



**ADDIS ABABA UNIVERSITY**  
**ADDIS ABABA INSTITUTE OF TECHNOLOGY**  
**AFRICAN RAILWAY CENTER OF EXCELLENCE**

Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria  
Decision-Making Method

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A Thesis Submitted to Africa Railway Center of Excellence, Addis Ababa  
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the Requirements for the Degree of Master of Science  
In Railway Engineering (Civil Infrastructure)

Advisor:- **Dr. Fiseha Nega**

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Addis Ababa Institute of Technology

Addis Ababa, Ethiopia

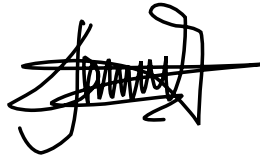
# Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

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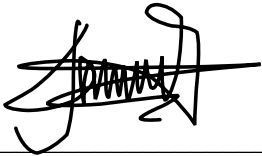
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## UNDERTAKING

I, the undersigned, certify that this research work entitled “*Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method*” is my original work and has not been presented in any award or degree in any other university or institute. this work does not include any content that has been previously published or written. However, all sources of information utilized in this thesis have been appropriately cited and acknowledged.

**Kirubel Firew Tamru**

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Signature

October, 2024

Addis Ababa, Ethiopia

**DEDICATION**

I dedicate this thesis to my family and friends, who have consistently inspired me throughout this journey.

# Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

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## ABSTRACT

*The safety and reliability of railway infrastructure are dependent on diligent maintenance and inspection practices. A well-organized maintenance approach is imperative in ensuring the safety and reliability of a railway system. One of the most important aspects of railway maintenance is the detection and monitoring of track defects, which can lead to catastrophic failures if left unaddressed. While existing techniques can be beneficial in certain respects, they are incapable to provide a comprehensive view of the structural conditions of railway tracks, compromising ride safety and quality. This research addresses this gap by developing a model for railway track structural condition assessment using Multi-Criteria Decision Making (MCDM).*

*Leveraging an extensive literature review the model assigns weights to key track components and defect categories through the Best-Worst method. Mamdani Fuzzy logic integrates diverse defect criteria and translates qualitative severity evaluations into numerical scores. The analysis reveals rails (48.16%) as the most critical component, followed by sleepers (21.05%). Within rail defects, transverse fissures hold the highest weight (43.75%).*

*Validated through a case study, the model demonstrates strong agreement with actual results. A user-friendly application built on FlutterFlow facilitates detailed track condition assessments, encompassing individual defect categories, component health, and overall track structure status.*

*This model empowers data-driven decision-making for railway authorities, enabling them to prioritize and address track issues effectively. The MCDM approach provides a structured framework for maintenance planning. Ultimately, this research aims to refine railway track infrastructure management through a structured and data-driven decision-making process.*

**Keywords:** Best-Worst method, Fuzzy logic, Multi-Criteria Decision-Making Method, Railway Track Structural Conditions

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**LIST OF ABBREVIATION AND ACRONYMS**

AAR	Association of American Railroads
AALRT	Addis Ababa Light Rail Transit
AASHTO	American Association of State Highway and Transportation Officials
AHP	Analytical Hierarchy Process
AREMA	American Railway Engineering and Maintenance-of-Way Association
BWM	The Best-Worst Method
EU27	European Union consists of 27 countries
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GPR	Ground Penetrating Radar
HSR	High Speed Railway
LIDAR	Light Detection and Ranging
MCDM	Multi Criteria Decision Making Method
RCF	Rolling Contact Fatigue
RMSE	Root mean Squared Error
TGMV	Track Geometry Measurement Vehicle
TMC	RailCorp Compilation of Manuals
TQI	Track Quality Index

## CHAPTER ONE

### INTRODUCTION

#### 1.1 Background

The global transportation sector is currently witnessing a significant rise in demand due to the rapid growth of the population [1]. Between 2020 and 2050, passenger and freight transportation demand is predicted to grow significantly by 196% and 200%, respectively [2]. This surge in demand undoubtedly contributes to increased energy consumption and following greenhouse gas emissions [3]. Rail transportation is one of the energy-efficient modes of transportation, accounting for 2% of the total energy demand in the transportation industry [3]. Railways release fewer greenhouse gases per passenger-kilometer than cars or planes. Electrified rail systems are even more environmentally friendly [4].

Rail transportation is an important part of modern day infrastructure because it allows for the smooth and efficient transportation of individuals and goods across extensive distances [5]. The safety and reliability of railway infrastructure are of paramount importance, as they directly impact the well-being of both passengers and freight transportation. Inspection and maintenance of railway infrastructure are essential for ensuring its safety and reliability. By completing proper condition assessments and conducting maintenance techniques, the railway infrastructure safety and reliability can be maintained. Efficient railway track maintenance and repair need the implementation of a comprehensive management system that allows for the development of both short-term and long-term repair plans [6]. A systematic railway maintenance process is essential to keeping a railway system safe and reliable. However, railway maintenance is costly, and its requirements usually comprise a significant amount of the budget [7]. In 2018, railway maintenance expenditure in the European Union (EU27) was estimated at 20.6 billion Euros, accounting for more than half of the total rail infrastructure expenditure [8].

One of the critical aspects of railway maintenance is the detection and monitoring of track defects, which can lead to catastrophic failures if left unaddressed [9]. Track defects rank as the second leading cause of railway accidents in the United States, as reported by the Office of Safety Analysis of the United States Federal Railroad Administration [10]. Human error is

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identified as the primary cause of railway accidents. Despite the fact that the budget allocated for the upkeep and restoration of railway tracks is significantly higher in comparison to other modes of transportation, the lifespan of railway assets is remarkably lasting [6]. The International Union of Railways (UIC) estimates that the global cost of railway infrastructure failures, including those caused by track defects, amounts to billions of dollars annually. Railway infrastructure failures can have a substantial and widespread economic impact [3], [11]. In addition to the immediate costs of repairs, these failures can result in significant disruptions to both businesses and supply chains. Railway infrastructure failures disrupt the supply chain, causing delays in transporting goods and adversely affecting just-in-time inventory systems, potentially leading to shortages for businesses [12]. The costs incurred while the infrastructure is being repaired, such as the expenses for alternative transportation methods and temporary storage of goods, can also add significantly to the overall economic burden [13].

Condition evaluations have become increasingly prevalent to determine the time and location of repair for many components of railway infrastructure, including power supply, signaling, track, and catenary systems [14]. The condition assessment of railway track primarily involves the measurement of parameters associated with the wear and positioning of the rail, also known as track geometric quality [15]. The evaluation of tracks has become a vital aspect of both the operation and maintenance of a railway system [16]. Many attempts have been made in the past three decades to develop techniques for evaluating the quality of track conditions. Geometric data analysis is usually required for railway track condition inspection and assessment [6]. An integral part of asset management is condition assessment, which guarantees accurate, reliable, and effective decision-making. However, assessing track geometry conditions and the structural integrity of railway infrastructure is the main emphasis of the current condition assessment models. The inspection of tracks has become an essential component of railway operations and the maintenance of a railway network [16]. Inspections can be conducted using both visual inspection and nondestructive testing procedures such as ultrasonic testing equipment, inspection trucks, and gauge rulers [15]. Visual inspections conducted by experts are the primary method utilized in railways for assessing the condition of tracks [17]. Visual inspections conducted by experts are the primary method employed in

the railway industry to evaluate the condition of tracks. The majority of railway infrastructure condition assessment methods currently in use are constrained by either a lack of components or limited techniques, leading to an inadequate portrayal of the overall condition of the railway infrastructure [6].

These methodologies do not provide a comprehensive and accurate picture of the railway track's status [18]. As a result, there is a need for a comprehensive, robust, and standardized model for assessing the state of railway infrastructure. To address these limitations, researchers have explored the application of multi-criteria decision-making (MCDM) methods to enhance the assessment of railway track structural condition. The application of Multicriteria Decision-Making (MCDM) methods in railway track structural condition assessment offers a systematic and comprehensive approach to evaluating various criteria and making well-informed decisions [19]. These methods prove invaluable in tackling intricate and multifaceted decision challenges within railway infrastructure management, particularly when it comes to assessing the structural condition of tracks [19]. Research models developed using MCDM to evaluate the structural condition of railway tracks include the Uzarski model by the US Army and the Fuzzy Method-based Railway Track Structural Conditions Index (FTSI). Despite their utility, these models have limitations such as overlooking certain components and relying on subjective judgments. Hence, there is a critical need to create a comprehensive, reliable, and standardized model that can overcome these shortcomings and offer a precise evaluation of railway track structural conditions and provide a more accurate assessment of the structural condition of railway tracks. Therefore, the main objective of this study is to develop a comprehensive, robust, and standardized model for assessing the structural condition of railway track.

### **1.2 Statement of Problem**

In order to preserve the economic advantages of railway transportation, it is crucial to minimize the operational expenses. Among these expenses, infrastructure maintenance costs constitute a significant portion of the overall expenditure. In 2020 the yearly budget given for rail infrastructure in Europe is 40.65 billion euros, infrastructure maintenance costs expenses make up from 37% to 61% of total funding for rail infrastructure budget [20]. As the demand for rail transportation grows, optimizing maintenance costs becomes more important.

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Condition assessment is an essential component of asset management, ensuring that decisions are made based on accurate, reliable, and efficient assessments. The use of the condition assessment index is essential in the Track Management System in track quality and select appropriate maintenance strategies. To achieve minimization of maintenance costs it is important to develop a reliable condition index that can assess structural conditions of railway tracks. Inaccurate or inadequate railway track condition assessments can have significant consequences. since they could result in unnecessary repairs may be performed if assessments overestimate the severity of track defects, leading to wasted resources, increased costs, and disruptions to rail operations. Conversely, underestimating the severity of track defects can result in missed critical failures, which may lead to accidents, derailments, and safety hazards. Additionally, inaccurate assessments can cause operational delays due to unexpected track failures, as trains may need to slow down or stop, affecting schedules and efficiency.

Existing methods lack a holistic view of structural conditions, which compromises safety and performance. With aging infrastructure and increasing demands, there is an urgent need for comprehensive approaches that extend beyond traditional track geometry assessments. Many current methodologies are limited in scope, affecting the components covered and the overall reliability of assessments, which can lead to increased maintenance costs and safety risks. Furthermore, the absence of a reliable and unified method for evaluating structural health undermines the resilience of the railway system. This research aims to address these gaps by developing a standardized, data-driven model that integrates various assessment criteria, thereby enhancing the overall management of railway track infrastructure.

The pivotal need for this research arises from the critical absence of a reliable method to assess the structural conditions of railway tracks. Despite frequent evaluation of track geometry, the lack of a robust approach to evaluating structural conditions significantly jeopardizes ride safety, compromises track quality and inflates infrastructure maintenance costs. Bridging this gap is imperative. Thus, this research endeavors to create an integrated system that merges a structural condition model with geometrical assessment, aiming to decisively enhance track safety, quality, and cost-effectiveness in railway track maintenance.

## 1.3 Research Questions

The following research questions are the focus of the study:

- What approach should be used to establish a condition grading scale for different railway components?
- What are the limitations of current railway track condition assessment methods, and how does those limitations going to be addressed?
- What role do track components, defect categories, defects and severities play in determining the overall condition of a railway track, and how can these be quantified?

## 1.4 Objectives

### 1.4.1 General Objectives

The main objective of this research is to develop a model for assessment of the railway track structure using a multi-criteria decision-making method.

### 1.4.2 Specific Objective

- To create a condition grading scale for various the railway components.
- To identify and address the limitations of current railway track condition assessment methods.
- To quantify the impact of track components, defect categories, specific defects, and their severities on the overall condition of a railway track and develop a method to integrate these factors into a cohesive assessment model.

## 1.5 Scope

The scope of this research entails developing an accessible Railway track structural condition assessment model using multi-criteria decision methods that include assessing the level of importance and severity. The model is tailored for UIC class I ballasted track, considering design speeds from 80km/h to 120km/h. This track classifications are in line with the Ethiopian rail standard, rendering them appropriate for the research. The study will involve categorizing the railway track components - rails, rail joint, sleeper, ballast, and fastening system - based on their importance levels in the overall structural integrity. Additionally, the research will focus on evaluating the severity of defects within these components to understand their impact on the track's condition. By integrating these parameters into the assessment model, the study aims to provide a comprehensive framework for effectively prioritizing maintenance and

repair efforts based on both the importance and severity considerations of defects within the railway track.

### **1.6 Limitations of the Study**

The following are some of limitations that should be considered in this study:

- To handle the complexity of special track structures like turnouts and level crossings, the research scope excludes these structures from the model development.
- The research heavily relies on a comprehensive literature review, suggesting that incorporating expert judgments could further enhance its effectiveness.
- The research focuses solely on the superstructure of the railway component, omitting consideration of the subgrade due to its wide-ranging and complex nature

### **1.7 Research Contributions**

The main contribution of this thesis is the development of a new approach track structural condition assessment model using a Multi-Criteria Decision Making (MCDM). This research aims to address the lack of a reliable index to assess the structural conditions of railway tracks, which compromises ride safety and quality. By developing a comprehensive model for assessing the condition of railway tracks, model will enhance the accuracy and quality of the data collected. The developed model will standardize data collection methodology ensures accurate and meaningful data capture by field inspectors, making it consistent over time. The model provides a comprehensive set of performance metrics, indicating appropriate timing for track inspection and maintenance activities, asset history, and compliance data, facilitating valuable insights and informed decision-making. Furthermore, aligning inspection goals with data models provides real-time visibility into operations, allowing for the development of safety models and the identification of areas for improvement. This, in turn, will lead to reduced operational costs, increased efficiency, improved asset maintenance, and enhanced safety. The benefits involve reduced maintenance expenses due to timely defect detection, improved resource allocation by prioritizing high-risk zones, and proactive maintenance based on historical data to reduce operational interruptions and improve safety measures. Additionally, automated data collection decreases manual effort and ensures high-quality data, while model-generated insights enhance decision-making, leading to better prioritization of repairs and budget allocation. Ultimately, accurate defect detection boosts safety by

preventing accidents and reducing related costs. The outcomes of this research will have a considerable impact on future research, policy, and practice in the field of railway track management. The development of a reliable track condition assessment index will open doors for further research and improvement in track maintenance strategies. The findings may influence policy decisions aimed at enhancing the safety and quality of railway tracks.

### **1.8 Thesis Organization**

This thesis is structured into six chapters.

**Chapter I:** Outlines the background study, objectives and problem formulation.

**Chapter II:** Presents a comprehensive review of the literature, providing a foundation for the model development. It discusses the key inspection technologies utilized in the condition assessment of railway infrastructure, as well as the manuals employed in railway asset management. Additionally, it examines previous research in the field of railway condition assessment and summarizes the multi-criteria decision-making (MCDM) techniques used in model development..

**Chapter III:** Offers a detailed explanation of the research model development. It introduces the Track Structural hierarchy and discusses the comparison of railway infrastructure components, defects, and their categories. Furthermore, it presents the fuzzy membership model for converting linguistic assessments into numerical values, along with the aggregation process and model development.

**Chapter IV:** Presents the results of the MCDM analysis on components, defects, and their categories. It defines and presents the weights and severities.

**Chapter V:** Demonstrates the model development and the application of various techniques. Case studies are utilized to validate the developed model.

**Chapter VII:** Concludes the thesis with research findings and outcomes, providing recommendations for future researchers.

## **CHAPTER TWO**

### **LITERATURE REVIEW**

#### **2.1 General**

This chapter offers a comprehensive overview of the components comprising the railway track, an in-depth analysis of the condition assessment concept, defects found in railway tracks, and the inspection of railway tracks. This literature review serves as a foundation for research by identifying the current state of knowledge and understanding in the field and identifying areas of improvement and innovation for the development of a model for assessing the structural condition of railway tracks. Inspection of railway rail components is critical to assessing the structural condition of railway tracks, as any defects or weaknesses in these components can affect the overall integrity and safety of the railway track. Different kinds of defects can occur on track components. Identifying common defects and their causes can help develop effective inspection and maintenance strategies to prevent accidents and ensure the smooth and safe operation of railway tracks. This knowledge can help select the most appropriate techniques for assessing and maintaining the structural condition of railway lines.

#### **2.2 Track Structural Condition Assessment**

The structural condition of railway tracks directly impacts the safety and performance of train operations. Timely detection and evaluation of track defects are crucial to preventing accidents and reducing maintenance costs [21]. With advancements in technology, various assessment methods have been proposed and implemented to assess the condition of railway tracks. According to the literature, if the track superstructure is not repaired at an appropriate time, the repair cost exponentially increases as the track deteriorates [6].

Regular inspections to assess the condition of the track provide the basic data for assessing track quality [17]. This information allows maintenance managers to assess current track conditions and determine short- and long-term maintenance and repair needs. Track conditions in most countries are assessed by analyzing data collected by either manual or automated track recording vehicles. Through this analysis, the geometric condition of the track is determined, which indicates both the safety and comfort of the driver. However, this approach is unable to identify the reasons for geometric tracking anomalies [22]. In other

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words, existing methods can be used to identify geometric deviations, but not precise track structure defects. This is one of the main disadvantages of the current approach to optimal maintenance planning and repair [23].

### **2.3 Railway Track Manuals and Standards**

Condition assessment plays a crucial role in the decision-making process and aids in determining the necessary maintenance and rehabilitation measures to prolong the lifespan of assets [17]. Therefore, several manuals and codes have been generated by different countries and companies to attain this goal [17], [23]. The railway track manual is a crucial document that provides guidelines and procedures for track maintenance and inspection. It is used for track condition assessment to ensure the safety and efficiency of railway operations.

The manual provides standardized procedures for inspecting and assessing the condition of railway tracks. It ensures consistency in assessments and allows for comparison across different sections. The manual also covers types of track defects and how to assess their severity. This information is crucial for planning maintenance activities, prioritizing repairs, and allocating resources effectively. Regular assessments of track conditions allow railway operators to monitor performance over time, identify trends, and make informed decisions to improve the overall railway system.

The International Union of Railways (UIC) is a global organization that promotes rail transport and collaboratively develops the railway system. It standardizes the design, construction, operation, and maintenance of railways through its manual, which covers infrastructure, rolling stock, safety, interoperability, and technical specifications. The manual serves as a comprehensive guide for railway professionals and industry stakeholders.

Furthermore, The American Railway Engineering and Maintenance-Of-Way Association (AREMA Manual) is a guide that contains information on the engineering, design, and construction of railways. It provides plans, economic principles, and data for railways to establish their policies and practices. The Manual aims to assist in the engineering and construction of a safe, economical, and low-maintenance railway plant.

The Federal Railroad Administration (FRA) oversees the safety and regulation of the railroad industry in the United States. A detailed manual has been created by the FRA to establish the guidelines and standards that dictate the functioning of railroads [24]. In addition to The FRA

manual the Federal Transit Administration (FTA) manual, provides guidelines, standards, and best practices for railway operations, safety, and maintenance in the United States [25].

The Australian company RailCorp created a compilation of manuals on railway tracks, covering components, defects, maintenance procedures, and designs. These manuals can be accessed on the TMC manuals website [26], [27]. The two most used manuals are TMC 203 Track Inspection and TMC 224 Rail Defects and Testing [27]. TMC 203 provides requirements, processes, and guidelines for track asset management and inspection activities, while TMC 224 describes rail defects, limitations, and inspection techniques [26], [27].

### 2.4 Track Inspection and Maintenance

Railway track inspection and maintenance is a critical part of railway operations. Regular inspection and maintenance of the track is necessary to ensure its safe and reliable operations [28], [29]. The track must be inspected for track geometry, track alignment, and track surface conditions. Track alignment inspection involves checking the track alignment for straightness, level, and cants. Track Structural inspection involves checking for sleepers, ballast, rail fastenings, and other track components. Maintenance activities include replacing or repairing worn components, adjusting track alignment, and conducting rail lubrication [28].

#### 2.4.1 Track Inspection

Track defects that can lead to failures are identified by inspecting the track [30]. Qualified personnel are expected to carry out inspections, which may be carried out manually or using equipment. Each component of a track section is inspected and any discrepancies or defects are noted on an inspection form that documents the condition of each component. It is necessary to take corrective actions for defects per the guidelines of the applicable standard [31].

### 2.5 Railway Track Defects

The term “Defect” is defined as any anomaly in the shape or internal structure of an element and material(s) that adversely affects its functional capacity or service life [32].

majority of standards and manuals categorize Track defects into:

**Track Structure:** These can include defects with the rails, ballast, sleepers, anchor plates, fasteners, bolts, rail connections, etc. This can also include defects where parts are missing.

**Track Geometry:** These defects include deviations from the ideal track gauge, deviations from curved/tangential tracks, misalignments when re-laying tracks, etc.[33].

## **2.6 Track Structure Defects**

These can include defects with the rails, ballast, sleepers, anchor plates, fasteners, bolts, rail connections, etc. This can also include defects where parts are missing.

### **2.6.1 Rail Defects**

Internal discontinuities of rail that may give rise to rail fatigue are called rail defects. Rail alterations of a mechanical nature occurring under the influence of passing trains are also considered defects [34]. Several factors can lead to the development of rail defects in rails of any type or rail welds. These conditions typically result from rail vehicles, rail wear, plastic flow in the rail manufacturing process, and cyclic loading [35].

#### **I. Rail Head Defects**

are any progressive fractures occurring in the head of a rail and have a transverse separation, however slight.

- i. **Transverse Break Without Apparent Origin:** The abrupt occurrence of these breaks, especially in extremely cold weather, makes it challenging to promptly ascertain their cause or origin [36], [37].
- ii. **Transverse Fissure:** A progressive transverse break originating from a crystalline core within the head, extending outward as a polished, shiny, or opaque circle [37].
- iii. **Compound fissure:** A progressive fracture arises from a horizontal split head that can either turn upwards or downwards or in both directions, within the rail's head [35], [38].
- iv. **Horizontal Split Head:** Typically emerging from within the rail head, positioned at least 0.635 cm or more beneath the running surface and advancing horizontally, often accompanied by a level area on the running surface [36], [37].
- v. **Vertical Split Head:** Refers to a division that runs vertically either through or close to the center of the head, extending into or through it [33], [39].

#### **II. Rail surface defects**

Rail surface defects refer to any irregularities or imperfections found on the surface of a railway track.

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

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- i. **Head Checks:** Are superficial or fine cracks that can be observed on the gage corner of the rail head, appearing at various angles along the length of the rail [39].
- ii. **Spalling:** Refers to the occurrence of cracks and chips on the surface of a rail. It is characterized by a gradual development of head checking and flaking [37].
- iii. **Shelling:** Refers to a condition found in rail heads where there are gradual horizontal separations beneath the surface that can lead to cracking on the gage side of the rail head [37].
- iv. **Wheel burns:** Occur as a result of the driving wheel of locomotives slipping on the surface of the rail [38].
- v. **Squat:** Defects manifest themselves in the crown region of straight rail segments. These defects are initiated on the surface and take the form of two cracks, namely a leading crack and a trailing crack .
- vi. **Corrugations:** A recurring longitudinal arrangement of shallow undulating indentations on the surface of the rail [33].

