	Only detected after failure occurs requiring immediate maintenance.	7	Cannot detect under sleeper due to reinforcement.	8	Possibly indicate through statistical methods but only after failure requiring unplanned maintenance.	7	Can detect cracks in up to 5 categories, even within ballast layer.	2	Does not detect under sleeper, but defects tend to occur with cracking on top.	4
Longitudinal Cracking	Visible once cracked	4	Only detected	9	Can possibly detect but only	4	Possibly indicate through	7	Can detect cracks in up to 5	2	Visible cracks for time-based	1

Defect	Visual Inspections		Gauge Widening (OTM)		Radar (Manual)		Track Quality Indices (Including Gauge Geometry and Rail Inclination)		Ultrasonic Echo (Acoustic Impedance Vehicle-Mounted)		Vehicle-Mounted Imaging Assessments	
			after failure occurs.		in specific use cases.		statistical methods but only after failure requiring unplanned maintenance.		categories, even within ballast layer.		assessments of crack progression.	
Rail Seat Deterioration (RSD)	Often not visible until pad removed.	7	Can indicate progressive gauge widening due to rail inclination changes.	4	Cannot detect	10	Can detect change in rail inclination under load and gauge widening.	4	Does not detect abrasion under rail seat or inclination of the rail.	8	Does not detect	10
Sleeper Body Abrasion	Not visible, ballast provides indication but defect requires immediate work.	5	Only detected after failure occurs.	10	Cannot detect under reinforcement.	10	Possibly indicate discrete or statistical deviations that correlate to sleeper defects but not direct method.	6	Possibly indicate changes in backwall reflection, but in severe cases.	6	Does not detect	10
Tamping Damage (Damage around rail seat)	Not visible, ballast provides indication but defect requires immediate work.	6	Will indicate gauge if defect affects fastenings.	6	Can possibly detect but only in specific use cases where damage is above the reinforcement and away from fastenings anchors.	4	Possibly indicate through statistical methods but only after failure requiring unplanned maintenance.	7	May not detect due to boundary conditions with air and unevenness of type of defect.	8	Does not detect small defects or defects under sleeper base.	8
Derailment Damage (Wheel drop damage/cracking at impact)	Visible once cracked	3	Will indicate gauge if defect affects fastenings.	6	Can possibly detect but only in specific use cases.	4	Possibly indicate through statistical methods but only after failure requiring unplanned maintenance.	7	May not detect due to boundary conditions with air and unevenness of type of defect.	8	Does not always detect small defects.	4

4.1.3. Residual Risk of Defect after Information to Mitigate

The methods of concrete sleeper condition assessment must prioritise the detection of defects that pose the largest risk to the continued operation of the network. The Residual Profile Number (RPN) from the FMEA shows how each of these methods is able to provide information to mitigate the risks associated with failure of the concrete sleepers. Figure 4-3 shows the residual risk to the continued operation of the network if the defect is known. The track quality and visual inspection methods are indicated with the larger rectangles on the graph because these two methods are already in use and the visual indicators of the lines create an easier viewing and analysis experience on the graph. Therefore, the value of new methods to detect defects must be at least as good as current methods otherwise the technical requirement for feasibility is not met.