### III. Rail Web Defects

A rail web defect is a type of imperfection or damage found on the web of a rail track. The web is the vertical section of the rail that connects the head and the base of the rail.

- i. **Head and Web Separation:** A horizontal defect that develops in the fillet area between the head and web is considered to be progressive. Separation can take place either at the rail end or within an open rail, advancing horizontally [37], [38], [39].
- ii. **Bolt Hole Crack:** Cracks typically emerge due to the combined effects of vertical, horizontal, and lateral forces acting on the rail. These forces primarily concentrate at the interface between the bolt and rail, where the pressure is at its maximum.
- iii. **Piped Rail:** Refers to a vertical division within a rail, typically occurring in the web, as a result of the shrinkage cavity in the ingot failing to merge during the rolling process [39], [40].
- iv. **Rail Corrosion:** Occurs when the surface of the rail disintegrates due to chemical decay, primarily oxidation, commonly known as rusting [41].

#### IV. Rail base defects

The Rail base defects refer to any issues or damage that occur to the base of a rail track. The base of a rail track is the part that supports the rail and helps to distribute the weight of the train. The most common rail base defects include Broken bases and corrosion. broken base occurs when the base of the rail track is cracked or broken, which can lead to instability and potential derailment of trains. Corrosion of the rail base can occur due to exposure to moisture, chemicals, or other environmental factors[39].

#### V. Rail Wear

Rail wear is the result of separation or cutting caused by friction and excessive loads, leading to three distinct types of wear on railway tracks [42]. Three primary flaws encompass curve wear, tangent wear, and the percentage of head loss [17].

#### VI. Rail buckling

Track buckling refers to the occurrence of significant lateral misalignments in continuous welded rail (CWR) tracks, which can lead to severe derailments [43]. Curved as well as straight tracks are prone to buckling, with curve buckle amplitudes usually falling between 6" to 14" and tangent buckles ranging from 12" to 28" [43]. The formation of buckles is commonly attributed to a combination of three primary factors: elevated compressive forces, deteriorated track conditions, and the impact of vehicle loads (train dynamics).

### **2.6.2 Rail Joint Defects**

The rail joint is the weak link of the line, and the maximum inertial force of the wheel acting on the rail joint is about 60% larger than other parts. The main defect of rail joints is screw hole cracks, followed by rail jaw cracks and saddle wear [44].

Defective welds are field or plant welds containing any discontinuities or pockets exceeding 5% of the rail head (cross-sectional) area individually or 10% of the aggregate (in or near the transverse plane) due to incomplete penetration of the weld metal between the rail ends, lack of fusion between weld and rail end metal, entrapment of slag or sand, under bead or other shrinkage cracking, or fatigue cracking [27], [40].

### **2.6.3 Sleeper Defects**

Sleeper defects refer to issues that arise during the manufacture, transportation, installation, and operation of concrete sleepers, affecting their structural integrity and functionality [45]. These

defects can include tear damage in the prefabricated system, plug breakage or cracking, and issues related to nonstandard plug materials or improper installation [45]. Statistical analysis shows that a significant number of concrete sleepers are replaced annually due to defects identified during operation and maintenance, highlighting the importance of addressing these issues for efficient track performance [46].

Cracks: Concrete Sleepers cannot withstand unusually high repeated shock loads.

- Causes of center-tied sleepers include inadequate tamping techniques, poor drainage, foul ballast, and sufficiently shallow ballast depth to an inferior subgrade.

### **2.6.4 Ballast Defects**

Ballast defects are frequently easily identified by their signs of degrading structure and poor geometry [39]. FRA believes that a location with a combination of a ballast defect with a marginal geometry condition warrants additional monitoring, more restrictive remedial action, or both, to correct or safely compensate for the combined defect and condition.

Ballast profile defects are utilized for the interpretation of the ballast quantity, the condition of their profile, and the extent of their severity [17]. Drainage deficiencies within a ballast serve as indicators of the condition and extent of its drainage properties. The obstruction of ballast drainage can be attributed to two primary factors. Firstly, fouling occurs when fine materials fill the voids, resulting in blockage. Secondly, vegetation growth within the ballast system obstructs the voids and leads to water entrapment along the tracks [17], [33], [37].

### **2.6.5 Rail fastening System Defects**

Railway track fastening defects refer to various issues that can compromise the stability and safety of railway tracks. These defects can include loose bolts, worn-out clips, broken spikes, damaged baseplates, corrosion, and improper installation of fastening components. When left unaddressed, these defects can lead to track misalignment, increased wear and tear on track components, and potentially unsafe conditions for train operations.

## **2.7 Track Defect Development**

There are several causes that can lead to defects in railway tracks, including:

1. Loading at The Rail/Wheel Interface

Those are forces exist at the rail/wheel interface in train operations [33], [34]. Vertical loading consists of static load (gross weight of the railcar), dynamic load (result of train speed), and

impact load (caused by rail head irregularities or flat spots on the wheel). Lateral loading occurs in curved tracks due to wheel/truck curving forces. Creep forces are generated by the rolling action of the wheel, including longitudinal creep forces from traction and transverse creep forces from lateral movement during truck hunting [34], [40].

### 2. Rail Stress

Rail stress is a key factor in the development of rail defects, such as cracks and fractures [38]. Bending and shear stresses from wheel-rail contact can cause rail defects, with vertical bending stresses being the main factor [40]. Contact stresses between the wheel and rail are influenced by various forces [47]. Thermal stresses from temperature changes can also impact rail flaws, with compressive stresses occurring above the neutral point and tensile stresses below. Residual stresses can arise from manufacturing processes and rail welding, potentially present at different points in the rail section.

### 3. Dynamic Effects

Dynamic effects on rail tracks and wheels can be caused by irregularities such as dips in joints and welds, as well as flat spots or out-of-round wheels. These irregularities create high dynamic forces, especially at high speeds. The occurrence of these dynamic forces can reduce the critical size of fatigue cracks and increase crack growth rates. Wheel-impact detectors are used to detect poorly performing bogies that cause high lateral forces [38], [40].

### 4. Manufacturing Process

The main causes of defects in railway track components during manufacturing include poor quality control, inadequate machinery maintenance, human error, environmental factors, and design flaws [39].

### 5. Rolling contact fatigue (RCF)

high normal and tangential stresses between the wheel and rail, resulting in severe shearing of the surface layer of the rail [40]. The material's fatigue or exhaustion of ductility leads to microscopic cracks that propagate through the heavily deformed surface layers of steel at a shallow angle to the rail running surface [38] [47].

### 6. Environmental Conditions

Environmental conditions such as water infiltration, freezing and thawing cycles, vegetation growth, erosion, and extreme temperatures can cause track structure defects. Water infiltration

can lead to degradation and loss of support [39], [44]. Freezing and thawing cycles can cause cracks and potholes in ballast and sleepers. Vegetation growth can displace the ballast material. Erosion can wash away the ballast material, resulting in uneven settlement. Extreme temperatures can soften or make the ballast brittle [40].

## **2.8 Track Inspection Practices and Technologies**

The evaluation of the railroad pathway is a fundamental duty in the procedure of assessing the state of the resources and devising maintenance schedules [12]. Railway track components inspection techniques are essential for maintaining the safety and efficiency of railway systems [3], [18]. These techniques involve the assessment and evaluation of various components of the tracks, including rails, fastenings, sleepers, ballast, and joints. Various inspection methods are employed in evaluating the condition of railway infrastructures, each presenting its own set of applications, benefits, drawbacks, and technical obstacles [16], [39], [48]. The diverse nature of railway components, composed of various materials, necessitates the utilization of distinct technologies for their assessment. The predominant form of railway inspection typically involves visual examinations conducted by skilled professionals [17].

The railroad industry currently uses several procedures and practices to maintain a safe rail network. Some of these procedures, including visual inspections and several automated inspection techniques, are required by the railroad agencies for different classes of track [17].

### **2.8.1 Manual Track Inspection Tools**

Various inspection methods are employed in evaluating the condition of railway infrastructures, each presenting its own set of applications, benefits, drawbacks, and technical obstacles. The diverse nature of railway components, composed of various materials, necessitates the utilization of distinct technologies for their assessment. The predominant form of railway inspection typically involves visual examinations conducted by skilled professionals [49]

#### **Visual Inspection**

Visual inspection is a widely employed method in contemporary times. Experts conduct visual inspections by traversing the tracks on foot, diligently seeking out any defects, and meticulously documenting them in inspection sheets [26], [39]. However, this technique is both time-consuming and expensive, as it requires a significant investment of resources. On average, a mere 10 kilometers of track can be inspected per day using this approach [17].

Visual inspection is a crucial aspect of track maintenance, involving the examination of geometry and structures through the unaided human senses or non-specialized inspection equipment. These inspections are carried out either by walking along the tracks or utilizing a hi-rail vehicle [50].

### **2.8.2 Automated Track Inspection Technologies**

Over the years, advances have been made in the field of automated track inspection. Automated inspection systems offer the advantage of rapid data collection, comprehensive coverage of the entire track network, and the avoidance of track personnel having to occupy the track to record measurements [40], [44]. While certain technologies are currently used for testing purposes only, ongoing developments could potentially make them suitable for widespread implementation in the future[49].

#### **1. Rail Flaw Detection Car**

Rail flaw detection cars utilize both ultrasonic and magnetic induction technologies for the detection of cracks and defects in rails [51]. The ultrasonic method entails the transmission of energy into the rail and the detection of echoes to identify flaws, whereas magnetic induction technology is employed to detect distortions in the energy flux field resulting from rail cracks [49]

#### **2. Track Geometry Car**

Track geometry measurement systems are utilized to assess a range of track geometry elements including gage, cross-level, alignment, and surface conditions [39], [44], [48]. By detecting current defects and potential defect-prone areas, these systems provide valuable data for transit agencies to proactively plan maintenance tasks and effectively address future track geometry issues [49].

#### **3. Ultrasonic**

In 1927, Dr. Elmer Sperry introduced ultrasonic inspection to the railway industry by creating a large rail inspection car for the American Railway Association. Ultrasonic technology involves sending ultrasonic energy into the rails and collecting the reflected energy using transducers [17]. The amplitude of these reflections can indicate the condition of the rails with a high accuracy rate of 90-95%. Although speeds of up to 65km/h are possible, operations are typically conducted at 45km/h for safety and precision [51]. However, ultrasonic inspection may face challenges in

extremely cold weather conditions due to ice interference, and heavy lubrication can also impact results by creating an intervening interface [17].

#### 4. Lasers

Lasers can assess the profiles of rail and wheel running surfaces through the process of scanning a laser across the specific component [49]. The laser is responsible for measuring the distance, while machine vision is employed to analyze the resulting image generated by the laser [52]. Subsequently, this image is compared to the established standard and condemning profiles to ascertain the necessary maintenance interventions.

#### 5. LIDAR

LIDAR technology is commonly utilized for accurate distance and speed measurements [53]. It is frequently employed in assessing track clearances and monitoring vehicle speeds. For instance, freight railroads utilize a LIDAR-based system to detect stuck brakes or wheel skids, as well as to identify surface defects in crossties and issues within the ballast section [49]

#### 6. Ground Penetrating Radar (GPR)

GPR, or Ground Penetrating Radar, is a radar-based system that is utilized to assess and monitor the conditions of substructures at different depths [17]. The properties of substructures can change due to factors such as fouling levels, moisture levels, or the presence of different layers within the substructure [49]. GPR provides valuable information such as the depth of the free-draining layer and the ballast fouling index. The ballast fouling index indicates the proportion of fines present within the ballast structure. An increase in fines can hinder drainage and weaken the overall structure of the track. GPR is employed to identify the underlying causes of recurring track geometry issues and to plan maintenance activities related to the ballast [49].

### **2.9 Related Studies on Railway Track Structural Condition Assessment**

Over the past thirty years, numerous efforts have been undertaken to create methods for assessing the quality of track conditions [6]. Typically, the inspection and assessment of railway track conditions involve analyzing geometric data collected from track-recording cars [6].

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Table 2.1 Current Track Geometry Indices

Geometry index	Developer	Description
Five-parameter track defectiveness (w <sub>5</sub> )	Austrian Railway (Madejski and Grabozyk 2000)	This method offers a detailed and independent assessment of track quality, which is beneficial for maintenance planning. However, its complexity and reliance on threshold values can pose challenges in practical applications
Geometry index (TGI)	Indian Railway (Mundray 2003)	TGI method offers a detailed and effective approach to track quality assessment, but its complexity and potential for over-categorization can pose challenges in practical applications.
USA Track Roughness Index	USA railway (Ebersohn and conarad 1998)	offers a reliable method for assessing track roughness, but its limitations in scope and potential for misinterpretation should be considered in maintenance planning.
FRA Track quality index (TQI)	USA railway (Zhang et al. 2004)	The FRA ,TQI method effectively evaluates track quality and aligns with Federal Track Safety Standards. However, it may not account for the nuanced effects of different track geometry parameters on overall ride quality, potentially oversimplifying the assessment
Chinese Track Quality Index		provides a conservative safety assessment and includes multiple track geometry parameters for a comprehensive evaluation.However, it gives equal weight to all parameters, which may not accurately reflect their varying impacts on ride quality.

Although various methods have been developed for the inspection and quantification of track geometry conditions, there is insufficient work for the development of a reliable method for the

evaluation of track structural conditions [6]. Track structural conditions significantly influence track geometry conditions. In other words, track geometry defects may be a result of some structural defects in railway components, including rail, sleeper, and ballast. While geometry conditions indicate the present condition and safety of running on the track, track structural conditions indicate a potential for failure [15]. This means that track geometry condition evaluation can provide a possibility of making appropriate repairs and maintenance for a short period, while track structural condition evaluation provides both short- and long-term maintenance planning [6].

### **2.9.1 US Army Uzarski Model**

The US Army [54] has produced a comprehensive report on the evaluation of railway conditions, specifically focusing on low-volume railroad tracks. The report introduces a set of condition indices that utilize a scale ranging from 0 to 100 [54]. This scale is divided into seven distinct condition categories, ranging from excellent (85-100%) to failed (0-10%) [17], [55]. The excellent condition category indicates minimal defects, where the track's functionality remains unaffected and immediate repair is unnecessary. However, routine or preventive maintenance may be scheduled to ensure continued optimal performance. On the other hand, the failed condition category signifies severe deterioration throughout the majority, if not the entirety, of the track. In such cases, major repairs, complete restoration, or even total reconstruction are imperative. To accurately describe the condition of each component within the railway infrastructure, multiple indices have been developed. These indices include the Rail and Joints Condition Index (RJCI), the Tie Condition Index (TCI), the Ballast and Subgrade Condition Index (BSCI), and the Track Structure Condition Index (TSCI), which aggregates the condition indices of the individual components. The TSCI was formulated using regression techniques, ensuring a comprehensive assessment of the track's overall condition [17].

The assessment of track structure using the [54] model is subject to various limitations. Firstly, it applies only to tracks that have wooden sleepers and experience high volumes of traffic. Additionally, the Uzarski model fails to account for disparities between the main line and its branches. Furthermore, this technique is time-consuming and heavily reliant on subjective judgments made by individuals. Lastly, it overlooks the presence of turn-outs on the railway lines [6], [54].

### **2.9.2 Track Condition Assessment Model Based on Visual Inspection**

[22] proposed a quality index to evaluate the structural condition of the track using a visual inspection technique. The track is divided into four components: rails, ballast, sleepers, and fasteners. The authors utilized a weighted deduction density model to establish the quality index for each component. Consequently, four indices were developed: rail quality index (RQI), ballast quality index (BQI), sleepers quality index (SQI), and fasteners quality index (FQI). These indices are based on the identification of defects and their respective severities. The severity levels, namely low, moderate, and high, are employed in the indices to describe the condition of the track. A low severity level indicates a track in good condition with minimal defects, while a moderate severity level signifies defects that may or may not impede operations or cause delays. On the other hand, a high severity level represents defects that restrict train operations and pose safety concerns. To facilitate maintenance activities, the track line is divided into management sections, which are further subdivided into segments. This division aids in the assessment of structural conditions through visual inspections of selected segments [15].

[23] has various constraints associated with evaluating the condition of track structures. One of these limitations is that it can only be applied to tracks with wooden sleepers and light traffic, thus limiting its universal applicability. Additionally, the suggested track visual inspection method outlined in the study is time-consuming, which could affect its feasibility in real-world scenarios. Moreover, the calculation of the proposed structural indices in the track evaluation model is deemed complex, potentially posing difficulties in implementation and comprehension.

### **2.9.3 Railway Track Structural Conditions Index Using Fuzzy Method**

Research conducted by [6] focuses on the development of the Railway Track Structural Conditions index using the fuzzy method. The study commenced with an extensive field investigation to analyze the structural behavior of the railway, collecting data on track defects, their frequency, severity, and progression rate. Subsequently, the fuzzy method was employed to establish an index that reflects the quality of the track conditions. The railway track structure comprises various elements including rail, sleeper, ballast, and turnout. The research identified four main defect categories: rail, sleeper, ballast, and turnout. A group of experts was convened to identify the predominant defects within each category, along with their frequency, severity, and impact on track quality. Defects were categorized into low, moderate, and high severity levels.

To create the new index, a panel of 30 railway experts specializing in track maintenance and construction services was assembled. This panel developed fuzzy membership functions for track defect frequency, severity, and significance in track deterioration [55]. The fuzzy track quality index (FTSI) was then formulated based on these membership functions. The efficacy of the new model was assessed by testing the fuzzy track quality index on a railway line.

The Railway Track Structural Conditions Index, formulated by [6], has certain drawbacks. Initially, the model's scope is confined to four component groups. It doesn't consider the influence of the fastening system and rail joints. Additionally, it relies on an outdated severity level adapted from [54] which is designed for low-volume traffic tracks. Moreover, method relies heavily on expert judgment for determining track defect importance, severity, and density, which introduces a degree of subjectivity [55].

### **2.9.4 A Hybrid Multi-Criteria Decision-Making Model by Laith El-khateeb**

Hybrid Multi-Criteria Decision Making Model was developed by Laith El-khateeb to assess the condition of railway infrastructure. The model is developed using two main inputs. The relative weight of importance for various components and defects, and the severities of these defects. The model categorizes railway infrastructure into five components, each with specific defect categories, leading to the identification of 33 distinct defects. The model employs an analytical network process to evaluate the importance of various railway components and defect categories, utilizing expert surveys for data collection. A three-level pairwise comparison structure is established to assess the relative importance of components, defect categories, and specific defects. The model integrates the weights and severities of defects using the TOPSIS algorithm, facilitating a comprehensive condition assessment of railway infrastructure. The research presents a novel fuzzy-based condition assessment model that addresses the complexities and uncertainties in evaluating railway infrastructure [17].

The model developed by Hybrid Multi-Criteria Decision-Making model proposed by Laith El-Khateeb serves as the foundational framework for this study. While their model provided significant insights into Multi-Criteria Decision Making, certain limitations were noted, particularly in relies on expert opinions and visual inspections, which may introduce subjectivity and potential biases in the assessment of railway conditions. The model does not account for all possible defect types or external factors that could influence railway conditions [17].

## **2.10 Multi-Criteria Decision-making**

Multi-criteria decision-making (MCDM) is a field within operations research (OR) that involves the systematic evaluation and selection of the most optimal solution among a given set of options. The consideration of various criteria drives this process and addresses common challenges that are often encountered in our everyday lives[19].

In the field of infrastructure asset management, numerous multi-criteria decision-making techniques are employed to ensure a strong and reliable decision-making process. These techniques commonly involve the integration of technical information and expert opinions. By combining data and assigning weights to various alternatives, these techniques aggregate the outcomes of each alternative to derive a single index that accurately reflects the condition of the asset. [17].

### **2.10.1 The Best-Worst Method (BWM)**

BWM is a Multi-Criteria Decision Making (MCDM) method, that offers versatility in addressing various stages of an MCDM problem. Its application extends to evaluating alternatives based on criteria, particularly in situations where objective metrics are lacking. Additionally, BWM aids in determining the significance of criteria employed to achieve the primary objective of the problem at hand [56].

BMW utilizes a pairwise comparison methodology to determine the weights ( $w_j$ ) assigned to each criterion. The pairwise comparison  $a_{ij}$  quantifies the extent to which the decision-maker favors criterion  $i$  over criterion  $j$ .

The BWM possesses inherent characteristics that make it superior to AHP and other MCDM, including improved consistency and the ability to yield optimal values. These advantages equip the BWM with the capability to effectively address decision-making problems [57].

### **2.10.2 The Fuzzy Set Theory**

Zadeh introduced the fuzzy set theory as a mathematical model that addresses uncertainties beyond the scope of traditional statistics. Following its inception, fuzzy decision-making has found applications in various disciplines, including civil engineering[58].

Fuzzy decision-making environments offer effective approaches for addressing uncertainties in the form of ambiguity and vagueness. Ambiguity pertains to a specific type of uncertainty where the selection of multiple options from a set of alternatives is plausible.

Fuzzy sets theory serves as an expansion of classical set theory by accommodating elements with diverse levels of membership. In certain cases, a logic system based solely on two truth values, True and False, falls short of accurately capturing human reasoning. To address this limitation, Fuzzy Logic employs the entire spectrum between 0 (representing false) and 1 (representing true) to effectively depict human reasoning. Consequently, a Fuzzy Set encompasses any set that permits its members to possess varying degrees of membership, which are quantified through a membership function within the interval of [58].

### **2.10.3 Fuzzification and Defuzzification**

The concept of fuzzification was elucidated by employing numerical values, mathematical operations, and interconnections, thereby converting a precise numerical value into a fuzzy set[59]. The identification of well-known crisp and deterministic quantities as entirely non-deterministic and highly uncertain can be accomplished [60]. This uncertainty may arise due to vagueness and imprecision, resulting in the representation of variables by a membership function as they exhibit fuzzy characteristics [17].

The defuzzification process involves the translation of the fuzzy output into a singular crisp value, similar to the fuzzification process, based on the degree of membership values [59]. Defuzzification serves as the reverse transformation of the fuzzification process, as it converts the fuzzy output into crisp values that can be utilized within the system.

### **2.11 Summary of the Literature review**

The aim of this literature review was to thoroughly understand the significance of conducting research in railway track Structural condition assessment. Generally, the following points are typically understood when examining the relevant literature in this chapter.

- Regular inspection of track components is essential to identify defects or weaknesses that could compromise safety and integrity.
- Understanding common defects and their causes is vital for developing effective maintenance strategies to prevent accidents.
- The review emphasizes the need for selecting appropriate techniques for assessing and maintaining the structural condition of railway lines,

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- Numerous studies have focused on assessing railway track conditions, but many methods face limitations, such as applicability only to specific track types and reliance on subjective judgments.
- process utilizes pairwise comparisons to evaluate the importance of various criteria, enhancing decision-making in complex scenarios.