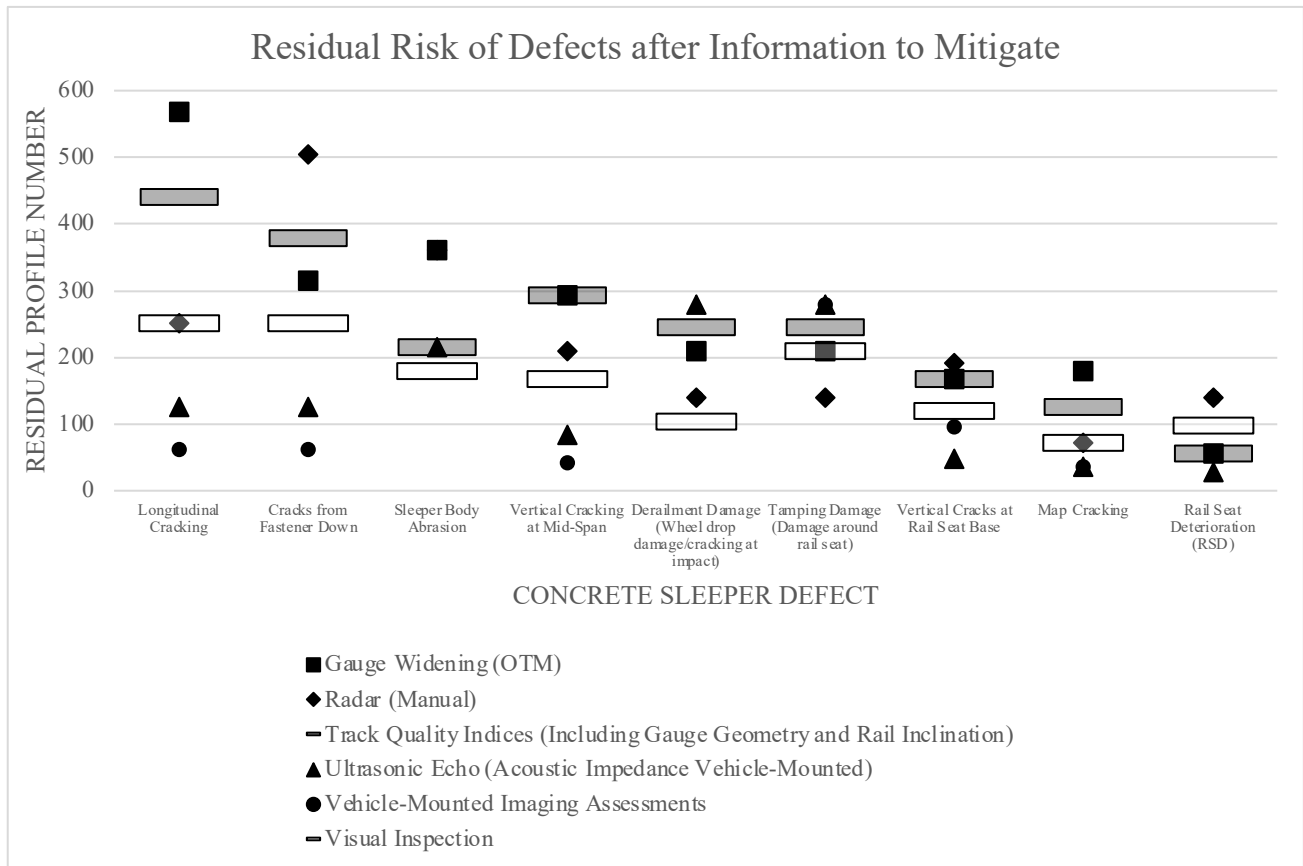


Figure 4-3: Residual Risk of Concrete Sleeper Defect after Information to Mitigate

The defects were sorted from most critical according to the severity/occurrence ratings, from left to right in Figure 4-3. The top four most critical defects show that the current visual inspection and track quality methods are not below the recommended RPN of 100. The vehicle-mounted imaging assessments and ultrasonic echo methods do provide better quality information than the current methods when looking at longitudinal cracks, cracks from the fastener down and vertical cracking at

mid-span. Only the assessment of sleeper body abrasion is not improved by these methods, but the RPN indicates that none of the methods are able to better mitigate this high residual risk. Between the visual imaging assessments and the ultrasonic echo method, the imaging method narrowly improves the detection of the defects but also provides an RPN number below the recommended 100 threshold. This shows that the imaging assessment are not just better than the current methods but meet all the demands for assessment of these defects and further methods will not significantly improve technical outcomes for this method.

Two gaps are identified in the condition assessment methods, those of defects related to sleeper body abrasion and tamping damage. These defects were not an area that was directly assessed in the condition assessment methods, and so the RPN values are higher than the recommended 100 but are not able to be reduced at this stage.