### 2.12 Knowledge Gaps in Literature

The literature review identifies several knowledge gaps in the field of railway track structural condition assessment as:

- **Defect Identification:** There is a need for more comprehensive understanding of various defects and their specific causes, which can enhance inspection and maintenance strategies .
- **Severity Levels:** The current classification of defect severity levels may not fully capture the impact of certain defects on train operations and safety, indicating a need for refined criteria.
- **Assessment Techniques:** The review highlights a lack of innovative techniques for assessing the structural condition of railway tracks, suggesting that existing methods may not be sufficient for modern railway demands.
- **Data Utilization:** There is an opportunity to improve how data from inspections is utilized to inform maintenance decisions, which could lead to more effective management of railway infrastructure.

## **CHAPTER THREE**

### **METHODOLOGY**

#### **3.1 Overview**

This chapter presents the comprehensive methodology employed in the research to assess the structural condition of railway tracks. The aim is to develop a systematic and detailed evaluation process using a Multi-Criteria Decision-Making (MCDM) approach. The methodology is designed to quantify the condition of railway tracks by examining multiple components and defect categories, integrating both qualitative and quantitative factors. Each component is further subdivided into distinct defect categories, and each category encompasses specific defect types. This hierarchical structure provides a framework for a detailed and granular analysis of track condition.

To determine the relative importance of each component, defect category, and defect, I have employed the Best-Worst Method (BWM). This technique involves pairwise comparisons of criteria, identifying the most important (best) and least important (worst) criteria, and assigning preference values based on their relative importance. The preference value of track components is determined through pairwise comparison, taking into account criteria such as structural integrity, durability, maintenance requirements, and cost. The average of the Saaty scales considered as preference value of comparison for each section. Similarly, when evaluating defect categories and defects, criteria such as safety risk, frequency of occurrence, cost of repair, potential for escalation, and criticality are considered in pairwise comparison to determine the preference value.

To classify the severity of defects, a six-level severity scale is used, ranging from normal to emergency. This scale is in line with Australian standards and provides a standardized framework for assessing defect severity across multiple components and categories. The severity of defects is quantified using fuzzy membership functions, specifically Gaussian membership functions. This approach acknowledges the inherent uncertainty associated with track inspection and allows for a more nuanced representation of defect severity.

The final step in the methodology involves aggregating the weighted severities of defects into a comprehensive condition assessment model using the Weighted Sum Mean Technique. This

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

technique combines the weights assigned to different components, defect categories, and defects with their respective severity scores, resulting in a single overall condition assessment score. This score provides a holistic evaluation of the track's structural condition, enabling informed decision-making regarding maintenance and repair strategies.

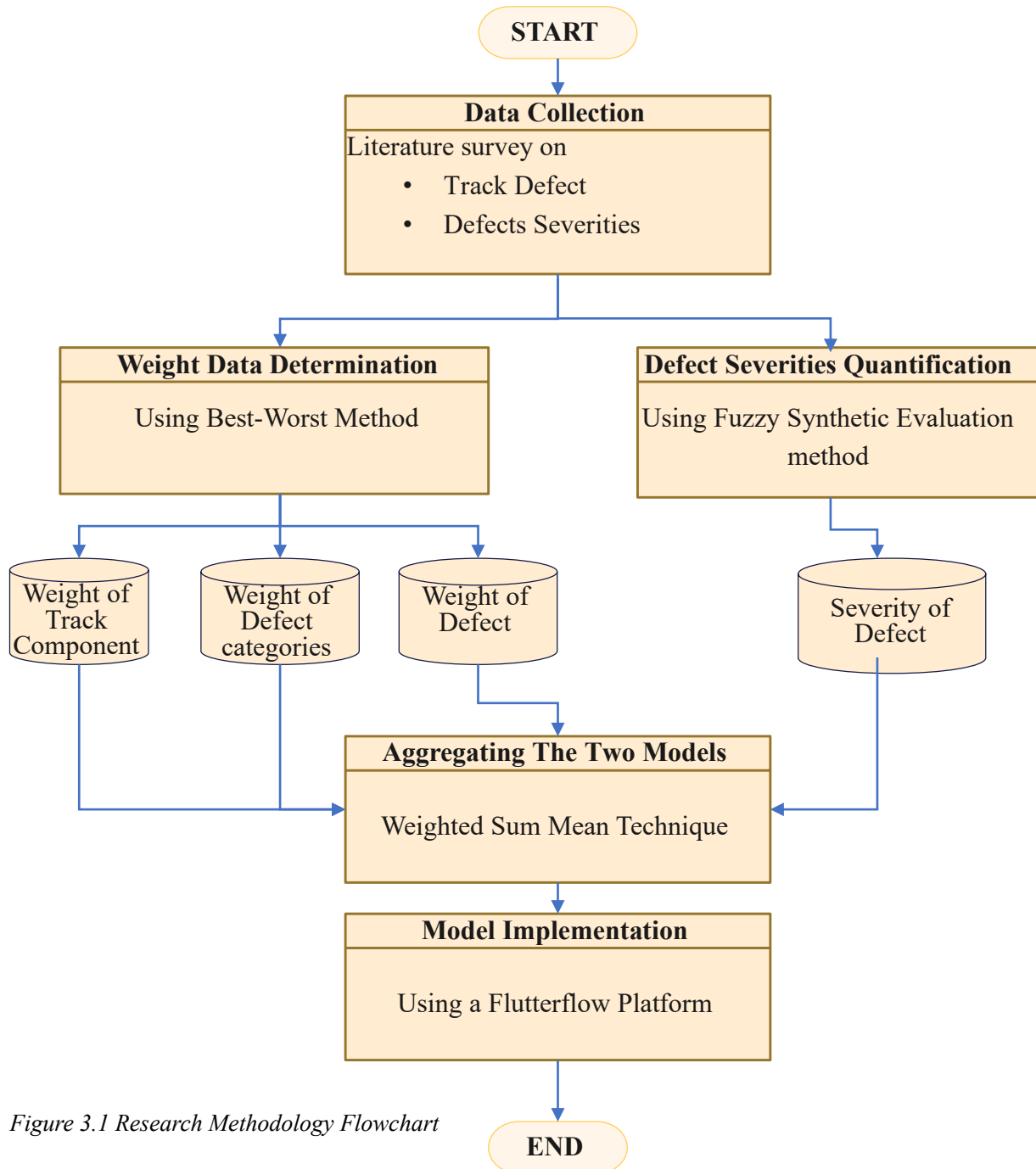


Figure 3.1 Research Methodology Flowchart

## 3.2 Data Collection

Data collection is a critical aspect of understanding and evaluating the structural condition of railway tracks. For this study, extensive research and analysis of various authoritative sources, including railway track manuals, inspection reports, and relevant research studies, were conducted. The aim was to gather comprehensive information on track defects and their impacts on the overall structural integrity of railway tracks.

To facilitate the construction of the track structural condition assessment model, the collected data was organized in a structured manner, allowing the research to systematically analyze and interpret the information gathered from diverse sources. Subsequently, the following sections will provide a detailed discussion on the collected data, delving into the specifics of each data type and elucidating how they are utilized in the development of the railway track structural condition assessment model. This thorough analysis will aid in clarifying the methodology employed in gathering and utilizing the data for the research.

## 3.3 Railway Track Structural Condition Hierarchy

The hierarchical structure of the railway track includes five main components: rails, rail joints, sleepers, ballast, and the fastening system. Various manuals, research papers, and books have been examined to identify the primary defects found in railway tracks. A total of 40 defects have been selected to develop a condition assessment model based on defects.

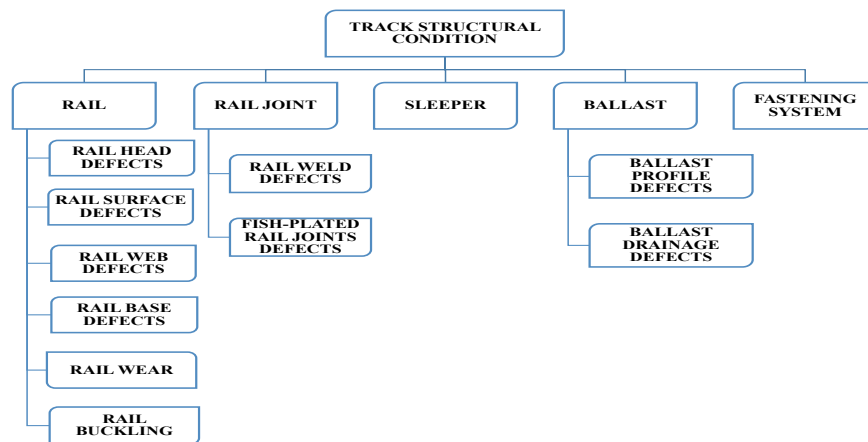


Figure 3.2 Track Structural hierarchy

### 3.4 Development of the Model

Railway track condition assessment model is a systematic approach used to evaluate the state of railway tracks to ensure safety, reliability, and efficiency. To evaluate the structural condition of railway tracks well structure framework is important. This study focuses on the development of the model, which is founded on the integration of three distinct frameworks. To determine the relative importance of each component, defect category, and defect best worst method is adopted. This approach has been deliberately chosen in order to focus on the interrelations between the Components, defect categories and defects within these hierarchies and the inter-relationships amongst them.

The conventional Fuzzy Synthetic Evaluation method, which includes both fuzzification and defuzzification processes, is utilized to standardize various defect criteria and convert the linguistic grading scale into numerical representations.

### 3.5 Weight Determination procedure Using Best Worst Method

The weights corresponding to the components, defect categories, and defects are obtained by adopting the best-worst method. BWM uses pairwise comparison to find the weights ( $w_j$ ) of the components, defect categories, and defects [56]. In this section, I have outlined the steps involved in the BWM (Best Worst Method) for deriving the weights of the criteria [56].

- **Step 1:** The first step is to determine a set of decision criteria.
- **Step 2:** Next, we need to identify the best and worst comparisons. The best comparison represents the most desirable or important criterion, while the worst comparison represents the least desirable or important criterion.
- **Step 3:** After determining the best criterion, we proceed to determine its preference over all the other criteria. This is done by assigning a numerical value between 1 and 9. The resulting vector, known as the Best-to-Others vector ( $AB$ ), shows the preference of the best criterion ( $B$ ) over each individual criterion ( $j$ ). It is important to note that the preference of the best criterion over itself is always 1 ( $a_{BB} = 1$ ).
- **Step 4:** Similarly, we determine the preference of all the criteria over the worst criterion. Again, a numerical value between 1 and 9 is assigned to each criterion. The resulting vector, called the Others-to-Worst vector, illustrates the preference of each criterion over the worst criterion.

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- **Step 5:** Find the optimal weights ( $w_1, w_2, \dots, w_n$ ). The optimal weight for the criteria is the one where, for each pair of  $W_B / W_j$  and  $W_j / W_W$   $W_B$  and  $W_W$  stands for the value of weight of the criteria, weight of the most important criteria, and weight of the least important criteria respectively, we have  $W_B/W_j = a_{Bj}$  and  $W_j / W_w = a_{jw}$ .

which  $a_{Bj}$  and  $a_{jw}$  assigned to the value of preference for comparison of the most importance criteria to the other criteria and other criteria to the least important respectively. In order to satisfy these conditions for all  $j$ , it is necessary to find a solution that minimizes the maximum absolute differences  $\left| \frac{W_B}{W_j} - a_{Bj} \right|$  and  $\left| \frac{W_j}{W_w} - a_{jw} \right|$  for all  $j$ .

Saaty recommended utilizing a nine-point scale, with 1 denoting equal weight between two criteria and 9 denoting the absolute importance of one criterion over another, to evaluate the relative importance or "intensity" of each pair of criteria. The average of the Saaty scales considered as preference value of comparison for each section.

*Table 3.1 Saaty's Scales of Relative Importance for Criterion Pairs*

Intensity of importance	Definition
1	Equal importance
3	Weak importance of one over the other
5	Essential or strong importance
7	Demonstrated importance
9	Absolute importance
2, 4, 6, 8	Intermediate values between the two adjacent judgements

*Adopted: from "Analytic Hierarchy Process" by Thomas L. Saaty*

### 3.5.1 Weight Determination Procedure for Track Components

**Step 1:** *The criteria assessed that should be used to arrive at a decision.*

In this research case the criterion are the track components, component defect categories, and defects. The selecting of those Criteria has based upon literature survey on manual, standard, journal and research paper.

**Step 2:** *determine the most important, and the least important components.*

In this step, several factors such as structural integrity, durability, maintenance requirements, and Cost considered for evaluation of the track component. Safety Risk, Frequency of

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Occurrence, Cost of Repair, Potential for escalation and Criticality for the defect categories and defects.

The rail is a fundamental component of railroad tracks, carrying the weight of locomotives and ensuring uniform load distribution over sleepers. It aids in both lateral train movement and stability, contributing to the train's operational efficiency and providing smooth and comfortable movement. Additionally, it conducts electricity for power transmission and signal currents for efficient control and communication within the railway network. Due to its flexibility and adaptability, rail is considered the most important part of the railway track components.

The critical structural elements essential for rail track stability and safety, which include rails, rail-joints, sleepers, and fastening systems. These elements' failure can pose immediate safety risks. Ballast, while important for drainage and load distribution, is less critical and can be replaced without immediate track failure. Modern design innovations like under-sleeper pads have reduced ballast's importance. High-speed and urban rail systems often use slab tracks that eliminate the need for ballast. It is concluded that in light of recent studies, ballast is the least important among these track components.

**Step 3:** *Determine the preference of the best criterion over all the other criteria using a number between 1 and 9*

The evaluation aims to determine a preference value for the best and worst methods. This evaluation is based on a thorough literature review to ensure the validity and reliability of the chosen criteria.

After evaluating that criterion using Saaty's scale. I used average of the Saaty scale value of each criterion for a summarized component comparison. The comparison table presented in the following section serves as a sample to illustrate the methodology employed in the comparison highlighting the most Important component to other components detailed in the appendix section.

### **Comparison of the Most Importance Component to the Other Component**

In assessing the selected component in comparison to alternative components, I utilized the following criteria, as the basis for comparison. These criteria, derived from an extensive literature review, provide a structured perspective for evaluating the component .This

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

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approach aids in determining the preference value, which is grounded in a literature review of various criteria. It is applicable to all components.

- **Structural Integrity:** components to resist loads and external stresses without breaking down or deforming. This could include characteristics like the material's strength and stiffness.[61]
- **Durability:** This entry refers to the ability of the components to endure for long periods of time against wear, fatigue and also environmental factors [18].
- **Maintenance Requirements:** This criterion introduces complication and frequency of expected cavity component maintenance into consideration.
- **Cost:** This criterion also covers the overall cost of procurement: the first acquisition of those elements, installation, following maintenance and perhaps periodic renewals.
- **Safety:** This criterion is concerned with the risks involved in the use of the identified components and the general reliability of the Assembly, such as the possibility of failure or derailing.

In the comparison tables, the initial column enumerates the above criteria employed to assess the two components under comparison. The subsequent column offers a description of each criterion, drawing from the existing literature pertaining to the components. The final column presents the numerical values attributed to each criterion using the Saaty values by the researcher.

Comparing Rail to Rail joint to determine their preference value for the best worst pairwise comparison.

*Table 3.2 Comparison table of Rail to Rail Joint*

Criteria	Description	Designated value
Structural Integrity	The strength of a rail joint is about half the strength of a rail[38].	5
Durability	Rail exhibit high resistance to fatigue and wear are likely to have better durability[38], [44].	3
Maintenance Requirements	Due to the impact of the moving loads rail joint require frequent maintenance[33].	5

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Cost	The initial rail and rail joint is close but maintenance costs of a rail joint is higher[34].	4
Safety	rail joint signifies a possible risk of fish plate detachment, weld and rail breakage[33].	7
The mean value of the above comparison is <b>5</b>		

Therefore, the preference value for the comparison Rail to rail Joint is 5.

**Step 4:** Define the preferences of all criteria ( $j$ ) over the worst criterion  $W$

### Comparison of the Other Component to the Least Importance Component

The comparison table presented in the following section serves as a sample to illustrate the methodology employed in the comparison. The rest Pairwise value determination of the other component to ballast depicted in the appendix section

Table 3.3 Comparison table of Rail Joint to Ballast

Criteria	Description	Designated value
Structural Integrity	exhibits slightly higher structural integrity compared to ballast [33]	3
Durability	In terms of durability, both rail joints and ballast are essential components[34].	1
Maintenance Requirements	Rail joints require more frequent maintenance than ballast [14].	1
Cost	rail joints tend to have higher overall costs compared to ballast[14], [34].	1
Safety	Rail joints and welds are critical components of the track structure that can impact safety [33].	3
The mean value of the above comparison is <b>2</b>		

Therefore, the preference value for the comparison rail joint to ballast is 2.

**Step 5.** Search for the optimal solution

The optimal weight for the Component is the one where, for each pair of  $W_B / W_j$  and  $W_j / W_w$ , we have  $W_B/W_j = a_{Bj}$  and  $W_j / W_w = a_{jw}$ .

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In order to satisfy these conditions for all  $j$ , it is necessary to find a solution that minimizes the maximum absolute differences  $\left| \frac{W_B}{W_j} - a_{Bj} \right|$  and  $\left| \frac{W_j}{W_w} - a_{jw} \right|$  for all  $j$ . The absolute maximum value assigned as  $\xi$ . Therefore

$$\left| \frac{W_B}{W_j} - a_{Bj} \right| \leq \xi \quad \text{Equation 3-1}$$

$$\left| \frac{W_j}{W_w} - a_{jw} \right| \leq \xi \quad \text{Equation 3-2}$$

let assign weight of each track components as  $W_{\text{Rail}}$ ,  $W_{\text{Rail Joint}}$ ,  $W_{\text{Sleeper}}$ ,  $W_{\text{Ballast}}$  and  $W_{\text{Fastening system}}$  for Track Components as mentioned above the selected the most important is Rail and the least important one is ballast.

$W_B$  (weight of the most important) =  $W_{\text{Rail}}$ ,

$W_j$  (weight of the least important) =  $W_{\text{Ballast}}$

$$\left| W_{\text{Rail}} - a_{Bj} W_j \right| \leq \xi \quad \text{Equation 3-3}$$

$$\left| W_j - a_{jw} W_{\text{Ballast}} \right| \leq \xi \quad \text{Equation 3-4}$$

$$\sum W_j = 1 \quad \text{Equation 3-5}$$

$$W_j \geq 0 \quad \text{Equation 3-6}$$

the value of  $a_{Bj}$  (preference value of most important to others) and  $a_{jw}$  (preference value of others to the least important) collected from the comparison tables, including tables 3.2 and 3.3, along with additional tables from appendix 1 for each comparison of the components. The values are depicted in the table below

*Table 3.4 Comparison of The Most Important Track Component to other track components*

<b>Most important to Others</b>	Rail	Rail Joint	Sleeper	Ballast	Fastening System
<b>Rail</b>	1	5	3	6	5
<b>Source</b>	Similar Components	Table 3.2	Appendix I	Appendix I	Appendix I

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Table 3.5 Comparison of other track components to the least important track component

Others to the least important	Ballast	Source
Rail	6	Appendix I
Rail Joint	2	Table 3.3
Sleeper	6	Appendix I
Ballast	1	Similar Components
Fastening System	5	Appendix I

Weight Solving Model for Comparison of The Most Important Track component to Other

$$|W_{\text{Rail}} - 1W_{\text{Rail}}| \leq \xi \quad \text{Equation 3-7}$$

$$|W_{\text{Rail}} - 5W_{\text{Rail Joint}}| \leq \xi \quad \text{Equation 3-8}$$

$$|W_{\text{Rail}} - 3W_{\text{Sleeper}}| \leq \xi \quad \text{Equation 3-9}$$

$$|W_{\text{Rail}} - 6W_{\text{Ballast}}| \leq \xi \quad \text{Equation 3-10}$$

$$|W_{\text{Rail}} - 1W_{\text{Fastening System}}| \leq \xi \quad \text{Equation 3-11}$$

Weight Solving Model for Comparison of Other Track Components to The Least Important

$$|W_{\text{Rail}} - 6W_{\text{Ballast}}| \leq \xi \quad \text{Equation 3-12}$$

$$|W_{\text{Rail Joint}} - 2W_{\text{Ballast}}| \leq \xi \quad \text{Equation 3-13}$$

$$|W_{\text{Sleeper}} - 6W_{\text{Ballast}}| \leq \xi \quad \text{Equation 3-14}$$

$$|W_{\text{Ballast}} - 1W_{\text{Ballast}}| \leq \xi \quad \text{Equation 3-15}$$

$$|W_{\text{Fastening System}} - 5W_{\text{Ballast}}| \leq \xi \quad \text{Equation 3-16}$$

$$|W_{\text{Rail}} + W_{\text{Rail joint}} + W_{\text{Sleeper}} + W_{\text{Fastening System}} + W_{\text{Ballast}}| = 1 \quad \text{Equation 3-17}$$

Values of Equation 3-7 and Equation 3-15 are zero. by solving the above linear equation the value of each component weight can be determined. An Excel program developed by Jafar Rezaei was utilized to solve the model, with the resulting output weights as illustrated below.

Table 3.6 Weight of track components from Excel

Components	Rail	Rail Joint	Sleeper	Ballast	Fastening System
Weights	0.48157895	0.12631579	0.21052632	0.05526316	0.12631579

### **3.6 Weight Determination for Rail Defect Categories and Defects**

In assessing the selected Defect Categories and Defects in comparison to alternative Defect Categories and Defects, I utilized the following criteria. This approach aids in determining the preference value, which is grounded in a literature review of various criteria. It is applicable to all Defect Categories and Defects.

- **Safety Risk:** The potential safety risk or threat that the identified defect category presents towards safety such as potential for accidents, injuries, or any kind of safety danger.
- **Frequency of Occurrence:** The rate of occurrence of defects within the category, which is useful in established whether or not the category is a significant problem for the company overall.
- **Cost of Repair:** The expenses that went into fixing defects within the named category, in terms of cost of materials used, manpower and other costs that the damages would have been likely to cause a dent on the company's revenues.
- **Potential for escalation:** The possibility of obtaining defects which if not addressed appropriately may reach more dangerous levels.
- **Criticality:** The criticality of defects within the category to the overall operation and safety of the rail system. Defects that are deemed critical should be prioritized for immediate attention and resolution.

#### **3.6.1 Weight Determination for Rail Defect Categories**

**Step 1:** *The criteria assessed that should be used to arrive at a decision*

Rail defects can arise in various types of rails or rail welds due to a combination of factors [38], [39], [40]. These factors typically stem from the rail manufacturing process, cyclical loading, and the impact caused by rolling stock, rail wear, and plastic flow [40], [62].

**Step 2:** *determine the most important, and the least important criteria.*

##### **1. Rail Defect Categories**

The classification of rail defects was established by conducting a comprehensive review of literature from AREMA, UIC, and RailCorp Network Rail. The defects categories has been arranged into listed below.

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▪ Rail Head Defects	▪ Rail base Defects
▪ Rail Surface Defect	▪ Rail Wear
▪ Rail web Defects	▪ Rail Buckling

Rail head defects are the most critical due to their high safety risks, frequency, cost of repair, and potential for worsening, leading to severe impacts like rail breaks, derailments, and accidents.

Rail wear would thus be fixed and solved through careful monitoring of the structures and key maintenance processes to avoid future safety disasters.

**Step 3:** *Determine the preference of the best criterion over all the other criteria using a number between 1 and 9*

The evaluation aims to determine a preference value for the best and worst methods. This evaluation is based on a thorough literature review to ensure the validity and reliability of the chosen criteria.

After evaluating that criterion using Saaty's scale. I used average of the Saaty scale value of each criterion for a summarized component comparison. The comparison table presented in the following section serves as a sample to illustrate the methodology employed in the comparison highlighting the most Important component to other components detailed in the appendix section.

### **Comparison of the Most Importance Rail Defect category to the Other Rail Defect category**

In the comparison tables, the initial column enumerates the five criteria employed to assess the two components under comparison. The subsequent column offers a description of each criterion, drawing from the existing literature pertaining to the components. The final column presents the numerical values attributed to each criterion using the Saaty's scale by the researcher.

*Table 3.7 Comparison of Rail Head defect to Rail Surface Defect*

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Criteria	Description	Designated value
Safety Risk	Rail head defects bear even more danger since they may cause derailment. While rail surface defects essence of the problem is somewhat less severe in comparison[26].	6
Frequency of Occurrence	Rail head defects; however, they develop less often as compared to rail surface defects. [41],[42].	1
Cost of Repair	In some cases, repairing rail head defects can be even more expensive since it need for advanced tools [26].	1
Potential for Escalation	rail head defects progressing to a more severe level such as broken rails or track failures that bring about catastrophic consequences[33], [34].	5
Criticality	Rail head defects are sensitive components if the rail system, impacting on the efficiency and availability of the network [33], [37].	6
The mean value of the above comparison is 4		

Therefore, the preference value for the comparison Rail head defects to rail surface defects 4. The determination of pairwise values for the remaining Rail head defects to other rail defect categories is detailed in the appendix.

**Step 4:** Define the preferences of all criteria (j) over the Least Important criterion W

### Comparison of Other Rail Defect category to Least Importance Rail Defect category

Table 3.8 Comparison of Rail web defects to Rail Wear

Criteria	Description	Designated value
Safety Risk	Rail web defects can result a sudden rail failures. Rail wear does not contribute immediate derailment[39].	6

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Frequency of Occurrence	The web defects are though not quite as common with the rail as the rail wear since they are often due to stress factors.  While rail wear is predictable wear caused by regular train operations.it is a more severe process and occurs more frequently[38][42].	5
Cost of Repair	Rails web defects need to be remediated by an immediate replacement or welding that incurs high expenses both in material and labor. [36], [40].	1
Potential for Escalation	A rail web defect has a high potential for escalation.Rail wear escalates more slowly [39].	4
Criticality	The criticality of rail wear lies in its pervasive impact on track quality and train operations over time[33].	5
The mean value of the above comparison is 4		

Therefore, the preference value for the comparison Rail web defects to Rail Wear is 4.

### Step 5. Search for the optimal solution

The optimal weight for the each defect and defect categories is determine by applying the same method used to find the weight of track components.as a sample a determination the weight of rail defect categories shown below.

let assign weight of each rail defect categories as  $W_{\text{Rail Head Defect}}$ ,  $W_{\text{Rail Surface Defect}}$ ,  $W_{\text{Rail Web Defect}}$ ,  $W_{\text{Rail Base Defects}}$ ,  $W_{\text{Rail Wear}}$   $W_{\text{Rail Buckling}}$  . for Rail Defect categories as mentioned above the selected the most important is Rail Head Defect and the least important one is Rail Wear.

$$W_B \text{ (weight of the most important)} = W_{\text{Rail Head Defect}}$$

$$W_w \text{ (weight of the least important)} = W_{\text{Rail Wear}}$$

$$|W_{\text{Rail Head Defect}} - a_{Bj}W_j| \leq \xi \quad \text{Equation 3-18}$$

$$|W_j - a_{jW}W_{\text{Rail Wear}}| \leq \xi \quad \text{Equation 3-19}$$

From the comparison tables the value of  $a_{Bj}$  and  $a_{jW}$  collect for each comparison of the components. The value is depicted in the table below.

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Table 3.9 Comparison of The Most Important Rail Defect Category to Other Rail Defect Category

<b>Best to Others</b>	Rail Head Defects	Rail Surface Defects	Rail web Defects	Rail base Defects	Rail Wear	Rail Buckling
<b>Rail Head Defects</b>	1	4	5	6	7	3
<b>source</b>	Similar Defects	Table 3.7	appendix	appendix	appendix	appendix

Table 3.10 Comparison of Other Rail Defect Category to The Least Important Rail Defect Category

<b>Others to the Worst</b>	<b>Rail Wear</b>	<b>Source</b>
Rail Head Defects	7	appendix
Rail Surface Defects	4	appendix
Rail web Defects	4	Table 3.8
Rail base Defects	3	Similar Defects
Rail Wear	1	appendix
Rail Buckling	6	appendix

Solving Model for Comparison of The Most Important Rail Defect Category to Other Rail

$$|W_{Rail\ Head\ Defect} - 1W_{Rail\ Head\ Defect}| \leq \xi \quad \text{Equation 3-20}$$

$$|W_{Rail\ Head\ Defect} - 4W_{Rail\ Surface\ Defect}| \leq \xi \quad \text{Equation 3-21}$$

$$|W_{Rail\ Head\ Defect} - 5W_{Rail\ Web\ Defect}| \leq \xi \quad \text{Equation 3-22}$$

$$|W_{Rail\ Head\ Defect} - 6W_{Rail\ Base\ Defect}| \leq \xi \quad \text{Equation 3-23}$$

$$|W_{Rail\ Head\ Defect} - 7W_{Rail\ Wear}| \leq \xi \quad \text{Equation 3-24}$$

$$|W_{Rail\ Head\ Defect} - 3W_{Rail\ Buckling}| \leq \xi \quad \text{Equation 3-25}$$

Solving Model for Comparison of Other Rail Defect Category to The Least Important

$$|W_{Rail\ Head\ Defect} - 7W_{Rail\ Wear}| \leq \xi \quad \text{Equation 3-26}$$

$$|W_{Rail\ Surface\ Defect} - 4W_{Rail\ Wear}| \leq \xi \quad \text{Equation 3-27}$$

$$|W_{Rail\ Web\ Defect} - 4W_{Rail\ Wear}| \leq \xi \quad \text{Equation 3-28}$$

$$|W_{Rail\ Base\ Defect} - 3W_{Rail\ Wear}| \leq \xi \quad \text{Equation 3-29}$$

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$$|W_{Rail\ Wear} - 1W_{Rail\ Wear}| \leq \xi \quad \text{Equation 3-30}$$

$$|W_{Rail\ Buckling} - 6W_{Rail\ Wear}| \leq \xi \quad \text{Equation 3-31}$$

$$|W_{Rail\ Head\ Defect} + W_{Rail\ Surface\ Defect} + W_{Rail\ Web\ Defect} + W_{Rail\ Base\ Defect} + W_{Rail\ Wear} + W_{Rail\ Buckling}| = 1 \quad \text{Equation 3-32}$$

Equation 3-20 and Equation 3-30 are zero. In similar manner as track component by with solving the above linear equation Model the value of each component defect's weight can be determined. To solve the model Excel program developed by Jafar Rezaei has been utilized. The output weight results are:

*Table 3.11 weight of Rail Defect categories from Excel*

Components	Rail Head Defects	Rail Surface Defects	Rail web Defects	Rail base Defects	Rail Wear	Rail Buckling
<b>Weights</b>	0.4374703	0.1355207	0.108417	0.09034712	0.04755112	0.18069425

### 3.6.2 Weight Determination for Rail Defect

Rail Head Defects

**Step 1:** *The criteria assessed that should be used to arrive at a decision*

are any progressive fractures occurring in the head of a rail and have a transverse separation, however slight [36], [39]. Rail head Defects has been listed below.

- *Transverse break without apparent origin*
- *Detail Fracture*
- *Transverse Fissure*
- *Compound fissure*
- *Horizontal Split Head*
- *Vertical split Head*

**Step 2:** *determine the most important, and the least important criteria.*

the most important rail head defect is Transverse Fissure due to a high safety risk. Transverse fissures are difficult to detect and often lead to sudden and catastrophic rail failures, posing serious safety concerns. If not promptly addressed, these defects can escalate and result in significant accidents. Repair costs are high due to the need for rail replacement, making preventative measures critical.

In contrast, the least important defect is Detail Fracture. when all defining factors are taken into consideration. Still it may not pose as high an inherent threat to the safety of a structure under

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construction or renovation as compared to others. Detail Fractures are likely to be identified at an early stage owing to the routine examination carried out prior to the worsening of the situation.

**Step 3:** *Determine the preference of the best criterion over all the other criteria using a number between 1 and 9*

### Comparison of the Most Importance Rail Head Defect to the Other Rail Head Defect

In the comparison tables, the initial column enumerates the five criteria employed to assess the two Defects under comparison. The subsequent column offers a description of each criterion, drawing from the existing literature pertaining to the Defects. The final column presents the numerical values attributed to each criterion using the Saaty scale values assigned by the researcher.

*Table 3.12 Comparison table of transverse Fissure to Compound Fissure*

Criteria	Description	Designated value
Safety Risk	Transverse Fissure Defects are serious and can lead to catastrophic failure[42], [63].	2
Frequency of Occurrence	Transverse Fissure Defects is Less common than of defects[52].	4
Cost of Repair	Repairing a Compound Fissure costs about the same as a Transverse Fissure[37], [63].	1
Potential for Escalation	[37], [43]	1
Criticality	Transverse Fissure might be considered more critical[62][61].	2
The mean value of the above comparison is 2		

Therefore, the preference value for the comparison Transverse Fissure to Compound Fissure is 2.

**Step 4:** *Define the preferences of all criteria (j) over the worst criterion W*

### Comparison of Other Rail Head Defect to Least Importance Rail Head Defect

*Table 3.13 Comparison table of Horizontal Split Head to Detail Fracture*

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Criteria	Description	Designated value
Safety Risk	Horizontal split heads can lead to rail breakage[47].	3
Frequency of Occurrence	Vertical and horizontal split heads are less frequent[64].	1
Cost of Repair	Repairing of Detail Fractures is more critical[41], [42].	1
Potential for Escalation	Horizontal split head are severe threatening defects that can cause potential for escalation[64], [65].	8
Criticality	[61], [65]	3
The mean value of the above comparison is 3		

Therefore, the preference value for the comparison Horizontal Split Head to Detail Fracture is 2.

### Step 5: Search for the optimal solution

The optimal weight for the each defect and defect is determine by applying the same method used to find the weight of track components as well as rail defect categories.as a sample a determination the weight of rail head defect shown below.

let assign weight of each rail head defect as  $W_{\text{Transverse break without apparent origin}}$ ,  $W_{\text{Compound fissure}}$ ,  $W_{\text{Detail Fracture}}$ ,  $W_{\text{Transverse Fissure}}$ ,  $W_{\text{Horizontal Split Head}}$   $W_{\text{Horizontal Split Head}}$ . for Rail Head Defect s as mentioned above the selected the most important Rail Head Defect is Transverse Fissure and the least important one is Detail Fracture.

$$W_B (\text{weight of the most important}) = W_{\text{Transverse Fissure}},$$

$$W_w (\text{weight of the least important}) = W_{\text{Detail Fracture}}$$

$$|W_{\text{Transverse Fissure}} - a_{Bj}W_j| \leq \xi \quad \text{Equation 3-33}$$

$$|W_j - a_{jw}W_{\text{Detail Fracture}}| \leq \xi \quad \text{Equation 3-34}$$

From the comparison tables the value of  $a_{Bj}$  and  $a_{jw}$  collect for each comparison of the rail head defect. The value is depicted in the table below.

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Table 3.14 Comparison of The Most Important Rail head Defect to Other Rail head Defect

<b>Best to Others</b>	Transverse break without apparent origin	Detail Fracture	Transverse Fissure	Compound fissure	Horizontal Split Head	Vertical split Head
<b>Transverse Fissure</b>	2	7	1	2	5	6
<b>Source</b>	appendix	appendix	Similar Defects	Table 3.12	appendix	appendix

Table 3.15 Comparison of Other Rail Head Defect to The Least Important Rail Head Defect

<b>Others to the Worst</b>	<b>Detail Fracture</b>	<b>Source</b>
Transverse break without apparent origin	5	appendix
Detail Fracture	1	Similar Defect
Transverse Fissure	7	appendix
Compound fissure	5	appendix
Horizontal Split Head	3	Table 3.13
Vertical split Head	4	appendix

Solving Model for Comparison of The Most Important Rail Head Defect to Other Rail

$$|W_{\text{Transverse Fissure}} - 1W_{\text{Transverse Fissure}}| \leq \xi \quad \text{Equation 3-35}$$

$$|W_{\text{Transverse Fissure}} - 2W_{\text{Transverse break without apparent origin}}| \leq \xi \quad \text{Equation 3-36}$$

$$|W_{\text{Transverse Fissure}} - 2W_{\text{Compound Fissure}}| \leq \xi \quad \text{Equation 3-37}$$

$$|W_{\text{Transverse Fissure}} - 7W_{\text{Detail Fracture}}| \leq \xi \quad \text{Equation 3-38}$$

$$|W_{\text{Transverse Fissure}} - 5W_{\text{Horizontal Split Head}}| \leq \xi \quad \text{Equation 3-39}$$

$$|W_{\text{Transverse Fissure}} - 6W_{\text{Vertical split Head}}| \leq \xi \quad \text{Equation 3-40}$$

Solving Model for Comparison of Other Rail Head Defect to The Least Important

$$|W_{\text{Transverse Fissure}} - 7W_{\text{Detail Fracture}}| \leq \xi \quad \text{Equation 3-41}$$

$$|W_{\text{Transverse break without apparent origin}} - 5W_{\text{Detail Fracture}}| \leq \xi \quad \text{Equation 3-42}$$

$$|W_{\text{Compound Fissure}} - 5W_{\text{Detail Fracture}}| \leq \xi \quad \text{Equation 3-43}$$

$$|W_{\text{Detail Fracture}} - 1W_{\text{Detail Fracture}}| \leq \xi \quad \text{Equation 3-44}$$

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$$|W_{\text{Horizontal Split Head}} - 3W_{\text{Detail Fracture}}| \leq \xi \quad \text{Equation 3-45}$$

$$|W_{\text{Vertical Split Head}} - 4W_{\text{Detail Fracture}}| \leq \xi \quad \text{Equation 3-46}$$

$$|W_{\text{Transverse Fissure}} + W_{\text{Transverse break without apparent origin}} + 1W_{\text{Detail Fracture}} + W_{\text{Compound Fissure}} + W_{\text{Horizontal Split Head}} + W_{\text{Vertical Split Head}}| = 1 \quad \text{Equation 3-47}$$

Equation 3-35 and Equation 3-44 are zero. In similar manner as track component and rail head defect by with solving the above linear equation Model the value of each defect's weight can be determined. To solve the model Excel program developed by Jafar Rezaei has been utilized.

### 3.7 Other Defect Categories and Defects

In a similar approach as applied to track components, rail defect categories and rail head defect as for the remaining defect Categories and defect such as Rail Surface Defects, Rail Web Defects, Rail Base Defects, Rail Wear, Rail Joints, Sleepers, Ballast, and Fastening Systems were also analyzed. To avoid redundancy and maintain conciseness, the first two steps of the Best Worst Method (BWM) selecting the most and least important defects are summarized in Table 3.14. The remaining steps in the weight determination process are detailed in the appendix. Each defect category and defect was assessed for its significance based on key factors such as safety risks, frequency of occurrence, and potential for escalation.

For example, Head Checks in rail surface defects are highlighted as a significant risk because they can evolve into cracks, potentially causing rail breaks and derailments. In contrast, Corrugation, which affects ride quality but poses less of a safety risk, is considered a lower priority. Similarly, Head and Web Separation in rail web defects and Broken Base in rail base defects are classified as critical due to their direct impact on rail safety. On the other hand, Corrosion in the web and Base Corrosion in the base are deemed less urgent, though still requiring attention.

In Rail Wear, Head Loss Max Percentage is noted as critical for maintaining train stability, while Tangent Wear, which progresses more slowly, is seen as less urgent. Rail Weld Defects, specifically Transverse Cracking, are identified as a high-priority issue in rail joints, while Fish-Plated Joint Defects such as Loose Fish Bolts are considered less significant.

Defects in Ballast, such as Ballast Fouling, are considered critical due to their potential to destabilize tracks, whereas Vegetation Growth is seen as a lower priority. Finally, in Fastening

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Systems, Broken Fasteners are highlighted as high-priority due to their association with derailments, while Severely Worn Pads are noted as less urgent.

*Table 3.16 List of Most Important and Least Important Defect Categories and Defects*

Component and Defect Category	Most Important Defect	Least Important Defect
Rail Surface	Head Checks	Corrugation
Rail Web	Head and Web Separation	Corrosion
Rail Base	Broken Base	Base Corrosion
Rail Wear	Head Loss Max Percentage	Tangent Wear
Rail Joints Defect Categories	Rail Weld Defects	Fish-Plated Rail Joint Defects
Fish-Plated Rail Joint	Fish Plate Cracks	Loose Fish Bolts
Rail Weld	Transverse Cracking	horizontal cracking of the web
Sleepers	Sleeper Breakage Due to Derailments	Sleeper Spacing
Ballast Defect Categories	Ballast Drainage	Ballast Profile
Ballast Drainage	Ballast Fouling	Vegetation Growth
Ballast Profile	Ballast Deficiency	Excess Ballast
Fastening System	Broken Fasteners	Severely Worn Pads

this prioritization of defects across various components, derived using the second steps of BWM, ensures that resources are directed toward addressing the most critical issues that pose the highest safety risks. The remaining steps for weight determination and further analysis are detailed in the appendix.

### 3.8 Defect Severities

Defect severity is a crucial factor in the process of model development. It signifies the degree to which a defect impacts a component or the entire system. To accurately define defect severities, an extensive review of various sources, including reputable online materials, manual and journals has been conducted. The defect severity grading scale, as well as the defect severities utilized in this study, have been taken from an Australian manual called Track

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Inspection TMC 203 [26] and TMC 224 Rail Defects and Testing [27]. According to [26] All defects are classified into one of six standard defect categories as outlined below.

*Table 3.17 Railway Track Defects Severity Levels*

<b>Response Category</b>	<b>Inspect and verify response</b>	<b>Action</b>
Emergency 1 (E1)	Prior to passage of next train	Prior to passage of next train
Emergency 2 (E2)	Within 2 hours or before the next train, whichever is the greater	Within 24 hours
Priority 1 (P1)	Within 24 hrs	Within 7 days
Priority 2 (P2)	Within 7 days	Within 28 days
Priority 3 (P3)	Within 28 days	Program for repair
Normal (N)	Nil	Routine inspection

Note: *adopted from Track Inspection TMC 203[43]*

To effectively categorize and assess the severity of railway track defects, it is essential to reference established guidelines and manuals such as the AREMA Manual for Railway Engineering, the Federal Railroad Administration (FRA) standards, Track Inspection TMC 203[43], and TMC 224 Rail Defects and Testing [72]. Based on these sources, defect severity tables have prepared. The table depicted below illustrates the severity of each defect identified in this research. Predominantly, the severity tables have adopted defects severity from Track Inspection TMC 203 [43] and TMC 224 Rail Defects and Testing [72], with additional insights from other manuals and research studies.

The Severity tables are primarily designed for types of tracks according to the specific speed classifications set by the International Union of Railways (UIC), only including Class I (80-120 km/h) and the Chinese National Railway Class 2 Standard. the rest of the table depicted in the appendix.

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

Table 3.18 Rails Head Defects Severities

Component	Defects Categories	Defects	N	P3	P2	P1	E2	E1
Rails	Rail Head defects	Transverse break without apparent origin						Stop trains if necessary and replace broken rail ASP
		Detail Fracture			Growth in rail head <15%		Growth in rail head 20%-40%	Growth in rail head 40%-60%
		Transverse Fissure			Growth in rail head <3 %	Growth in rail head between 3-10 % (40mm-56mm)	Growth in rail head between 11-30 % (57mm-90mm)	Growth in rail head >30 % (over 90mm)
		Compound fissure			Growth in rail head 4.9% or less (40mm-56mm)	Growth in rail head 30-35% (57mm-90mm)		Growth in rail head > 35% (over 90mm)

### 3.8.1 Defect Severity Quantification

This model uses fuzzy membership functions to translate the grading scales of the linguistic condition assessment into numerical values and standardize different defect criteria. An object class having a continuum of membership grades is called a fuzzy set. An item in this set is assigned a membership grade, which is a number between zero and one, using a membership (characteristic) function. Fuzzy sets theory is an extension of classical set theory [58], [66]. The membership function in fuzzy sets serves as an extension of the indicator function found in classical sets [58], [60]. Let us consider the fuzzy set  $A = \{(x, \mu_A(x)) \mid \forall x \in X\}$  where the membership function for the fuzzy set  $A$  is denoted by  $\mu_A(x)$ . The universe of discourse is called  $X$ . Every element  $X$  in the interval  $[0, 1]$  is assigned a value by the membership function. There are different shapes of membership functions[66].

- Triangular membership function
- Trapezoidal membership function
- Gaussian membership function
- Generalized bell membership function
- Sigmoid membership function

Membership functions may be selected by users based on their individual experiences, perspectives, and other factors [60]. Membership functions can also be created through the utilization of machine learning techniques such as artificial neural networks or genetic algorithms. In this study a Gaussian Membership functions selected to characterize fuzziness of the linguistic grading scales [66]. Gaussian functions capture gradual uncertainty, while triangular and trapezoidal functions serve specific purposes, Gaussian functions are preferred in fuzzy logic systems due to their smoothness and symmetry, effective noise handling, mathematical elegance, and flexibility. Their bell-shaped curves allow for continuous transitions, and their robust nature makes them suitable for handling imprecise data. Gaussian functions are also easily adjustable through mean and standard deviation parameters, which supports versatile modeling.

Gaussian Membership functions

$$\mu(x, c, s, m) = \exp \left[ -\frac{1}{2} \left| \frac{x-c}{s} \right|^m \right] \quad \text{Equation 3-48}$$

c: centres:

s: width          m: fuzzification factor

The quantification model for assessing severities has been outlined in the subsequent steps:

**Step 1:** Severity grades, or condition assessment grades, are defined as fuzzy sets, which are subsets of the discourse universe. The input space that includes all possible values that can be assigned to each defect severity is referred to as the universe of discourse. The discourse universe in the built model has an index of 0 to 10.

**Step 2:** The defect severities have been determined based on the Australian Manuals. As a result, the model that has been created incorporates six condition categories in order to align with the standards set by Australia Standard. The condition categories are normal priority 3, priority 2, priority 1, emergency 2 and emergency 1.