4.2. Results Testing for Defect Relevance

The concrete sleeper defects identified were sourced through the literature and industry experience, but a critical review of these defects must be done to ensure their relevance for local conditions.

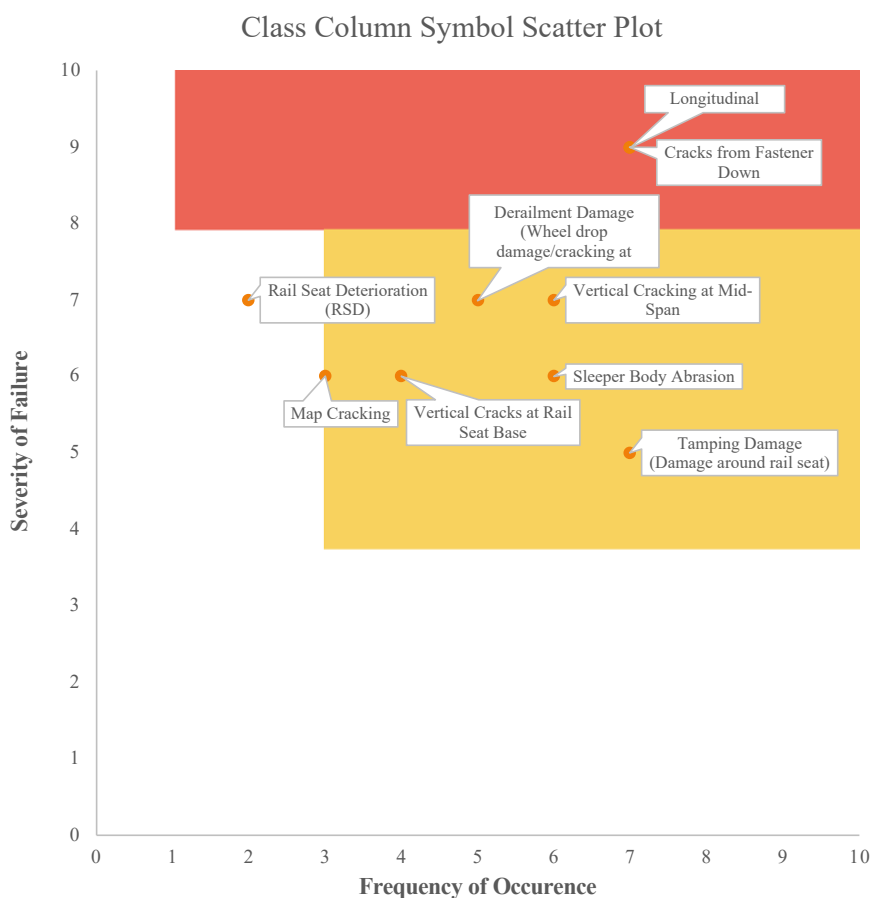


Figure 4-4: Class Column Symbol Scatter for Concrete Sleeper Defects

The results provided in Figure 4-4 separate out defects that are critical to safety, defects that require identification for routine or corrective maintenance, or defects that are not frequent or severe enough to require independent consideration. Two defects that enter the critical to safety category are those of longitudinal cracks and cracks from the fasteners down as the both occur frequently and have a severe outcome. Most of the other defects discussed fall into the category that requires identification due to routine and corrective maintenance requirement, as they are less severe and occur somewhat frequently. Sleeper Body Abrasion does not fall into the critical to safety category, and while this defect has a final RPN greater than 100 with all methods tested this defect is more important to identify for corrective maintenance demands than safety demands. The only defect that is completely excluded is that of RSD, as the frequency of the defect is not frequent within the South African network. This indicates that RSD does not require specific methods of condition assessment to mitigate the occurrence thereof. This is in line with Figure 4-3 as it shows that most methods enable a RPN under 100. Map Cracking is on the borderline of detection and so methods for assessment should be considered on a case-by-case basis.