**Step 3:** Fuzzy sets are used to represent each linguistic term in the defect severities, and severity quantification is carried out based on the analysis of the defect severities. The fuzzification process in this case involves categorizing the six severity levels into overlapping bins on a 0–10 grading scale. In order to quantify the inherent uncertainty related to railway component inspection, each Gaussian fuzzy Function is required to overlap with its neighboring fuzzy sets. Literatures suggests that an overlap between 25% and 50% of the fuzzy set base can provide a useful indicator of the impreciseness and vagueness [67]; this recommendation has been included in the current study investigation.

$$N = \{(0,2.5)\} \quad P3 = \{(1,5)\} \quad P2 = \{(3,6.5)\} \quad P1 = \{(5,8)\} \quad E2 = \{(6.5,9.5)\} \quad E1 = \{(0,2.5)\}$$

For Normal (N) Response Category

$$c=1.25 \quad s=2.5 \quad m=2$$

$$\mu(x, c, s, m) = \exp \left[ -\frac{1}{2} \left| \frac{x-1.25}{2.5} \right|^2 \right]$$

**Step 4:** Defuzzification is carried out in order to obtain a final score that can be applied to the evaluation of railway components, defect categories, and defects themselves. The developed model converts the fuzzy number into an exact numerical value using the an integration technique.

Defuzzification of the above function

$$\mu(x, c, s, m) = \exp \left[ -\frac{1}{2} \left| \frac{x-1.25}{2.5} \right|^2 \right]$$

$$\text{Defuzzified value} = \frac{\int_{x_1}^{x_2} x \mu(x, c, s, m) dx}{\int_{x_1}^{x_2} \mu(x, c, s, m) dx} \quad \text{Equation 3-49} \quad = \frac{\int_0^{2.5} x e^{\left[ -\frac{1}{2} \left| \frac{x-1.25}{2.5} \right|^2 \right]} dx}{\int_0^{2.5} \mu(x, c, s, m) dx} = 1.251$$

### 3.9 Development of Structural Condition Assessment Model

The Weighted Sum Mean Technique is employed as a comprehensive aggregation method is employed in the construction of the condition assessment model. The two main input sets, which are the weights and the defects severities, are defined first. These sets are then combined using the Weighted Sum to yield the desired condition. To efficiently determine the condition, a sequence of steps is employed to apply the best-worst technique.

1. Each defect's corresponding weights and severities are collected and arranged.
2. The condition's first phase includes the defect condition, which is the result of combining the defect weight and its corresponding severity. The 40 defects will be given a total of 40 condition ratings.

$$V_{Defect} = \sum_{j=1}^n W_j P_{ij} \quad \text{Equation 3-50}$$

$$W_j \geq 0, = \sum W_j = 1$$

$P_{ij}$  represents a performance matrix that comprises scores collected from tables through the inspection of each track component. The table is prepared in accordance with the TMC severity scale, and subsequently, it is converted into a crisp value using the table.

3. The second level of condition is represented by the defect category condition. It results from combining all of the defect condition ratings into one category. Some components don't have defect categories, so the defect is combined with the component itself in some cases. The weight assigned to each defect is combined with its severity at this stage.
4. The component's condition is determined by adding together the conditions of all related defect categories. The defects in sleeper and fastening system cases. At this point, the defect category's weight and its prior step's condition are combined.
5. The final phase of condition assessment is about the overall state of the Track Structure, which is based on the status of all of its constituent parts taken together.

## **CHAPTER FOUR**

### **RESULT AND DISCUSSION**

#### **4.1 Introduction**

The purpose of this section is to present and analyze the findings and implications of the study carried out to improve the structural condition assessment of railroad tracks. The main findings drawn from the application of a multi-criteria decision-making methods will be carefully reviewed in this section, offering insights into the efficacy and possible uses of this strategy. This section first presents the built-up defect hierarchy of the structural components of the railways along with their defects. The weights of relative importance are then presented. Defect categories, components, and defects are all included in the relative weights. Furthermore, the evaluation scale for condition grading and the levels of defect severity are illustrated.

#### **4.2 Weight**

Using the previously mentioned defect hierarchies, this study applies the Best worst Method (BWM) to determine the relative significance weights of the components, defect categories, and defects. This analysis considers the average outcome of comparing each component, defect categories, and defects determined by a review of the literature. Based on the three levels hierarchy, three weight levels are discovered. Component weights, defect category weights, and defect weights make up the first level.

##### **4.2.1 Track Component weights**

According to the component weights analysis, the rails weigh the most (48.16%) followed by the sleepers (21.05%), rail joints (12.63%), fastening system (12.63%), and ballast (5.5%), which is the component with the lowest weight. The weight results obtained from this model show a distinct difference from the outcomes of the model by Laith El-Khateeb (2017). Specifically, the El-Khateeb model generally considers the entire track infrastructure, including both track geometry and track structure. In contrast, this model focuses solely on the track structure. As a result, some part of the weight impact in the El-Khateeb model is

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influenced by the inclusion of track geometry, leading to differences in the results between the two models.

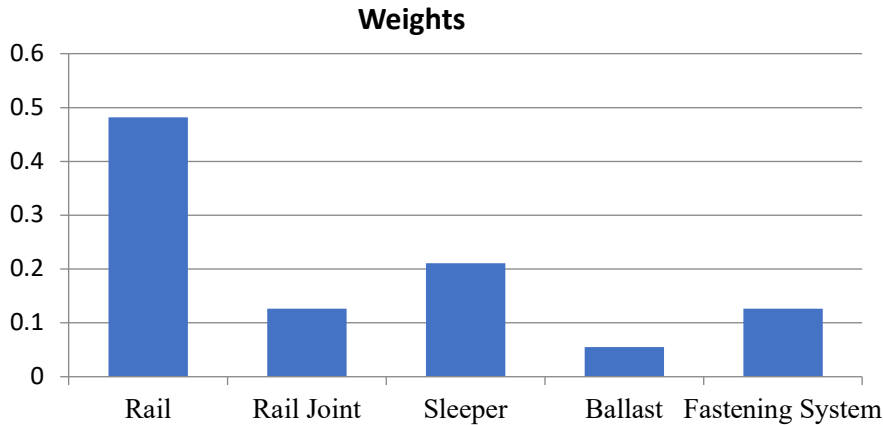


Figure 4.1 Weight of Track Components

### 4.2.2 Defect categories Weights

With regard to the rail defect categories weights, rail head defects in the rails account for 43.7% of the total weight. Rail Wear have the lowest weight (4.8%), Rail surface defects, Rail web Defects, Rail base defects have the weight (13.6%), (10.8%), (9.0%) respectively, while Rail Buckling come in second place with a weight of 18.1%.

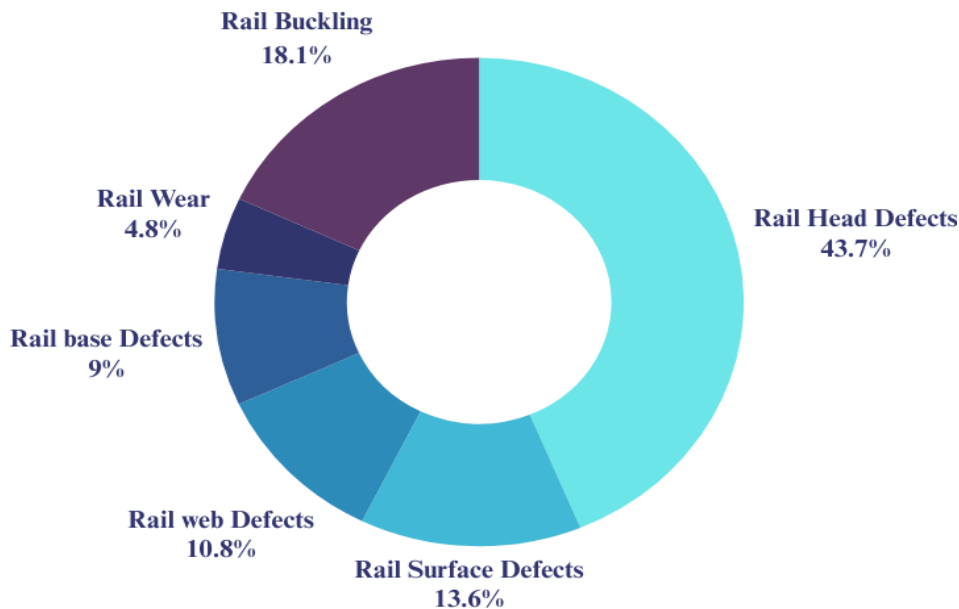


Figure 4.2 Weight of Rail Defect Category

Rail weld defects outweigh fish-plated rail joint defects, making up 66.67% and 33.33% of the total weight, respectively, according to the analysis of the rail joint categories weight

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extraction. Ballast Drainage Defects hold 80% of the weight in the assessment of ballast defect categories, while Ballast Profile Defects hold 20% of the weight.

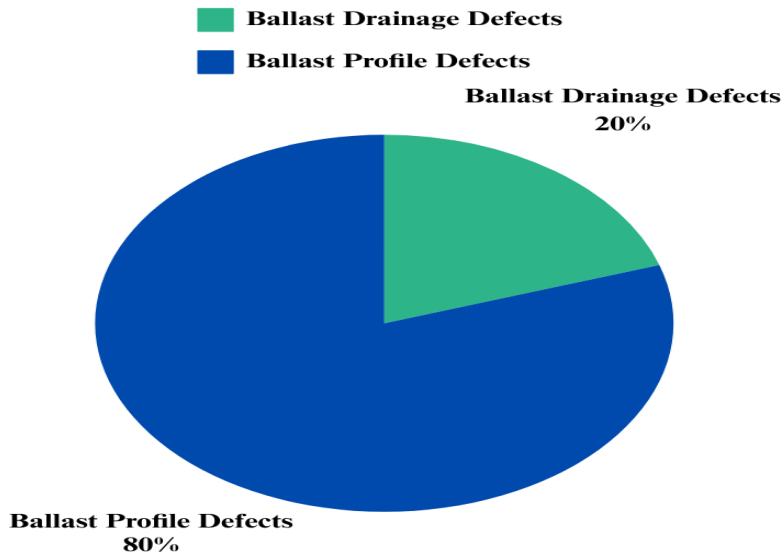


Figure 4.3 Ballast Defect categories weight

### 4.2.3 Rail Defect categories Weights

The Transverse Fissure is the most significant defect in the rail head classification, with 35.8% of the total weight. Transverse fissures are among the most severe types of defects, and this allocation makes sense. Similarly, Transverse Breaks without apparent origin and Compound Fissures are also categorized as detrimental defects. However, their weightage is comparatively lower due to factors such as their infrequent occurrence. With a weight of 3.92%, Detailed Fracture has the least weight.

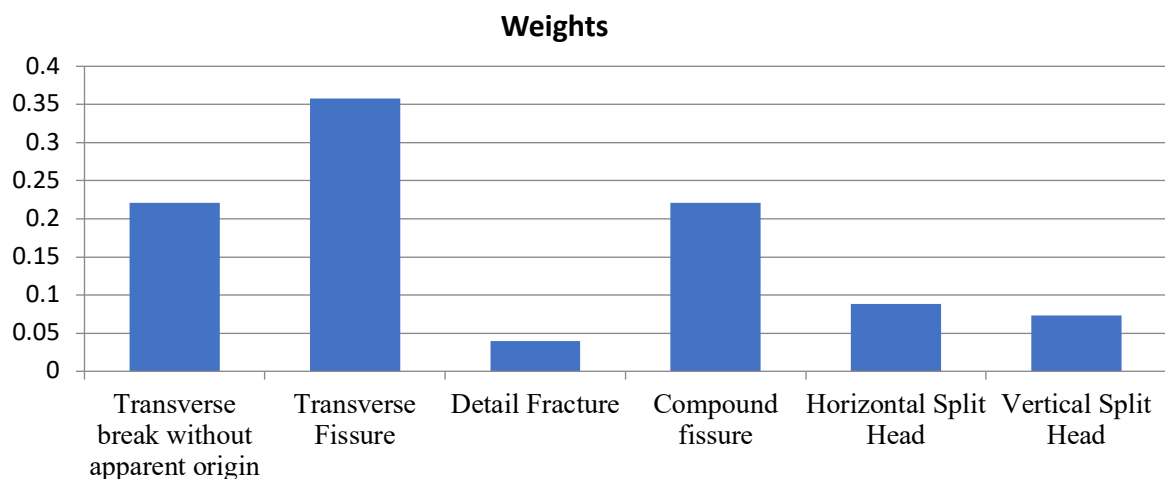
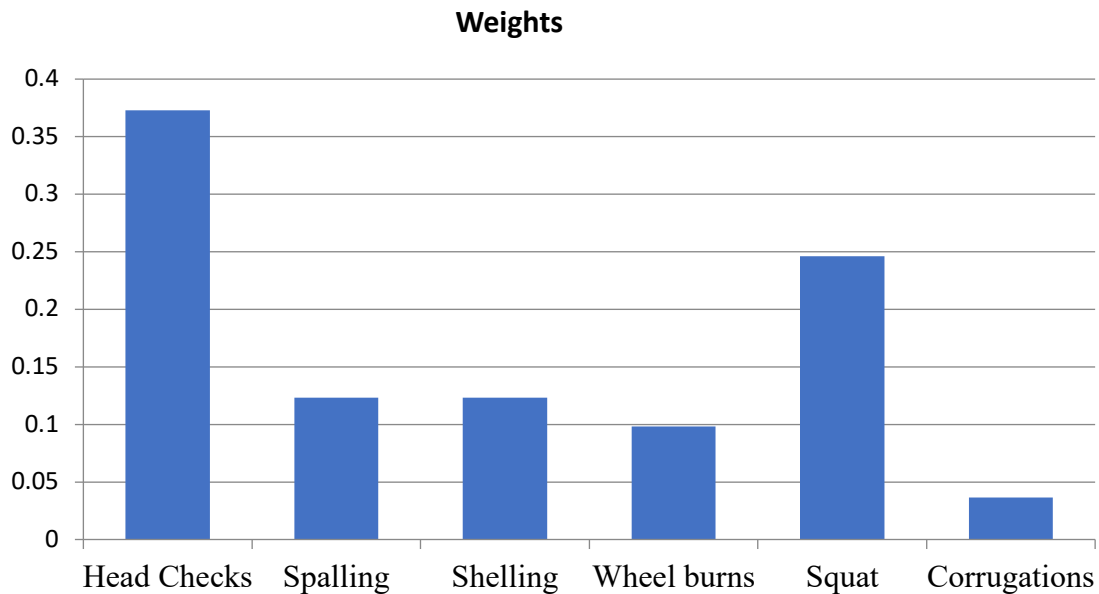


Figure 4.4 Weight of Rail Head Defects

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According to the analysis, head checks account for the highest weight at 37.31% in the rail surface defects category. This finding is logical as head checks are considered more severe. Similarly, squat is also identified as more severe than other defects, thus it holds the second highest weight at 24.61%. Spalling and shelling are equally weighted at 12.31%. Wheel burn is assigned a weight of 9.85%. The defect with the lowest weight is corrugation, which is at 3.63%.



*Figure 4.5 Weight of Rail Surface Defects*

In the category of rail web defects, the most significant weight of 64.67% is assigned to head and web separation due to its elevated safety risk and increased likelihood of causing more severe problems. On the other hand, broken base defects are assigned a relatively higher weight of 85.71% compared to base corrosion, which only receives a weight of 14.29%, in the rail base defect category. Curve wear, however, has the highest weight 58.93%. This result makes sense because curve defects are typically more severe than those found in tangent areas. Fish-Plated rail joint defects are less prevalent than rail weld defects, with a distribution of 33.33% and 66.67%, respectively. At 58.96%, sleeper breakage due to derailments is the reason for the greatest proportion of sleeper defects.

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

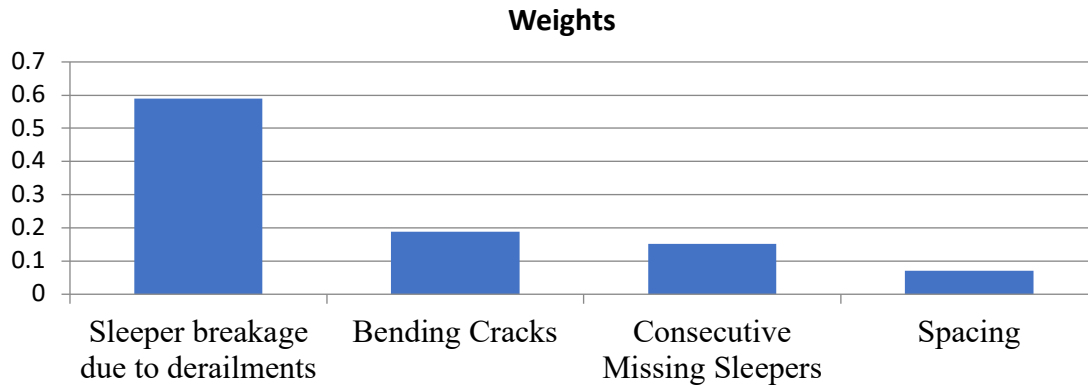


Figure 4.6 Weight of Sleeper Defects

Drainage defects possess a higher weight (80%) than Ballast Profile Defects (20%), according to the analysis of ballast weight extraction. The fouling defect, at 65.46%, is more severe than other drainage defects, suggesting that vegetation is less effective than fine materials at obstructing the ballast's ability to drain. Additionally, the study demonstrates that in terms of ballast profile defects, ballast deficiency (83.33%) is more significant than ballast excess (16.67%). Broken fasteners weigh the most out of all the flaws in the fastening system.

Table 4.1 Summary of The Weight Distributions

Component	$W_C$	Defects Categories	$W_{Dc}$	Defects	$W_d$
Rails	48.16%	Rail Head Defects	43.75%	Transverse break without apparent origin	22.06%
				Detail Fracture	3.92%
				Transverse Fissure	35.78%
				Compound fissure	22.06%
				Horizontal Split Head	8.83%
				Vertical split head	7.35%
				Total ( $\Sigma$ )	100%
		Rail Surface Defects	13.55%	Head Checks	37.31%
				Spalling	12.31%
				Shelling	12.31%
				Wheel burn	9.85%
Squat	24.61%				
Corrugation	3.63%				

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				Total ( $\Sigma$ )	100%
		Rail Web Defects	10.84%	Head and web separation	64.67%
				Bolt Hole Crack	12.55%
				Piped rail	15.06%
				Corrosion	7.72%
				Total ( $\Sigma$ )	100%
		Rail base Defects	9.03%	Broken base	85.71%
				Base corrosion	14.29%
				Total ( $\Sigma$ )	100%
		Rail Wear	4.76%	Head Loss Max %	33.93%
				Curve Wear	58.93%
				Tangent Wear	7.14%
				Total ( $\Sigma$ )	100%
		Rail Buckling	18.07%		
				Total ( $\Sigma$ )	100%
		Total ( $\Sigma$ )	100%		
Rail Joint	12.63%	Fish-Plated Rail Joint Defects	33.33%	Fish plate Cracks ((includes broken and cracked plates at insulated joints)	54.96% <sup>00</sup>
				Rail Joint Adjustment at Fish-Plated Joint	16.03%
				Ineffective Fish Bolts at Fish- Plated Joint	21.37%
				Loose Fish Bolts Fish-Plated Joint	7.63%
				Total ( $\Sigma$ )	100%
		Rail Weld Defects	66.67%	Transverse Cracking of The Profile	66.67%
				Horizontal Cracking of The Web	33.33%

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		Total ( $\Sigma$ )	100%	Total ( $\Sigma$ )	100%
Sleeper	21.05%	Sleepers Defects	100%	Bending Cracks	18.86%
				Sleeper breakage due to derailments	58.96%
				Consecutive Missing Sleepers	15.09%
				Spacing of Sleeper	7.08%
		Total ( $\Sigma$ )	100%	Total ( $\Sigma$ )	100%
Ballast	5.53%	Ballast Drainage Defects	80%	Ballast Fouling	65.46%
				Vegetation Growth	9.08%
				Ballast Wet Bed	25.46%
				Total ( $\Sigma$ )	100%
		Ballast Profile Defects	20%	Ballast Deficiency	83.33%
				Excess Ballast	16.67%
Fastening System	12.63%	Fastening System Defects	100%	Squeezed out missing or failed insulators	19.05%
				Severely worn pads	8.33%
				Broken fastener	72.62%
Total ( $\Sigma$ )	100%	Total ( $\Sigma$ )	100%	Total ( $\Sigma$ )	100%

### 4.3 Defect Severity

This study uses the fuzzy logic technique to standardize all defect criteria and translate the grading scales used for the linguistic condition assessment into numerical scores. Prior to this, all defect severities were gathered, and various measuring criteria were established for each defect. The severity of defects is determined based on the guidelines outlined in the Australian Manuals. The scale derived from the Australian manual Track Inspection TMC 203 is instrumental in guiding the inspection and maintenance scheduling for railway tracks.

Fuzzification is carried out on the six severity levels by categorizing them into intersecting bins on a 0-10 scale. Gaussian membership functions are employed to represent the six severity levels encompassing all defects. Defuzzification is conducted in order to derive a conclusive score that will be utilized in the assessment of defects, defect categories, and railway components. The center of gravity approach was used to defuzzify the fuzzy

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

membership functions, and the resulting six severity levels are shown in table 4.2 along with the grading scale and final score.

*Table 4.2 Defects' Severity Levels and Value with Their Membership Function*

Severity	Boundaries of Membership Function	Membership Function $\mu(x, c, s, m)$	Defuzzified value
Normal (N)	(0, 2.5)	$\exp\left[-\frac{1}{2}\left \frac{x-1.25}{2.5}\right ^2\right]$	1.251
Priority 3 (P3)	(1, 5)	$\exp\left[-\frac{1}{2}\left \frac{x-1.5}{3}\right ^2\right]$	2.91
Priority 2 (P2)	(3.5, 6.5)	$\exp\left[-\frac{1}{2}\left \frac{x-1.5}{3}\right ^2\right]$	4.72
Priority 1 (P1)	(5, 8)	$\exp\left[-\frac{1}{2}\left \frac{x-1.5}{3}\right ^2\right]$	6.31
Emergency 2 (E2)	(7.5, 9.5)	$\exp\left[-\frac{1}{2}\left \frac{x-1.25}{2.5}\right ^2\right]$	8.23
Emergency 1 (E1)	(9, 10)	$\exp\left[-\frac{1}{2}\left \frac{x-0.5}{1}\right ^2\right]$	9.45

For P1, the range of fuzzy membership functions is 5 to 8, which yields a defuzzified score of 6.31. Similarly, a membership function  $\mu(x, c, s, m) = \left[-\frac{1}{2}\left|\frac{x-1.5}{3}\right|^2\right]$  where  $1 \leq x \leq 5$  represents the linguistic term "P3". The severity values obtained, in conjunction with the calculated weighting vectors, are utilized together to assess the condition of defects, defect categories, and railway components across all specified speed levels.

*Table 4.3 Range of Condition Index*

Corresponding Condition Category	Range of Condition Index
Normal (N)	0–25%
Priority 3 (P3)	25–50%
Priority 2 (P2)	50–65%
Priority 1 (P1)	65–80%
Emergency 2 (E2)	80–95%
Emergency 1 (E1)	95–100%

### **4.4 Condition Assessment Model**

In the development of the condition assessment model for railway track structure, a Weighted Sum Mean Technique has been adopted as a robust aggregation method. This technique enables the combination of two crucial input sets: the assigned weights for different components and defect severities. By applying the Weighted Sum method, these sets are effectively merged to determine the overall condition of the railway track.

Upon inputting the defect weight and defect severity, the model generates an output encompassing the status of each defect, the condition of defect categories, the conditions of components, and the overall condition of the track. If all defects are in their most severe state, the model will indicate an Emergency 1 condition, regardless of whether each defect meets the criteria for Emergency 1 classification. In contrast, if the overall track condition is classified as "Emergency 1," a component with a non-critical defect may also be classified as "Emergency 1". As a result, the model displays each component's and defects condition.

The model acknowledges the limitations of expert judgment, which can introduce bias and subjectivity. It may be beneficial and possible given the current state of artificial intelligence and pattern recognition to investigate how the model can be integrated with technological advancements in railway track inspection. Automated defect detection systems, for example, could help with weight assignment and defect severity assessment. These systems can provide objective and consistent data on the prevalence and severity of defects, which reduces subjectivity and improves model accuracy. Similarly, track monitoring data collected by sensors and other monitoring systems can provide useful information about track performance and the evolution of defects over time. This data can be used to fine-tune the model's parameters and enhance its predictive abilities.

By incorporating technological advancements into the developed model, can further boost the accuracy, objectivity, and effectiveness of railway track condition evaluation. This integration will result in more well-informed decision-making concerning maintenance and repair strategies, ultimately contributing to safer and more efficient railway operations.

## **CHAPTER FIVE**

### **IMPLEMENTATION AND VALIDATION**

#### **5.1 Overview**

It is important to put the Track structural condition assessment model into practice after it has been developed to incorporate all of its defects and components. The implementation of the model to actual case studies using real inspection data and final decisions is a crucial aspect of model development. This step is essential to validate the model's practicality and reliability. The K-Fold Cross-Validation, Experts validation and sensitivity analysis allows us to validate the Track structural condition assessment model by comparing its predictions with real-world data and exploring different scenarios. A case study involving AALRT inspection data collected from a section running from Stadium Station to Lancha Station was carried out as part of the validation process.

#### **5.2 Model Validation**

The validation process involves a comparative analysis between this model and existing track structural models. This comparison will be conducted on a case study using inspection data collected from the AALRT, focusing specifically on a section from Stadium Station to Lancha Station. Additionally, K-Fold Cross-Validation will involve employing to assess consistency and robustness under various conditions. Sensitivity analysis will also be performed to identify the most influential factors affecting the model's performance and to ensure that the model's predictions remain consistent across different scenarios. These combined methods will provide comprehensive insights into the model's accuracy, reliability, and overall effectiveness in real-world applications. In-depth understanding of the model's precision, dependability, and general efficacy in practical applications will be possible thanks to the combination of these techniques.

##### **5.2.1 Case Study**

The data collection was carried out in the case study conducted on the Addis Ababa Light Rail, specifically on the north-south line spanning from the Stadium Station to Lancha Station, which covers a distance of 2 km. However, it is important to note that certain defects, which

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necessitate the use of an ultrasonic device, were left unmeasured due to the absence of appropriate facilities. The collected data is presented in the table below as a sample.

*Table 5.1 Collected Data for Case Study from Stadium to Lancha Station at AALRT*

Defects	W <sub>d</sub>	9+808- 9+971	9+971 - 10+113	10+113- 10+221	10+221- 10+330	10+331- 10+432
Transverse break without apparent origin	22.06%	N	N	N	N	N
Head Checks	37.31%	N	P1	N	P3	N
Spalling	12.31%	P3	P2	N	P2	P3
Shelling	12.31%	P2	P2	P1	P3	N
Wheel burn	9.85%	N	N	N	N	N
Squat	24.61%	N	P3	N	P2	P2
Corrugation	3.63%	P3	N	N	P2	P1
Head and web separation	64.67%	N	N	N	N	N
Bolt Hole Crack	12.55%	N	N	N	N	N
Piped rail	15.06%	-	-	-	-	-
Corrosion	7.72%	N	P2	P3	N	P3
Broken base	85.71%	N	N	N	N	N
Base corrosion	14.29%	N	N	P3	N	
Head Loss Max %	33.93%	N	N	N	N	P3
Curve Wear	58.93%	N	N	N	N	N
Tangent Wear	7.14%	N	N	N	N	N
Horizontal Cracking of The Web	33.33%	-	-	-	-	-
Bending Cracks	18.86%	N	N	N	N	N
Sleeper breakage due to derailments	58.96%	N	N	N	N	N
Consecutive Missing Sleepers	15.09%	N	N	N	N	N
Spacing of Sleeper	7.08%	N	N	P3	N	N

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Figure 5.1 Data collecting at AALRT

The data shown in the preceding table was collected from a 100-meter stretch of the track. As can be seen below, the model developed was used to evaluate the information gathered and assess the track components' conditions. Particularly, the analysis was done for a 100-meter stretch of the track.

Table 5.2 Condition of Component for Case Study

		<b>Sample from N-S Line of AALRT from Stadium to Lancha Station</b>				
<b>Component</b>	<b>W<sub>c</sub></b>	9+808-9+971	9+971 - 10+113	10+113-10+221	10+221-10+330	11+330-11+430
Rail	48.16%	2.095781	2.40725	1.353802	2.274890	1.9445
Condition of rail		N	N	N	N	N
Rail Joint	12.63%	1.4104	1.251	1.251	1.251	3.5077
Condition of Rail joint		N	N	N	N	P3
Sleepers	21.05%	1.251	1.251	1.251	1.251	1.251
Condition of the Sleeper		N	N	N	N	N
Ballast	5.53%	1.251	1.48624	2.080356	1.526656	2.077
Condition of Ballast		N	N	N	N	N
Fastening System	12.63%	1.388278	1.251	1.251	1.56623	5.34606
Condition of Fastening System		N	N	N	N	P2

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To determine the structural condition of each track segment, apply the previously mentioned system. This evaluation's summary is given below.

*Table 5.3 Summary of Condition of Track for Case Study*

	9+808 - 9+971	9+971 - 10+113	10+113 - 10+221	10+221- 10+330	11+330- 11+430
Structural condition of track section	16.95 %	18.20%	13.46%	17.99%	25.12%
	N	N	N	N	P3

### 5.2.2 K-Fold Cross-Validation

K-Fold Cross-Validation is a statistical method used to estimate model performance by splitting data into K subsets. The model is trained on K-1 folds and validated on the remaining fold, a process repeated K time. It helps prevent overfitting, utilizes all data points for training and validation, and offers reliable performance estimates. Key metrics include errors and accuracy metrics specific to task types. With common K values being 5 or 10, this approach enhances model accuracy assessment and generalizability in absence of comparison datasets. RMSE measures the accuracy of a model's predictions regarding railway track conditions, with larger values indicating worse accuracy. It calculates the average difference between actual and predicted values across cross-validation folds, and the mean RMSE is used to assess model performance.

A Python Code is employed to perform K-Fold Cross-Validation on defect categories, components and Track Structural Condition dataset, collected in the case study to validate the research model. Since this is the developed model the lack of sufficient comparison data, I set up the framework for K-Fold Cross-Validation. A dataset with six feature types and a target variable concerning Track Structural Condition is created. The dataset undergoes 5-fold cross-validation, with the model predicting the target variable and calculating RMSE for each fold. Ultimately, the average RMSE across all folds is determined and visualized in a plot displaying both individual and average RMSE values.

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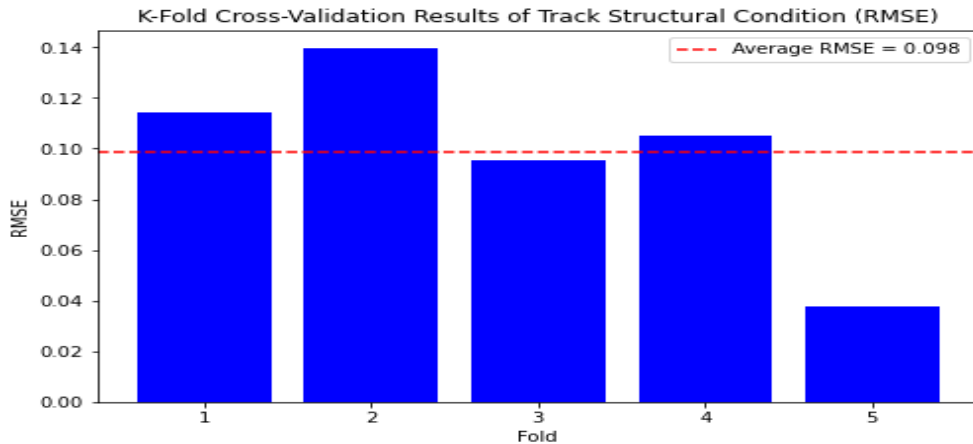


Figure 5.2 K-Fold validation of Track Structural Condition

The graph illustrates K-Fold Cross-Validation results for Track Structural Condition assessment using RMSE. RMSE varies slightly across folds, with fold 2 showing the highest error and fold 5 the lowest. The average RMSE is 0.098, shown by a red dashed line. The model has consistent performance and low error, indicating its reliability in predicting track structural conditions.

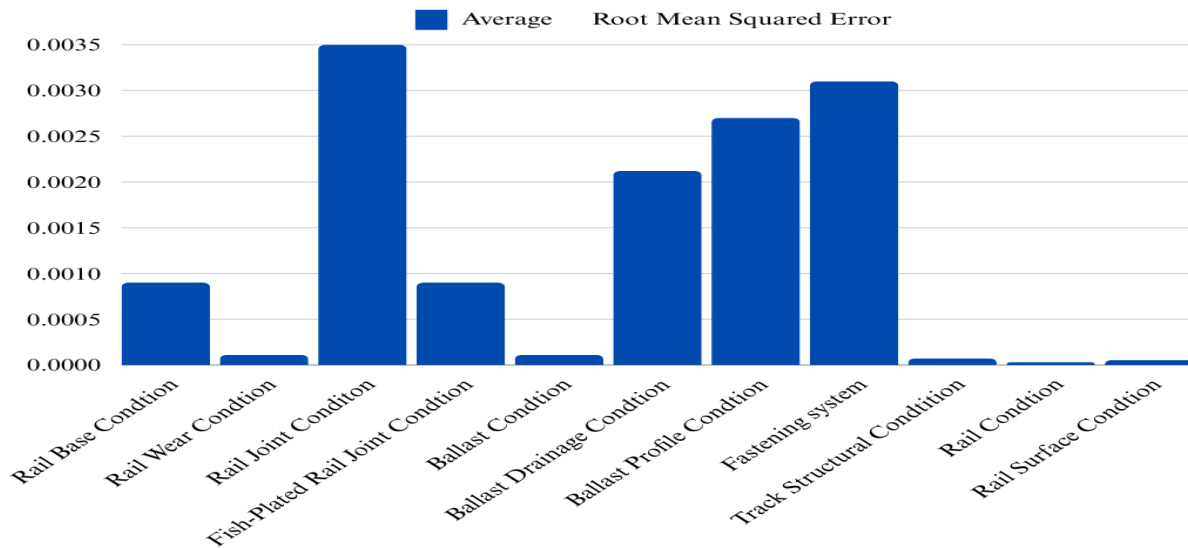


Figure 5.3 Error Level for Various Railway Track Conditions in K Fold Validation

The above graph shows the average Root Mean Squared Error (RMSE) for various railway track conditions, indicating the error level in the predictions of Developed model. The Rail Joint Condition has the highest RMSE but still shows a minor deviation of 0.35%, indicating high accuracy. Other conditions, like Ballast Drainage, Ballast Profile, and Fastening System,

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also have slightly higher yet insignificant errors. Rail Condition, Rail Wear Condition, Rail Surface Condition, Ballast and Track Structural Condition show the lowest RMSE values, reflecting highly accurate predictions. The analysis concludes that all RMSE values are close to zero, suggesting that the model's predictions are reliable and its performance in assessing railway track conditions remains robust despite minor errors.

### 5.2.3 Sensitivity Analysis

The sensitivity analysis was conducted on data collected in the case study to validate the research model. By varying the weights of track condition parameters (Rail, Rail Joint, Sleeper, Ballast and Fastening System) as a linear percentage ranging from -50% to +50% in steps of 5%. This helped to gauge alterations if any in the overall track condition score with respect to modifications in the severity of each of the conditions. The sensitivity of the weight for track components is illustrated in the graph below.

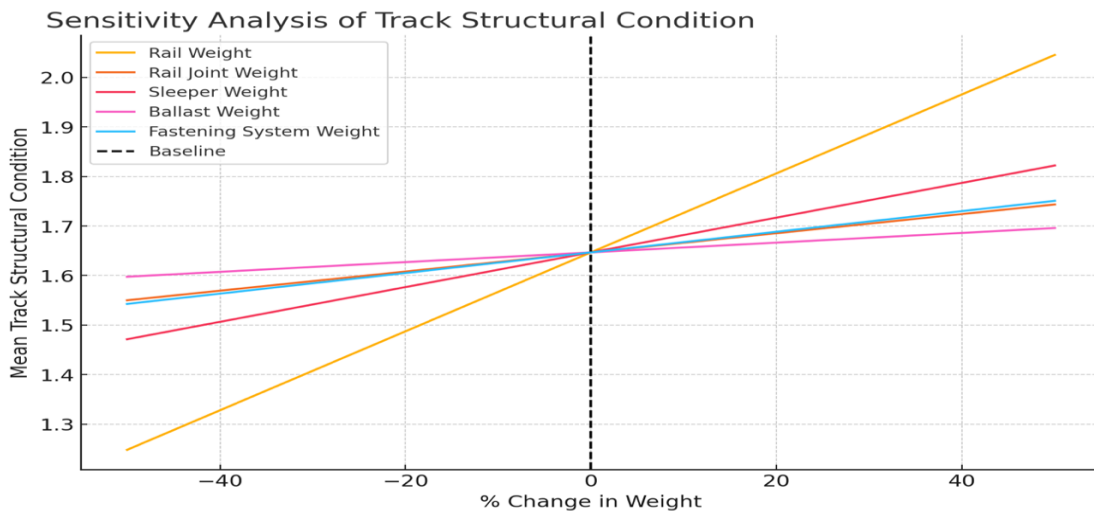


Figure 5.4 Sensitivity Analysis of Track Structural Condition

The Baseline (Dashed black line) at 0% change represents the original condition with no weight modifications. There are considerable changes in the condition of the track depending upon the profile of the weight of the rail. A critical increase in this weight could probably bump the track condition status from the Normal (N) condition range to Priority 3 (P3) level. This suggests that the rail's condition is critical to maintaining a lower severity level. Changes in the sleeper weight also cause noticeable changes in the track condition. This weight's influence suggests that while important, it doesn't escalate to other conditions as quickly as the rail weight. The conditions of the rail joint, ballast, and fastening system show

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

less impact on the overall track condition. Adjustments in these weights are less likely to cause immediate jumps to high-priority or emergency states.

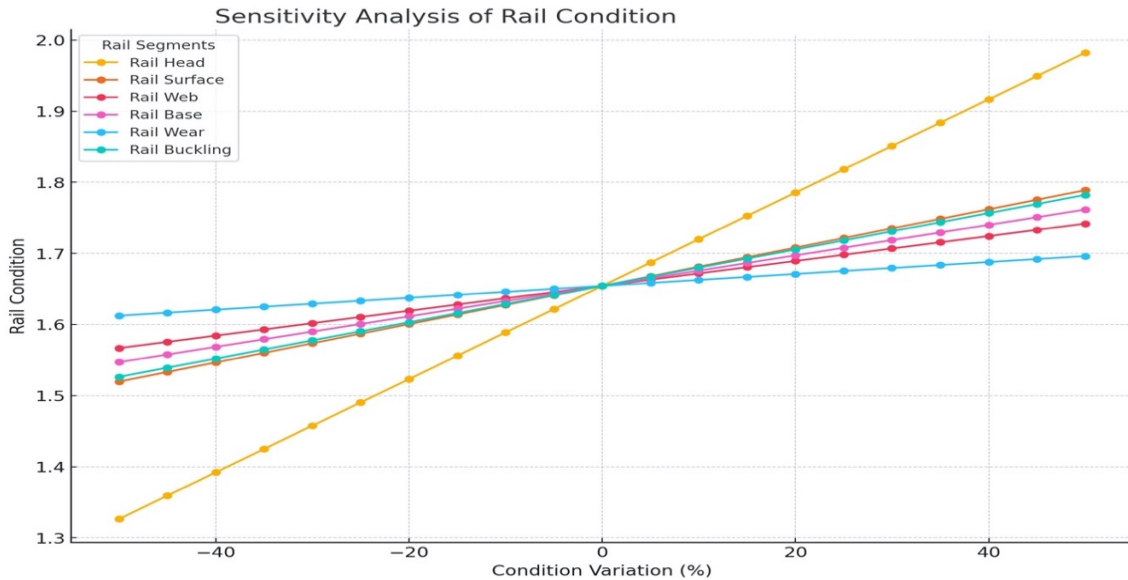


Figure 5.5 Sensitivity Analysis of Rail Defect Categories Condition

In a similar scenario to track components for rail defect categories, the above graph illustrates weight variations ranging from -50% to 50%. Rail Head has the most significant impact on the overall condition, as its curve shows the largest deviation across the range of variation because it has high weight. This weight's influence suggests that while important, it doesn't escalate to above range to Priority 3 (P3) range. Rail Surface and Rail Buckling also have notable impacts but to a lesser extent. The segments Rail Wear, Rail Web, and Rail Base have relatively less influence on the overall rail condition, as their curves show smaller changes.

### 5.2.4 Expert Validation

to validate the effectiveness of the developed Multi-Criteria Decision-Making (MCDM) model, in the railway industry, surveys or interviews with Railway Experts and decision-makers are recommended. The process includes identifying diverse participants, designing questionnaires or interview guides and distributing surveys. To assess the validity of the developed model, a survey was administered utilizing the JotForm online platform. The survey is designed to gather qualitative data on the model's effectiveness. It includes sections for participants to rate the importance of each criterion used in the model, as well as assess how well the model reflects their practical decision-making needs. The questionnaire also

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allows space for open-ended feedback to capture new ideas or potential improvements to the model. A diverse group of 15 experts in the railway industry was assembled. These experts have backgrounds in various areas crucial to railway track maintenance and assessment, including railway engineering, maintenance management, and safety and infrastructure planning. Their collective experience and roles in decision-making processes related to railway infrastructure will provide a well-rounded perspective. The survey was structured to gather ratings on a 1-5 scale, with 1 being not important and 5 being very crucial, across a variety of components and defect categories. The table below summarizes the results of the survey.

In the table below the second column presents the average or most common expert rating for each component, defect category, or specific defect, and the last column indicates the percentage of experts who selected the most common rating shown in the second column as the "best response." For example, 60% in the last column means that 60% of the 15 experts gave that specific rating.

*Table 5.4 Summary of Experts Survey*

<b>Weight Data rated on the Survey</b>	<b>Best Response Given on 1-5 Rating Scale</b>	<b>Percentage of The Best Response</b>
Components	4	60 %
Rail Defect Categories	3	40 %
Rail Head Defects	4	53%
Rail Surface Defects	4	73%
Rail Web Defects	4	60%
Rail Base Defects	4	40%
Rail Wear Defects	4	40%
Rail Joint Defect Categories	5	53%
Fish Plated Rail Joint Defects	4	60%
Rail Weld Defects	4	60%
Sleeper Defects	4	73%
Ballast Defect Categories	5	33%
Ballast Drainage Defects	4	53%
Ballast Profile Defects	4	47%
Fastening System Defects	4	60%

## **Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method**

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The survey result indicates that track components weight in general were rated 4 by the experts, with 60% considering them a top priority in terms of safety or importance. Sleeper defects were among the top-rated concerns, showing that a majority of experts view these as critical issues. The survey shows that rail surface defects received one of the highest percentages 73% with rating 4, indicating significant concern about surface defects. Rail Head Defects and Rail Web Defects received solid ratings of 4, with best response percentages above 50%, indicating they are significant but perhaps not as critical as surface or sleeper defects. While ballast defects were given a high rating of 5, the lower percentage of experts considering them a top priority indicates varying views on their impact. Ballast defects, while important to some experts, saw more varied opinions, suggesting this category may require further investigation or differentiated weighting based.

Overall, the results affirm the reliability of the best -worst model in accurately reflecting the priorities of railway infrastructure experts, providing useful insights for maintenance and repair planning.

### **5.3 Model Implementation**

This model will be implemented using an application developed by Flutter Flow, a no-code development platform for creating application software. FlutterFlow provides a graphical interface for developing native mobile and web applications. FlutterFlow allows users to speed up the app development process without sacrificing overall app quality or functionality. To manage data for larger and more complex railway networks, the application could employ scalable database systems designed to handle significant amounts of data efficiently. It could also utilize advanced data modeling techniques to optimize data storage and retrieval processes. Custom data types combine existing data types, allowing for easier grouping and more flexibility in handling complex data structures.

#### **5.3.1 Description of Application**

The application contains

- The track registry serves as the entry section within the application, encompassing vital access points that facilitate the provision of essential information pertaining to the track.

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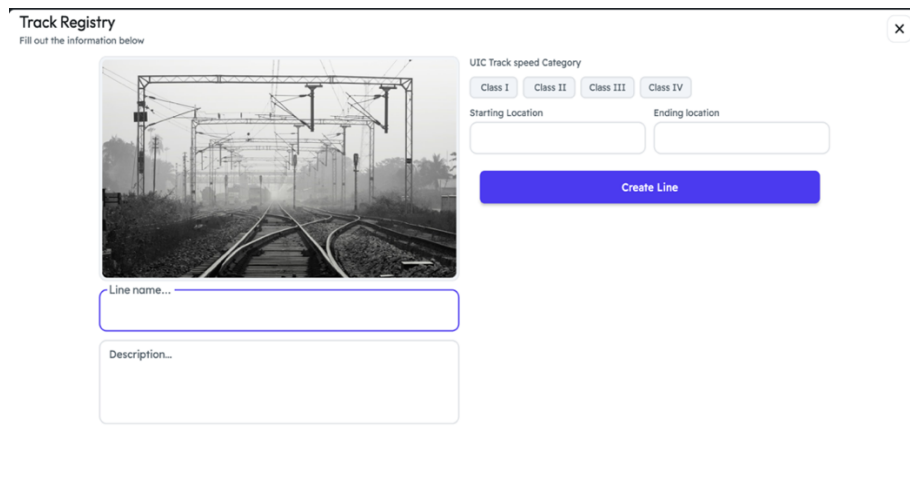


Figure 5.6 Track Registry page

- The dashboard section functions as the menu component that includes the track inspection and track condition sections.