4.3. Benchmarking Feasibility Against Current Methods

Each of the methods is discussed in Table 4-5, to show their feasibility with regard to cost, lead time and effect on operations. The ratings for each are based on Tables 3-6 and 3-7 in the Methodology.

Table 4-3: Benchmarking Descriptions and Ratings for Condition Assessment Methods

Method	Description Cost	Cost	Description Lead Time	Lead Time	Discussion Effect on Operations	Effect on Operations	Total
Gauge Widening (OTM)	Requires external service provider and does not remove the need for methods currently in use. But results will not increase demand on current staff to process.	-1	Possible to implement 3 years from initiation as method is established but needs to be applied to local conditions and lead time required for procurement and manufacture of specialist machine.	0	Can run as on-track machine. Requires single +2 hour occupation per 100 km per year for section.	1	0
Radar (Manual)	Requires external service provider and does not remove the need for methods currently in use. But results will not increase demand on current staff to process.	-1	Possible to implement 3 years from initiation. External contract for national demand will require long lead times.	0	Will require time on track for manual assessment setup and result capture. Requires +30 occupations per year per 100 km section for +2 hours daily	-1	-2

Method	Description Cost	Cost	Description Lead Time	Lead Time	Discussion Effect on Operations	Effect on Operations	Total
Track Quality Indices (Including Gauge Geometry and Rail Inclination)	No Additional Cost or Breakeven	0	Possible to implement 3 years from initiation as already in use, but procurement of new machines require lead times over 18 months for configuration.	0	Runs as on-track machine. Requires single +2 hour occupation per 100 km per year for section.	1	1
Ultrasonic Echo (Acoustic Impedance Vehicle-Mounted)	Requires external service provider but reduces demand for large-scale visual assessments.	0	Possible to Implement from Initiation to Assessment within 5 Years at scale due to less common industry use.	-1	Can run as on-track machine, speeds up to 40 km/hr. Requires single +2 hour occupation per 100 km per year for section.	1	0
Vehicle-Mounted Imaging Assessments	Requires external service provider but reduces demand for large-scale visual assessments.	0	Possible to implement 3 years from initiation.	0	Can run at section speed as an on-track machine. Requires single +2 hour occupation per 100 km per year for section.	1	1
Visual Inspection	No Additional Cost or Breakeven	0	Possible to implement 3 years from initiation.	0	Can be conducted on trolley trips at inspection speed of 50 km/hr. Requires single +2 hour occupation per 100 km per year for section.	1	1

The comparison of the cost of the methods shows the gauge widening and radar methods will be a greater cost when compared to current methods.

The ultrasonic echo and vehicle-mounted imaging methods will reduce demand on current staff but requires an external provider, thereby having a breakeven effect in line with those of current methods.

The lead time for most methods is within 3 years, which is in line with current methods. The methods possible within 3 years are often already well-defined, or have technology that is already available and tested but will need procurement and internal technical reviews. The only method that will take longer than current methods is that of the ultrasonic echo, as this has not been demonstrated within the industry, only used in test cases. This will then require more time before it is available for implementation.

Most methods are feasible from an operations standpoint as they either require short occupations between trains, or they can run on the track as an on-track machine which are in line with current methods used. The only method that requires more time on track than current methods is that of the manual radar. The overview of these methods is shown in Figure 4-5.