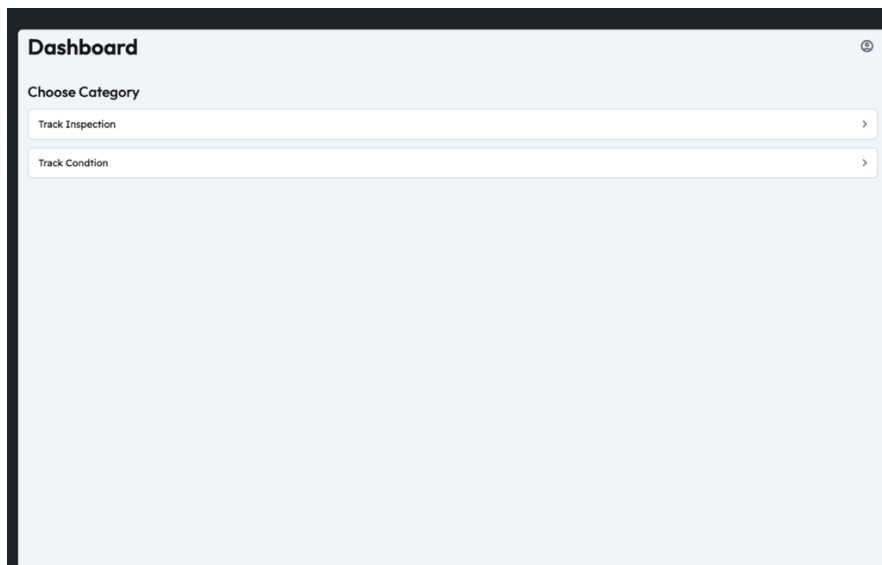


Figure 5.7 Dashboard Page of the application

- To obtain track condition data, it is necessary to conduct a track inspection beforehand.
- The track inspection is carried out using the track inspection module, which consists of five component sections. Within each component section, there are defect categories followed by specific defects.

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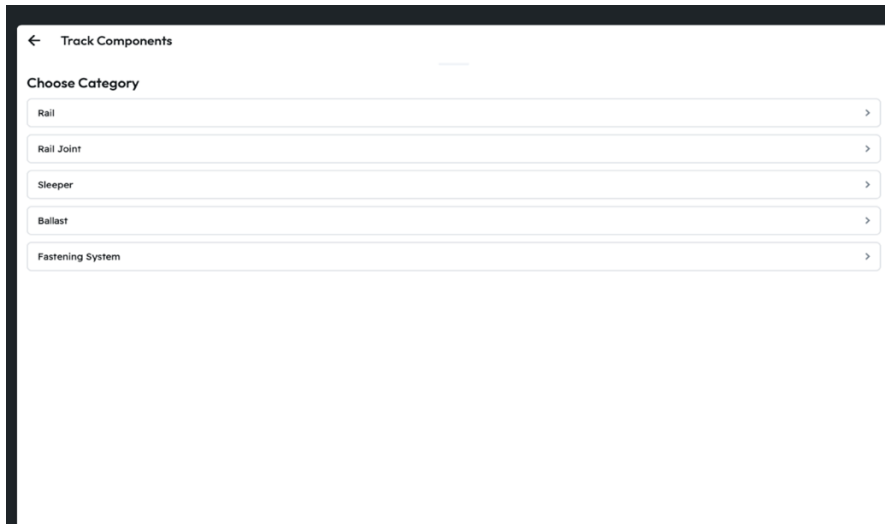


Figure 5.8 Track Components Page in the inspection menu

- In the defect page, the severity of the defect is outlined in six distinct levels. The select button functions as a means to determine the condition of the defect based on the severity level.

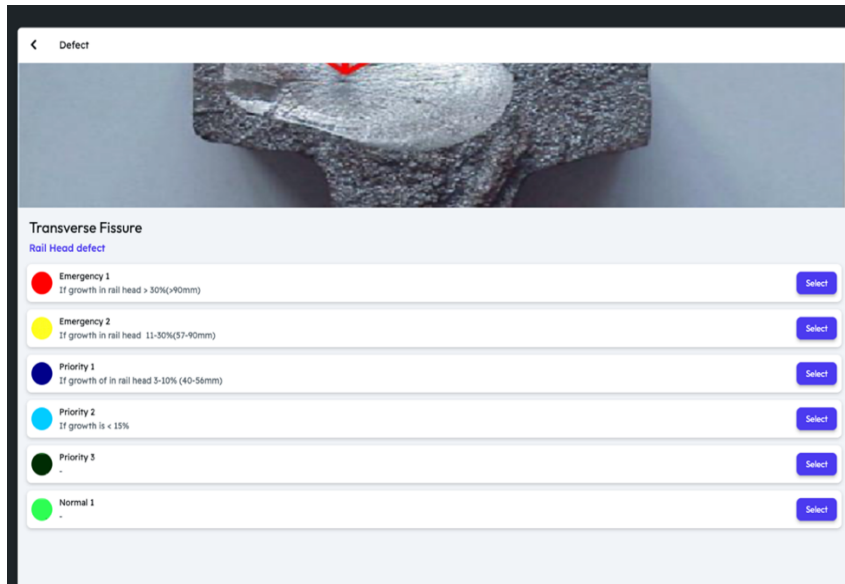


Figure 5.9 Defect Inspection Page

- Upon completion of the track inspection, users are able to access the track condition module in order to obtain information regarding the condition of individual defects, defect categories, components, and overall structural condition of the track.

## **CHAPTER SIX**

### **CONCLUSIONS AND RECOMMENDATIONS**

#### **6.1 Conclusions**

The model for railway tracks was established by employing multi-criteria decision methods. This study expanded on the foundational model proposed by Laith El-khateeb, 2017 introducing key modifications to enhance its applicability in Structural condition assessment of railway track. These modifications resulted in different findings, particularly in relation to weight of components and defects. Future research may explore further refinements to this model or test its applicability in different contexts.

The model divides the railway track into five key components: rails, rail joint, sleeper, ballast, and fastening system. Subsequently, defects related to each component are classified according to their characteristics. Through an in-depth examination of existing literature, an extensive review was carried out to determine the level of importance various components, defect categories, and defects. Utilizing the findings from this literature review, the best-worst method was utilized to ascertain the respective weights of each component.

In addition, defect severities have been collected from Australian manuals. Consequently, fuzzy membership functions have been created to standardize the various criteria for measuring defects and to establish linguistic severity levels with numerical values. The results of the fuzzy membership functions are utilized in conjunction with the Best-worst weights as inputs in the developed weighted sum model. This enables the aggregation of severities and weights, facilitating the determination of the condition for defect categories, components, and the overall aggregated condition.

The study's findings, based on its execution and evaluation, can be summarized as follows:

- The extensive literature review conducted to compare components, defect categories, and defects lends credibility to the weights. The literature review included over one hundred different sources, including articles, books, journals, webpages, scientific studies, thesis and dissertations, manuals, and standards from various rail companies.

- By applying the Best-Worst Method, the study accurately determined the relative importance of key track components, defect categories, and individual defects. This ensures that high-risk defects are prioritized in maintenance schedules.
- Among Components Rail carry the most weight, accounting for 48.16% of the total weight. Following by Sleeper, which is 21.05%. The rail joints and fastening system shares an equal weight of 12.63%. ballast has 5.5% weight, which is the component with the lowest weight.
- The incorporation of fuzzy logic and Gaussian membership functions allowed for a more nuanced interpretation of defect severity, reducing subjectivity and improving decision-making.
- The defect severity classification system employed in this research, were sourced from an Australian guide known as Track Inspection TMC 203[23].This system aids in determining the appropriate timing for track inspection and maintenance activities.
- If all defects are in their worst condition, the model will signal an Emergency 1 condition, irrespective of whether each defect individually meets the criteria for Emergency 1 classification.
- The Developed model shows strong reliability in predicting railway track conditions, with low RMSE values from K-Fold Cross-Validation and minimal variations across defect categories.
- The sensitivity analysis indicates that altering the weights of the components does not exert a significant impact on the overall condition.
- Experts' validation confirms the model aligns with expert priorities, highlighting sleeper and surface defects as top concerns, though ballast defects require further investigation.

### **6.2 Recommendations for future work**

The following points could be interesting for further study.

- Additional railway track components, such as the subgrade, turnouts and level crossing have the potential to be incorporated into the model. By doing so, a more comprehensive depiction of the track's condition can be achieved, encompassing a broader spectrum of components and defects.

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- By integrating the developed model with a track quality index, a more enhanced model can be achieved. This improved model has the capability to assess both the structural and geometric condition of the railway track.
- By integrating the developed model with a comprehensive rehabilitation and maintenance approach, the defects can be effectively addressed by aligning each one with its most appropriate maintenance method.
- A risk assessment model may be formulated utilizing the established condition assessment model. Similarly, a prediction model can be constructed to assess the potential risks associated with postponing maintenance tasks.
- Integrate a risk assessment framework to quantify the potential consequences of different defect scenarios. This can inform weight assignment and prioritize critical issues.
- Static weight assignment: Weights assigned to components and defects might not adapt to changing track conditions or advancements in maintenance techniques.
- Developing a dynamic weight assignment i.e., to adjust weights based on real-time data or periodic reviews. This can account for changing track conditions and maintenance practices.
- Defect interaction: Exploring methods to assess how co-existing defects might amplify their impact on track health. This could involve a scoring system or a risk matrix.
- Leveraging machine learning and AI algorithms can further enhance the model's capabilities to learn from data patterns and improve the accuracy of maintenance recommendations over time.

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**APPENDIXES**

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## Appendix I

### Weight Data Collection for Track Components

The comparison tables consist of three columns: the first lists five criteria for evaluating components, the second explains each criterion based on existing literature, and the third assigns numerical Saaty values to each criterion as determined by the researcher.

#### **Comparison of the Most Importance Component to the Other Component**

##### *Comparison of Rail to sleeper*

Criteria	Reference for Evaluation	Designated value
Structural Integrity	[1][2]	5
Durability	[3]	2
Maintenance Requirements	[4]	1
Cost		4
Safety		1
The mean value of the above comparison is 3		

##### *Comparison of Rail to Ballast*

Criterion	Evaluation	Saaty scale result
Structural Integrity	[5], [6]	9
Durability	[7]	9
Maintenance Requirements		3
Cost		3
Safety		4
The mean value of the above comparison is 6		

##### *Comparison of Rail to Fastening System*

Criterion	Evaluation	Saaty scale result
Structural Integrity	[8],	5
Durability		5
Maintenance Requirements	[9]	6
Cost	[10]	3
Safety		7
The mean value of the above comparison is 5		

#### **Comparison of the Other Component to the Least Importance Component**

##### *Comparison of Sleeper to Ballast*

Criterion	Evaluation	Saaty scale result
Structural Integrity	[11]	5

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Durability	[11]	7
Maintenance Requirements	[11]	8
Cost	[10], [12]	3
Safety		5
The mean value of the above comparison is 6		

### *Comparison of Fastening System to ballast*

Criterion	Evaluation	Saaty scale result
Structural Integrity	[10]	4
Durability	[13]	7
Maintenance Requirements		6
Cost	[13]	4
Safety		4
The mean value of the above comparison is 5		

### Weight Data Collection for Defect Categories and Defects

The comparison tables consist of three columns: the first lists five criteria for evaluating two components, the second describes each criterion using existing literature, and the third assigns numerical values to each criterion based on Saaty's scale.

### Rail Defect Categories and Defects

Comparison of the Most Importance Rail Defect Categories to the Other Rail Defect Categories

#### *Comparison of Rail Head Defects to Rail web Defects*

Criterion	Evaluation	Saaty scale result
Safety Risk	[14], [15]	7
Frequency of Occurrence	[16]	5
Cost of Repair	[3], [17]	5
Potential for Escalation		1
Criticality	[18]	7
The mean value of the above comparison is 5		

#### *Comparison of Rail Head Defects to Rail base Defects*

Criterion	Evaluation	Saaty scale result
Safety Risk	[3]	9
Frequency of Occurrence	[3], [14]	1
Cost of Repair		2
Potential for Escalation	[17], [19]	8
Criticality	[19]	9

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The mean value of the above comparison is 6

### *Comparison of Rail Head Defects to Rail Wear*

Criterion	Evaluation	Saaty scale result
Safety Risk	[14], [20]	9
Frequency of Occurrence	[20]	6
Cost of Repair	[3]	1
Potential for Escalation	[19]	9
Criticality	[21]	9
The mean value of the above comparison is 7		

### *Comparison of Rail Head Defects to Rail buckling*

Criterion	Evaluation	Saaty scale result
Safety Risk	[22]	1
Frequency of Occurrence	[22], [23]	6
Cost of Repair	[24]	7
Potential for Escalation	[24]	1
Criticality		1
The mean value of the above comparison is 3		

### **Comparison of the Other Rail Defect Categories to the Least Importance Rail Defect Categories**

#### *Comparison of Rail Surface defects to Rail Wear*

Criterion	Evaluation	Saaty scale result
Safety Risk	[14], [19]	8
Frequency of Occurrence	[3], [25]	4
Cost of Repair	[14]	2
Potential for Escalation		1
Criticality	[17]	5
The mean value of the above comparison is 4		

#### *Comparison of Rail web defects to Rail Wear*

Criterion	Evaluation	Saaty scale result
Safety Risk	[14]	6
Frequency of Occurrence	[19][25]	5
Cost of Repair	[15], [20]	1
Potential for Escalation	[14]	4
Criticality	[23]	5
The mean value of the above comparison is 4		

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### *Comparison of Rail base defects to Rail Wear*

Criterion	Evaluation	Saaty scale result
Safety Risk	[14], [17]	4
Frequency of Occurrence	[17]	6
Cost of Repair	[10]	1
Potential for Escalation	[24], [25]	3
Criticality		3
The mean value of the above comparison is 3		

### *Comparison of Rail Buckling to Rail Wear*

Criterion	Evaluation	Saaty scale result
Safety Risk	[16], [24]	9
Frequency of Occurrence	[19], [26]	8
Cost of Repair		1
Potential for Escalation	[19]	7
Criticality	[3]	8
The mean value of the above comparison is 6		

### Rail Head Defects

#### Comparison of the Most Importance Rail Head Defect to the Other Rail Head Defect

### *Comparison of Transverse Fissure to Detail Fracture*

Criterion	Evaluation	Saaty scale result
Safety Risk	[14], [17]	9
Frequency of Occurrence	[17]	1
Cost of Repair	[27]	7
Potential for Escalation	[17]	8
Criticality	[14], [17]	9
The mean value of the above comparison is 7		

### *Comparison of Transverse Fissure to Compound Fissure*

Criterion	Evaluation	Saaty scale result
Safety Risk	[19], [27]	2
Frequency of Occurrence		4
Cost of Repair	[14]	1
Potential for Escalation	[24], [28]	1
Criticality	[28]	2
The mean value of the above comparison is 2		

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## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

### *Comparison of Transverse Fissure to Horizontal Split Head*

Criterion	Evaluation	Saaty scale result
Safety Risk	[17], [28]	7
Frequency of Occurrence	[14], [15], [17]	1
Cost of Repair	[24]	7
Potential for Escalation	[3], [28]	8
Criticality	[3]	3
The mean value of the above comparison is 5		

### *Comparison of Transverse Fissure to Vertical Split Head*

Criterion	Evaluation	Saaty scale result
Safety Risk	[27][14], [17]	9
Frequency of Occurrence	[19]	1
Cost of Repair	[20]	9
Potential for Escalation	[3]	8
Criticality	[3], [19]	3
The mean value of the above comparison is 6		

### **Comparison of the Other Rail Head Defect to the Least Importance Rail Head Defect**

#### *Comparison of Transverse break without apparent origin to Detail Fracture*

Criterion	Evaluation	Saaty scale result
Safety Risk	[14], [19]	9
Frequency of Occurrence	[17]	1
Cost of Repair	[14]	5
Potential for Escalation	[14]	3
Criticality	[14], [19]	9
The mean value of the above comparison is 5		

#### *Comparison of Compound fissure to Detail Fracture*

Criterion	Evaluation	Saaty scale result
Safety Risk	[19]	6
Frequency of Occurrence	[18]	1
Cost of Repair	[19]	7
Potential for Escalation	[19], [24]	8
Criticality	[14]	5
The mean value of the above comparison is 5		

#### *Comparison of Horizontal Split Head to Detail Fracture*

Criterion	Evaluation	Saaty scale result
Safety Risk	[29]	3

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Frequency of Occurrence	[14], [29]	1
Cost of Repair	[14]	1
Potential for Escalation	[16], [17], [30]	8
Criticality	[17]	3
The mean value of the above comparison is 3		

### *Comparison of Vertical Split Head to Detail Fracture*

Criterion	Evaluation	Saaty scale result
Safety Risk	[16], [29]	4
Frequency of Occurrence	[16]	1
Cost of Repair	[24], [29]	3
Potential for Escalation	[15]	8
Criticality	[14], [15]	5
The mean value of the above comparison is 4		

### **Rail Surface Defects**

Comparison of the Most Importance Rail Surface Defect to the Other Rail Surface Defect

### *Comparison of Head checks to Spalling*

Criterion	Evaluation	Saaty scale result
Safety Risk	[31] [14], [19]	5
Frequency of Occurrence	[18],[29]	6
Cost of Repair	[20], [24]	1
Potential for Escalation	[14], [15]	5
Criticality	[15], [17]	4
The mean value of the above comparison is 4		

### *Comparison of Head checks to Shelling*

Criterion	Evaluation	Saaty scale result
Safety Risk	[26], [31], [32]	8
Frequency of Occurrence	[14], [19]	7
Cost of Repair	[14]	1
Potential for Escalation	[17]	1
Criticality	[32]	4
The mean value of the above comparison is 4		

### *Comparison of Head checks to Wheel burn*

Criterion	Evaluation	Saaty scale result
Safety Risk	[33]	9
Frequency of Occurrence	[19], [33]	7
Cost of Repair	[14], [19]	1
Potential for Escalation	[17]	2

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

Criticality	[3], [14], [23]	4
The mean value of the above comparison is 5		

### *Comparison of Head checks to Squat*

Criterion	Evaluation	Saaty scale result
Safety Risk	[34]	1
Frequency of Occurrence	[34]	6
Cost of Repair	[35]	1
Potential for Escalation	[19], [35]	3
Criticality	[19], [34]	1
The mean value of the above comparison is 2		

### *Comparison of Head checks to corrugation*

Criterion	Evaluation	Saaty scale result
Safety Risk	[34], [36]	9
Frequency of Occurrence	[34], [37]	1
Cost of Repair	[38]	6
Potential for Escalation	[34], [37]	9
Criticality	[14], [17], [31]	8
The mean value of the above comparison is 7		

### **Comparison of the Other Rail Surface Defect to the Least Importance Rail Surface Defect**

#### *Comparison of Spalling to corrugation*

Criterion	Evaluation	Saaty scale result
Safety Risk	[37]	6
Frequency of Occurrence	[37], [39]	1
Cost of Repair	[38]	3
Potential for Escalation	[36], [39]	7
Criticality	[38], [39]	4
The mean value of the above comparison is 4		

#### *Comparison of Shelling to Corrugation*

Criterion	Evaluation	Saaty scale result
Safety Risk	[31], [40]	8
Frequency of Occurrence	[14], [31], [40].	1
Cost of Repair	[31].	5
Potential for Escalation	[17], [19], [37].	7
Criticality	[17], [32], [40].	9
The mean value of the above comparison is 6		

#### *Comparison of Wheel burn to Corrugation*

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

Criterion	Evaluation	Saaty scale result
Safety Risk	[33], [40]	5
Frequency of Occurrence	[38]	1
Cost of Repair	[36]	9
Potential for Escalation	[32], [38]	6
Criticality	[14], [34], [38]	8
The mean value of the above comparison is 6		

### *Comparison of Squat to Corrugation*

Criterion	Evaluation	Saaty scale result
Safety Risk	[35]	7
Frequency of Occurrence	[41]	9
Cost of Repair	[35], [40]	1
Potential for Escalation	[40], [41]	8
Criticality		9
The mean value of the above comparison is 7		

### **Rail Web Defects**

#### *Comparison of Head and web separation to Bolt Hole Crack*

Criterion	Evaluation	Saaty scale result
Safety Risk		6
Frequency of Occurrence	[14], [42]	1
Cost of Repair		5
Potential for Escalation	[20], [24]	8
Criticality		9
The mean value of the above comparison is 6		

#### *Comparison of Head and web separation to Piped rail*

Criterion	Evaluation	Saaty scale result
Safety Risk	[42], [43]	5
Frequency of Occurrence	[42], [44]	1
Cost of Repair	[43]	3
Potential for Escalation	[42], [44], [45]	7
Criticality	[44]	8
The mean value of the above comparison is 5		

#### *Comparison of Head and web separation to Corrosion*

Criterion	Evaluation	Saaty scale result
Safety Risk	[14], [44]	7
Frequency of Occurrence	[43], [46], [47]	1
Cost of Repair		8

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

Potential for Escalation	[14], [44], [46]	8
Criticality	[47]	9

The mean value of the above comparison is 7

### Comparison of the Other Rail Web Defect to the Least Importance Rail Web Defect

*Comparison of Bolt Hole cracks to Corrosion*

Criterion	Evaluation	Saaty scale result
Safety Risk	[48]	3
Frequency of Occurrence	[48], [49]	1
Cost of Repair	[47], [49]	5
Potential for Escalation	[44], [47]	4
Criticality	[50]	1

The mean value of the above comparison is 3

*Comparison of Piped Rail to Corrosion*

Criterion	Evaluation	Saaty scale result
Safety Risk	[42], [51]	5
Frequency of Occurrence	[42], [44]	1
Cost of Repair	[16], [18], [24]	5
Potential for Escalation	[16], [19]	3
Criticality	[32], [52]	1

The mean value of the above comparison is 3

### Rail Base Defects

Comparison of the Rail base Defect

*Comparison of Broken base to Corrosion*

Criterion	Evaluation	Saaty scale result
Safety Risk	[14], [53]	8
Frequency of Occurrence	[20]	1
Cost of Repair	[3], [17].	6
Potential for Escalation	[17], [19], [20]	9
Criticality	[15], [19]	7

The mean value of the above comparison is 6

### Rail Wear

Comparison of Head Loss Max Percentage to Curve Wear

Criterion	Evaluation	Saaty scale result
Safety Risk	[38], [40], [54], [55]	5
Frequency of Occurrence	[38], [56]	1
Cost of Repair	[38]	1

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

Potential for Escalation	[38], [56]	3
Criticality	[25], [38], [40], [56]	4
The mean value of the above comparison is 3		

*Comparison of Head Loss Max Percentage to Tangent Wear*

Criterion	Evaluation	Saaty scale result
Safety Risk	[38][57]	8
Frequency of Occurrence	[55], [56], [57]	1
Cost of Repair	[17], [56]	8
Potential for Escalation	[14], [55], [56]	9
Criticality		8
The mean value of the above comparison is 7		

### Comparison of the Other Rail Wear Defect to the Least Importance Rail Wear Defect

*Comparison of Curve Wear to Tangent Wear*

Criterion	Evaluation	Saaty scale result
Safety Risk	[56]	7
Frequency of Occurrence	[44]	1
Cost of Repair	[53]	1
Potential for Escalation	[55], [56]	6
Criticality	[54], [55], [56]	7
The mean value of the above comparison is 4		