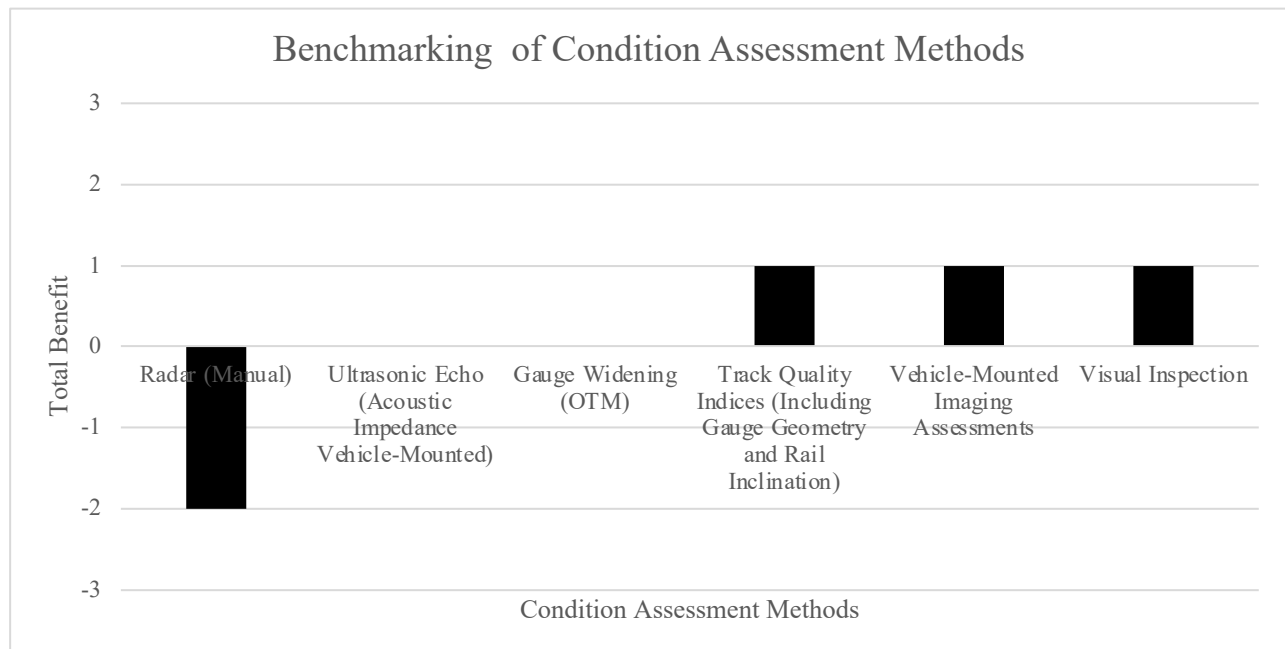


Figure 4-5: Benchmarking of Concrete Sleeper Condition Assessment Methods

The vehicle-mounted imaging assessment method is at least as feasible as current methods in use, when considering cost, lead time and effect on network operations. The ultrasonic echo and gauge widening methods are less feasible than current methods, but are still overall considered an option as their final score represents a breakeven result. The manual radar method is not considered feasible as it bears greater costs than current methods and is more demanding to operate on the network.

4.4. Summary

The results from Chapter 4 consider the factors required to assess the feasibility of condition assessment methods of concrete sleepers for South African applications. A Failure Mode and Effect Analysis provided a technical review of how well each condition assessment method was able to mitigate the risk of a concrete sleeper defect. A further test for defect relevance grouped defects to assess which were the most severe defects, defects that require typical corrective maintenance, and defects which are not severe or frequent enough to require large-scale assessment. A benchmarking

assessment considered the cost of implementation of a method, the effect of the method to the continued network operations, and the lead time required for procurement of a method.

In Table 4-4 the results of the analysis in Chapter 4 are summarised.

Table 4-4: Summary of Feasibility of Sleeper Condition Assessment Method

Condition Assessment Method	Percentage of Defects Acceptably Assessed (RPN < 100) using Failure Mode and Effect Analysis		Final Benchmarking Score
	Severe Defects	Typical Corrective Maintenance Defects	
Gauge Widening (OTM)	0%	17%	0
Radar (Manual)	0%	33%	-2
Track Quality Indices	0%	17%	1
Ultrasonic Echo (Acoustic Impedance Vehicle-Mounted)	0%	66%	0
Vehicle-Mounted Imaging Assessments	100%	66%	1
Visual Inspection	0%	50%	1

Only vehicle-mounted imaging assessments were able to adequately assess all severe concrete sleeper defects, but only adequately assessed 66% of typical corrective maintenance defects. The final benchmarking score for vehicle-mounted imaging assessments was 1, which shows it is feasible when compared to methods currently in use.