### Rail Joint Defect Categories and Defects

Comparison of the Rail Joint Defect Categories

*Comparison of Fish-Plated Rail Joint Defects to Rail Weld Defects*

Criterion	Evaluation	Saaty scale result
Safety Risk	[13], [58], [59], [60]	3
Frequency of Occurrence	[13], [53], [59].	3
Cost of Repair	[10]	5
Potential for Escalation	[13], [23]	4
Criticality	[10]	5
The mean value of the above comparison is 4		

### Fish-Plated Rail Joint Defect

Comparison of The Most Importance Fish-Plated Rail Joint Defect to The Other Fish-Plated Rail Joint Defect

*Comparison of Fish-Plate Cracks to Rail Joint Adjustment at Fish-Plated Joint*

Criterion	Evaluation	Saaty scale result
Safety Risk	[53], [61]	2

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

Frequency of Occurrence	[53], [61]	4
Cost of Repair	[62]	1
Potential for Escalation	[60], [61]	5
Criticality	[53], [61], [62].	7
The mean value of the above comparison is 4		

*Comparison of Fish-Plate Cracks to Ineffective Fish Bolts at Fish- Plated Joint*

Criterion	Evaluation	Saaty scale result
Safety Risk	[61], [62]	6
Frequency of Occurrence		2
Cost of Repair	[62]	1
Potential for Escalation	[53]	4
Criticality	[44], [53]	1
The mean value of the above comparison is 3		

The mean value of the above comparison is 3

*Comparison of Fish-Plate Cracks to Loosen Fish Bolts Fish-Plated Joint*

Criterion	Evaluation	Saaty scale result
Safety Risk	[44], [53], [61]	8
Frequency of Occurrence	[58], [59]	2
Cost of Repair	[62]	8
Potential for Escalation	[13], [61]	3
Criticality	[17], [44]	7
The mean value of the above comparison is 6		

**Comparison of The Other Fish-Plated Rail Joint Defect to The Least Importance Fish-Plated Rail Joint Defect**

**Comparison of Rail Joint Adjustment at Fish-Plated Joint to Loose Fish Bolts Fish-Plated Joint**

Criterion	Evaluation	Saaty scale result
Safety Risk	[14], [53]	7
Frequency of Occurrence	[13], [61]	2
Cost of Repair	[62]	2
Potential for Escalation	[61], [63]	5
Criticality		1
The mean value of the above comparison is 3		

**Comparison of Ineffective Fish Bolts at Fish- Plated Joint to Loose Fish Bolts Fish-Plated Joint**

Criterion	Evaluation	Saaty scale result
Safety Risk	[13], [53], [63]	3
Frequency of Occurrence	[61]	1

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

Cost of Repair	[62]	3
Potential for Escalation	[63]	4
Criticality	[61]	5
The mean value of the above comparison is 4		

### Rail Weld Defects

#### Comparison of the Rail Weld Defects

Comparison of Fish-Plated Rail Joint Defects to Rail Weld Defects

Criterion	Evaluation	Saaty scale result
Safety Risk	[64]	4
Frequency of Occurrence	[53], [65]	2
Cost of Repair	[64]	1
Potential for Escalation	[63], [65]	1
Criticality	[65], [66]	1
The mean value of the above comparison is 2		

### Sleeper Defect

#### Comparison of The Most Importance Sleeper Defect to The Other Sleeper Defect

*Comparison of Sleeper Breakage Due to Derailments to Bending Cracks*

Criterion	Evaluation	Saaty scale result
Safety Risk	[11], [17], [61]	4
Frequency of Occurrence	[11]	1
Cost of Repair	[11], [67]	3
Potential for Escalation	[11], [68]	7
Criticality	[67], [69]	3

The mean value of the above comparison is 4

*Comparison of Sleeper Breakage Due to Derailments to Consecutive Missing Sleepers*

Criterion	Evaluation	Saaty scale result
Safety Risk	[11], [69]	4
Frequency of Occurrence	[11], [53]	1
Cost of Repair	[11]	5
Potential for Escalation	[53], [57], [67], [70]	7
Criticality	[57]	7

The mean value of the above comparison is 5

*Comparison of Sleeper Breakage Due to Derailments to Sleepers spacing*

Criterion	Evaluation	Saaty scale result
Safety Risk	[11], [53]	8
Frequency of Occurrence	[53], [67]	2

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

Cost of Repair	[11]	1
Potential for Escalation	[17], [53]	8
Criticality	[53], [69].	9
The mean value of the above comparison is 6		

### Comparison of The Other Sleeper Defect to The Least Importance Sleeper Defect

*Comparison of Bending Cracks to Sleepers spacing*

Criterion	Evaluation	Saaty scale result
Safety Risk	[53], [57], [71]	7
Frequency of Occurrence		4
Cost of Repair	[11]	4
Potential for Escalation	[11], [53], [57], [71]	5
Criticality	[11].	5
The mean value of the above comparison is 5		

Comparison of Consecutive Missing Sleepers to Sleepers spacing

Criterion	Evaluation	Saaty scale result
Safety Risk	[44], [53]	5
Frequency of Occurrence	[57], [71]	3
Cost of Repair	[11]	1
Potential for Escalation	[11], [67]	6
Criticality	[44], [53]	4
The mean value of the above comparison is 4		

### Ballast Defect Categories and Defects

Comparison of the Ballast Defect Categories

*Comparison of Ballast Drainage Defects to Ballast Profile Defects*

Criterion	Evaluation	Saaty scale result
Safety Risk	[7], [72], [73], [74]	5
Frequency of Occurrence	[75], [76].	7
Cost of Repair	[75], [77], [78]	3
Potential for Escalation	[7], [72], [74], [76], [79]	3
Criticality		1
The mean value of the above comparison is 4		

### Ballast Drainage Defects

Comparison of The Most Importance Ballast Drainage Defect to The Other Ballast Drainage Defect

*Comparison of Ballast Fouling to Vegetation Growth*

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Criterion	Evaluation	Saaty scale result
Safety Risk	[73], [80].	8
Frequency of Occurrence	[57], [72], [73]	1
Cost of Repair	[57], [80]	7
Potential for Escalation	[73], [80], [81]	7
Criticality	[72], [73], [77], [78]	5
The mean value of the above comparison is 6		

### *Comparison of Ballast Fouling to Ballast Wet Bed*

Criterion	Evaluation	Saaty scale result
Safety Risk	[7].	5
Frequency of Occurrence	[7], [72].	1
Cost of Repair	[73], [81].	4
Potential for Escalation	[7], [81].	1
Criticality	[82].	4
The mean value of the above comparison is 3		

### Comparison of The Other Ballast Drainage Defects to Least Important Ballast Drainage Defect

### *Comparison of Ballast Wet Bed to Vegetation Growth*

Criterion	Evaluation	Saaty scale result
Safety Risk		6
Frequency of Occurrence	[3], [82].	1
Cost of Repair	[7], [23], [81].	5
Potential for Escalation	[3], [7], [83]	3
Criticality	[3]	4
The mean value of the above comparison is 4		

## **Ballast Profile Defects**

### **Comparison of the Ballast Profile Defect**

#### Comparison of Ballast Profile Defects

Criterion	Evaluation	Saaty scale result
Safety Risk		5
Frequency of Occurrence	[81], [82]	7
Cost of Repair	[76]	1
Potential for Escalation	[57], [82]	8
Criticality	[76]	3
The mean value of the above comparison is 5		

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### Fastening System Defects

#### Comparison of The Most Importance Fastening System Defects to The Other Fastening System Defects

Comparison of Broken fastener to Squeezed out missing or failed insulators

Criterion	Evaluation	Saaty scale result
Safety Risk	[3], [13], [44], [84]	8
Frequency of Occurrence	[44], [53]	2
Cost of Repair		4
Potential for Escalation		5
Criticality		5
The mean value of the above comparison is 5		

Comparison of Broken fastener to Severely worn pads

Criterion	Evaluation	Saaty scale result
Safety Risk	[44], [53]	8
Frequency of Occurrence	[13]	2
Cost of Repair		5
Potential for Escalation	[3], [23]	7
Criticality	[44], [53]	5
The mean value of the above comparison is 4		

#### Comparison of The Other Fastening System Defects to The Least Important Fastening System Defects

Comparison of Squeezed out missing or failed insulators to Severely worn pads

Criterion	Evaluation	Saaty scale result
Safety Risk	[13], [53], [84]	6
Frequency of Occurrence		4
Cost of Repair	[13]	1
Potential for Escalation	[13].	7
Criticality	[44], [53]	5
The mean value of the above comparison is 5		

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## Appendix II

### Python Code for K-Cross Validation

```
import numpy as np
import pandas as pd
from sklearn.model_selection import KFold
from sklearn.metrics import mean_squared_error
import matplotlib.pyplot as plt

# Sample data representing 5 types (replace with actual dataset)
data = {
    'Condition of Rail':
    [1.343767491,1.706329339,1.369747029,1.552304159,1.556613359,1.621385243,1.297256177,1.406200334,
    1.482720247,1.678798954,1.331910105,1.3698091,1.809857622,1.822031126,1.778949608,1.611580911,2.1
    96760182,2.369116036,1.477387209,2.303934758],
    'Condition of Rail Joint':
    [1.380960903,1.25,1.338690463,1.672317097,1.25,4.72,1.554081589,1.25,1.803278,1.25,1.25,1.368235509,1
    .292270439,1.368235509,1.25,1.368235509,1.338690463,1.368235509,1.292270439,1.25],
    'Condition of Sleeper':
    [1.25,1.25,1.25,2.91,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,2.91,2.91,2.91,2.91],
    'Condition of Ballast':
    [1.5881088,1.469755,2.3509614,2.1247268,1.5881088,1.3705824,1.25,1.3705824,1.8401696,1.9393422,1.84
    48274,1.25,1.5881088,1.3705824,1.5020608,1.7086912,2.8625572,2.6254428,2.6254428,1.25],
    'Condition of Fastening
    System':[1.388278,1.25,1.25,2.336636,1.25,1.400728,1.25,1.565076,1.823364,1.565076,1.25,2.336636,1.25,1.
    400728,2.59291,1.400728,2.487364,1.25,2.487364,1.400728],

    'Track_Structural_Condition':[1.347860713,1.481920661,1.37975494,1.983972851,1.41636241,1.892825286,
    1.31116408,1.371688386,1.537009335,1.534424299,1.322341862,1.459875334,1.543663604,1.566128488,1.
    688290626,1.483473081,2.312044795,2.229391414,1.946619497,2.126041926] # Target variable
}

# Convert the data to a pandas DataFrame
df = pd.DataFrame(data)

# Features (5 types)
X = df[['Condition of Rail', 'Condition of Rail Joint', 'Condition of Sleeper', 'Condition of Ballast', 'Condition
of Fastening System']].values

# Target variable
y = df["Track_Structural_Condition"]. values

# Define the number of splits for K-Fold
```

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```
kfold = KFold(n_splits=5, shuffle=True, random_state=42)

# Placeholder for storing the Mean Squared Error (MSE) scores
rmse_scores = []

# Model function based on the given combination of Best-Worst and Fuzzy method
def combined_model(X):
    # Coefficients as per the combined model
    weights = [0.4816, 0.1263, 0.2105, 0.0553, 0.1263]

    # Apply the model formula to the features (matrix multiplication)
    return np.dot(X, weights)

# K-Fold Cross Validation process
for train_index, test_index in kfold.split(X):
    # Splitting the data into training and testing sets
    X_train, X_test = X[train_index], X[test_index]
    y_train, y_test = y[train_index], y[test_index]

    # Use the combined model to predict on the test set
    y_pred=combined_model(X_test)

    #Calculate the RMSE between predicted and actual values
    mse = mean_squared_error(y_test, y_pred)
    rmse = np.sqrt(mse)
    rmse_scores.append(rmse)

# Calculate the average RMSE across all folds
average_rmse = np.mean(rmse_scores)
# Print the results
print(f"RMSE for each fold: {rmse_scores}")
print(f"Average RMSE across all folds: {average_rmse}")
# Plotting the RMSE scores for each fold
plt.figure(figsize=(8, 5))
plt.bar(range(1, len(rmse_scores) + 1), rmse_scores, color='blue')
plt.axhline(average_rmse, color='red', linestyle='--', label=f'Average RMSE = {average_rmse:.3f}')
plt.title('K-Fold Cross-Validation Results of Track Structural Condition (RMSE)')
plt.xlabel('Fold')
plt.ylabel('RMSE')
plt.xticks(range(1, len(rmse_scores) + 1))
plt.legend()
plt.show()
```

# Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

---

## Python Code for Sensitivity Analysis

```
import numpy as np
import matplotlib.pyplot as plt

# Given data
weights = np.array([0.4375, 0.1355, 0.1084, 0.0903, 0.0476, 0.1807])
conditions = {
    'Rail Head':
[1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,2.91,2.91,1.25,2.91],
    'Rail Surface':
[1.942011,4.403437,1.873136,3.481027,2.492241,2.357011,1.454596,1.454596,1.942011,1.658776,1.25025,2.
1342,2.5429722,1.737665,1.454596,1.454596,1.454596,1.310508,1.869596,1.454596],
    'Rail Web':
[1.25,1.517884,1.378152,1.25,1.378152,1.378152,1.378152,1.25,2.531852,4.447414,1.378152,1.25,1.378152,
1.378152,1.378152,1.25,1.378152,1.586482,2.323522,1.25],
    'Rail Base':
[1.25,1.25,1.487214,1.25,1.487214,2.672786,1.25,2.672786,1.25,1.25,1.487214,1.25,4.215566,5.82414,6.584
368,4.947211,3.168649,1.487214,1.487214,1.25],
    'Rail Wear':
[1.25,1.25,1.25,1.25,3.413395,2.91,1.368524,1.25,1.25,1.813238,2.228238,1.25,3.413395,2.91,1.368524,1.25,
1.368524,1.813238,1.368524,1.25],
    'Rail Buckling':
[1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,1.25,2.91,1.25,2.91],
}

# Average condition for each segment
avg_conditions = np.array([np.mean(conditions[segment]) for segment in conditions])

# Base rail condition (summation of weights * average conditions)
base_rail_condition = np.sum(weights * avg_conditions)

# Sensitivity analysis: vary conditions of each segment by -50% to +50% in 5% increments
increments = np.arange(-0.5, 0.55, 0.05)
sensitivity_results = {}

# Calculate sensitivity results by varying conditions for each segment
for segment in conditions:
    sensitivity_results[segment] = []
    avg_condition = np.mean(conditions[segment])
    for inc in increments:
        varied_condition = avg_condition * (1 + inc)
        varied_conditions = avg_conditions.copy()
        idx = list(conditions.keys()).index(segment)
        varied_conditions[idx] = varied_condition
```

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```
rail_condition = np.sum(weights * varied_conditions)
sensitivity_results[segment].append(rail_condition)

# Plotting the sensitivity analysis
plt.figure(figsize=(12, 8))

for segment, results in sensitivity_results.items():
    plt.plot(increments * 100, results, marker='o', label=segment)

plt.title('Sensitivity Analysis of Rail Condition with Condition Variation')
plt.xlabel('Condition Variation (%)')
plt.ylabel('Rail Condition')
plt.grid(True)
plt.legend(title="Rail Segments")
plt.show()
```

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**Defect severity table**

Component	Defects Categories	Defects	N	P3	P2	P1	E2	E1
Rails	Rail Head defects	Transverse break without apparent origin						Stop trains if necessary and replace broken rail ASP
		Detail Fracture			Growth in rail head <15%		Growth in rail head 20%- 40%	
		Transverse Fissure			Growth in rail head <3 %	Growth in rail head between 3-10 % (40mm-56mm)	Growth in rail head between 11-30 % (57mm-90mm)	Growth in rail head >30 % (over 90mm)
		<i>Compound fissure</i>			Growth in rail head 4.9% or less (40mm-56mm)	Growth in rail head 30-35% (57mm-90mm)		Growth in rail head > 35% (over 90mm)
		<i>Horizontal Split Head</i>			Size definition Probe Movement 25mm -100m	Size definition Probe Movement 101mm -200m		Size definition Probe Movement >200mm long
		<i>Vertical split head</i>		Size definition Probe Movement <50mm long	Size definition Probe Movement	Size definition Probe Movement 201-400mm long	Size definition Probe Movement >400 mm long	Visible

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					50mm -200m long			
	Rail Surface defects	Head Checks			Length of crack <10mm	Length of crack between 10mm-20mm	Length of crack Between 20mm-30mm	Length of crack Over 30mm
		Spalling	No surface cracking in gauge corner or on rail head	Spalling present: Gauge Corner, and Top of rail head	Minor Spalling Present: Gauge Corner, and Top of rail head	Significant Spalling Present: Gauge Corner, and Top of rail head		
		Shelling	No visible cracking on rail head		Cracks visible	Cracks 1mm deep		
		Wheel burn	No Wheel Burns		Indents or Head Flow Visible	Indents 1mm or signs of minor ballast disturbance	Indents 2mm or ballast disturbance or minor track geometry deterioration	
		Squat		Size of defect < (30mm wide by 30mm long)	Size of defect < (60mm wide by 80mm long)	Size of defect > (60mm wide by 80mm long)		If Sub-surface cracking associated with squat defect

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		Corrugation		Short Pitch ( $<0.1$ mm in depth)	(mild) Short/Long Pitch (0.1-0.3 mm in depth)	Moderate Long Pitch ( $<0.5$ mm in depth)	Severe Long Pitch (0.5-1.5mm in depth)	Very severe Long Pitch ( $>$ 1.5 mm in depth)
Rail Web Defects	Head and web separation				Size of defect is $< 20$ mm	Size of defect is between 20mm - 75mm	Size of defect is between 76mm - 200mm	Size of defect is over 200mm
	<i>Bolt Hole Crack</i>					Size definition 20 mm - 40mm	Size definition 41 mm - 75mm	Size definition Over 150mm
	Piped rail				Size definition 25 mm - 150mm	Size definition 150 mm - 300mm		Size definition Over 300 mm
	<i>Web Corrosion</i>	Web thickness measured $>15$ mm	Web thickness measured between 13mm- 15mm			Web thickness measured $<13$ mm		
Rail Base Defects	<i>Broken base</i>			Size of defect is $< 20$ mm	Size of defect is between 20mm - 40mm	Size of defect is between 41mm - 75mm	Size of defect is between 76mm - 150mm	Size of defect is over 150mm
	<i>Base Corrosion</i>	Rail foot width – measured edge to edge $>139$ mm	Rail foot width – measured edge to edge 130mm- 139mm			Rail foot width – measured edge to edge $<130$ mm		

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

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			Rail foot (flange) thickness >10 mm	Rail foot (flange) thickness 6mm-10mm		Rail foot (flange) thickness <6 mm		
	Rail Wear	Head Loss Max %				55		
		Curve Wear		Rail head width – measured=52mm		Rail head width measured = 46mm		
		Tangent Wear		Rail head depth measured =32mm		Rail head depth measured =24mm		
	Rail Buckling						Stop trains if necessary and replace rail ASP	

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

Component	Defects Categories	Defects	N	P3	P2	P1	E2	E1
Rail Joint	Fish-Plated Rail Joint Defects	Fish plate Cracks ((includes broken and cracked plates at insulated joints)	No visible crack in ether fishplate		Visible crack in 1 fishplate - other location	Visible crack in both fishplates - other location	1 fishplate broken, other with no crack	Both fishplates broken
		Rail Joint Adjustment at Fish-Plated Joint	Effective fish bolts / swaged fastenings	fish bolts / swaged fastenings Visibly bent	fish bolts / swaged fastenings Bent > 5mm Joint Gaps 15 - 20mm	Joint Gaps 20mm- 30mm	Joint Gaps >30mm	
		Ineffective Fish Bolts at Fish-Plated Joint	No ineffective fastenings			2 on each side effective	1, 2 or 3 effective on 1 side, and 1 on the other side	0 effective on 1 side and 0 or 1 on other side
		Loose Fish Bolts Fish-Plated Joint	No loose fastenings	2 on each side remaining tight	2 or 3 loose on 1 side, and 1 tight on the other side	1 on each side remaining tight	0 effective on 1 side and 1 on other side, but with sufficient integrity to provide lateral and vertical support	All bolts loose, vertical and lateral support lost

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

		Transverse Cracking of The Profile				Size of the 40mm-56mm	Size of the defect 57mm-90mm	Size of the defect over 90mm
	Rail Weld Defects	Horizontal Cracking of The Web					Size of defect 15 mm - 75mm	Size of defect 76 mm - 150mm

Component	Defects	N	P3	P2	P1	E2	E1
Sleeper	Bending Cracks	Crack width < 0.3 mm		Crack width 0.3 mm-3mm	Crack width over 3mm		
	Sleeper breakage due to derailments						Stop trains if necessary and replace sleeper ASP
	Consecutive Missing Sleepers	Number of sleeper = 0			Number of sleeper = 1	Number of sleeper =2	Number of sleeper >2
	Spacing of Sleeper	Spacing between the sleepers < 700mm			Spacing between the sleepers 700mm-900mm	Spacing between the sleepers 900mm-1200mm	Spacing between the sleepers >1200 mm

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

Component	Defects Categories	Defects	N	P3	P2	P1	E2	E1
Ballast	Ballast Drainage Defects	Ballast Fouling	Minimal fines in ballast, Fines in ballast, Based on Selig and Water scale percentage of fouling <1%	Fines in ballast, visible contamination on surface of ballast. Selig and Water's scale percentage of fouling 1-10%	Ballast fouled by fines and debris. Selig and Water's scale percentage of fouling 10-20%	Ballast visibly pumping and unable to maintain track within geometry maintenance limits. Based on Selig and Water scale percentage of fouling 20-40 %	Based on Selig and Water scale percentage of fouling > 40 %	
		Vegetation Growth	Minimum vegetation		Some vegetation are blocking the voids	Highly vegetated that cause water being trapped in the ballast		
		Ballast Wet Bed	Minor saturation - The ballast material is slightly damp.	Moderate saturation - The ballast material is moderately wet	Significant saturation - The ballast material is substantially wet,	Severe saturation - The ballast material is highly saturated,	Critical saturation - The ballast material is	

## Enhancing Railway Track Structural Condition Assessment Using Multi-Criteria Decision-Making Method

									completely saturated,
	Ballast Profile Defects	Ballast Deficiency (combination of the Crib and shoulder)	Ballast thickness per 20m 0-4	Ballast thickness per 20m 4-8	Ballast thickness per 20m 8-10	Ballast thickness per 20m 10-12	Ballast thickness per 20m 12-16	Ballast thickness per 20m >16	
		Excess Ballast							

Component	Defects	N	P3	P2	P1	E2	E1
Fastening System	Squeezed out missing or failed insulators				Failure of 1 consecutive rail fasteners	Failure of 1-3 consecutive rail fasteners	Failure of >3 consecutive rail fasteners
	Severely worn pads						
	Broken fastener						

To prevent damage to sleepers & the rail foot insulators and pads that have failed on a face should be replaced within a nominal period of 6 months.