Visual inspections and ultrasonic echo methods did not adequately assess the severe concrete sleeper defects, but respectively assessed 50% and 66% of all defects that require typical corrective maintenance. These two methods had a final benchmarking score of 1 and 0 respectively, shows the method at least as feasible when compared to methods currently in use.

The gauge widening OTM and track quality indices only assess 17% of the defects which require typical corrective maintenance. These methods benchmark acceptably against methods currently in use, with final benchmarking scores of 0 and 1 respectively.

Manual radar methods adequately assessed 33% of the defects which require typical corrective maintenance, but performed poorly when benchmarked against methods currently in use.

5. Conclusions

Concrete sleepers are a key component of railway systems, with estimates showing between 20 million to 35 million currently installed within the South African railway network. The condition assessment of concrete sleepers in South Africa poses a challenge for two main reasons: the scale at which condition measurements need to be conducted, and the poor access to sleepers within the ballast structure.

To assess feasibility of concrete sleeper assessment methods, the quality of technical results were reviewed to ensure the information required for long-term lifecycle needs of concrete sleepers can be produced and that the risk associated with failures due to critical defects are mitigated.

The work established in the literature review was consolidated through a three-phase methodology to provide results for the assessment. This involved a Failure Mode and Effect Analysis (FMEA) that measured how well each of the methods can detect the failure modes, and then benchmarked the condition assessment methods against similar technology currently in use within the South African network. A test for defect relevance checked that the defects identified in the literature were relevant for South African applications and allowed for further categorisation of criticality.

The results present conclusions related to the Failure Mode and Effect Analysis, the test for defect relevance and the benchmarking against current methods. A summary of the analysis conclusions related to the defects of concrete sleepers and methods used for their condition assessment is presented below.

Failure Mode and Effect Analysis

The severity and occurrence of defects provides insight to which concrete sleeper defects are most important to assess in the South African railway network.

The defects with the highest severity of failure are those of longitudinal cracking and cracks from the fastenings down. This is because these defects are critical to the safety and continued operations of a network even if they occur with warning. The defects that occur most frequently are also both longitudinal cracking and cracks from the fastener down, but include damage related to mechanised ballast tampers. Mechanised ballast tamping is an activity, that while critically important to the geometric maintenance of the track, creates frequent defects to the concrete sleepers.

The method that scored the best when assessing detection of the full array of defects as an independent variable was the ultrasonic echo method, followed by vehicle-mounted imaging assessments and then thirdly by visual inspections. These three methods provided condition measurements detailed enough to meet most planning demands for corrective to predictive concrete sleeper defects. The ultrasonic echo method showed limitations to testing defects that possibly interrupt the contact of the ball hammer, such as derailment damage. Imaging methods showed limitations when assessing sleeper body abrasion and rail seat deterioration as these have no visual indicators from a rail-mounted position. Visual inspections provided good condition information across all defects, but the scale of assessment limited the detail required for long-term and predictive maintenance planning requirements.

The ultrasonic echo method, when compared to the visual imaging methods, suffered in the final detection rating due to lack of overlay capability of current methods at scale. This reduces the way in which consecutive measurements can be compared, and limits the predictive capabilities of the method.

The final Residual Profile Number (RPN) values for each method shows only vehicle-mounted imaging and ultrasonic echo methods provide better data than the best control method (visual assessments) for longitudinal cracks and vertical cracking from the rail seat down. Only vehicle-mounted imaging methods provide a final RPN value lower than 100 for the two safety-critical defects and therefore is not just better than current methods it achieves a level that cannot be significantly improved upon in future.

There is no method identified for assessing sleeper body abrasion better than the current visual inspection methods. The resultant risk of sleeper body abrasion is currently the highest of all defects assessed, showing a gap in the assessment methods of this specific defect.

Testing for Defect Relevance

The test for defect relevance lists two defects as critical to safety of the network: longitudinal cracking and cracking from the fastening down. Testing for defect relevance shows that Rail Seat Deterioration (RSD) defects do not meet the minimum thresholds for inclusion as a defect of relevance within the South African network.

The remaining defects from the test for defect relevance (tamping damage, derailment damage, sleeper body abrasion, vertical cracks under rail seat, and map cracking) are all still important to detect as they fall into the category that requires the defect to be regularly maintained due to loss of a primary, secondary or serviceability function.

Benchmarking

Vehicle-mounted imaging method presented as feasible when considering cost, lead time, and impact on operations when benchmarked against methods currently in use. Ultrasonic Echo methods, while less feasible than vehicle-mounted imaging, still shows promise as a future detection method as the technology further develops in the industry.

Track quality methods benchmarked in line with current methods as the scale of measurements sees a reduction in the time required on track as well as falling within reasonable procurement timeframes. Visual inspections benchmarked in line with current methods as they often have very little effect on network operations as their use is well-established within current maintenance practises. The cost of visual inspections is also considered a sunk cost, as it is currently in place and does not need further resources to implement.

Manual radar methods are not considered feasible as the lead time to implementation is much longer than current methods and will incur costs above current resource requirements.

General

Both the FMEA and Benchmarking show that Visual Imaging Assessment methods are feasible to produce the quality of information required for detailed condition assessments for the two critical to safety concrete sleeper defects. These imaging assessments are the only method to currently assess all defects that have a severe effect on continued network operations and occur frequently.

Sleeper base abrasion is a defect that currently does not have a method to detect condition at scale. This defect poses the third highest risk to the network maintenance planning, and the highest unmitigated residual risk to the network.

Current research does not conclude on failure modes of concrete sleepers due to prestressing corrosion. As concrete sleepers on the network are approaching the end of their expected useful life, the presence of corrosion induced defects will increase. The lack of information about how they fail, when they collectively reach critical condition, and to the extent that exposure conditions play a role in the deterioration of concrete sleepers is unknown and therefore poses a long-term but large risk to the network.

6. Recommendations

The conclusions from this research present recommendations in two categories: recommendations where future research is required, and immediate practical recommendations for industry use.

Gaps in the current literature relate to the current assessment methods for sleeper body abrasion, and the failure modes of prestressing steel corrosion in concrete sleepers. Sleeper body abrasion is a defect that may not cause immediate failure of a sleepers, but groups of these sleepers present a serious challenge to the immediate and long-term geometric maintenance of a railway track. Possible assessment methods for sleeper body abrasion are recommended to combine more traditional concrete sleeper assessments with longitudinal track quality measurements.

The failure modes related to the corrosion of prestressing tendons in concrete sleepers was not widely present in the literature at this stage. As the local and international asset railway portfolios age, the study of how prestressing corrosion within concrete sleepers' manifests and the associated failure modes need further investigation. Scrap concrete sleepers are recommended as specimens for continued corrosion research in South Africa, as they provide uniform test samples that are dated and can be traced back to the unique supplier and manufacturing location. Limited manufacturers supply sleepers around the country, so comparison of samples under different climatic conditions simplified.

The ultrasonic echo method should consider the inclusion of GPS or tracking technology to allow the alignment and overlay of consecutive measurements for time-based and predictive analysis. This advancement would be important, as while visual-imaging methods provide good data about the important defects, ultrasonic echo methods would be able to assess more defects with the same quality of data generated.

This research recommends the use of vehicle-mounted imaging technology to assess the large-scale condition of concrete sleepers within the South African network. The immediate recommendations require the development of technical specifications based on the requirements of the national South African network. These specifications should be developed in parallel with the supporting business case for the assessment, aimed at showing the importance of this information to the planning requirements for corrective, preventative and predictive maintenance requirements.

The data collected from these assessments may take years to develop into empirical deterioration models, and so theoretical models should be developed in the short term to

understand how these defects influence the lifecycle predictions of concrete sleepers. Network reliability and risk mitigation should be the focus of these models, as these cover both short-term and long-term defects and deterioration. Statistical approaches used in similar linear assets fields such as the rail or pavements are recommended for initial modelling choices, but outlying fields that deal with risk should be reviewed for relevance.

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