Defect-based Condition Assessment Model of Railway Infrastructure

by

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ABSTRACT

The condition of railway infrastructure, such as rails, ballasts and sleepers, should always be monitored and analyzed to ensure ride safety and ride quality for both passengers and freight. Railway infrastructure is hard to assess ~~and monitor~~ in terms of its condition due to various types of infrastructure components. The existing condition assessment models are mostly limited in terms of the components and/or the techniques when several models focus only on the assessment of track geometry condition. A few other condition assessment models evaluate the structural condition of the railway infrastructure by considering one component or utilizing one inspection technique. Therefore, a comprehensive condition assessment tool should be developed to cover the numerous railway infrastructure components. Different inspection techniques are also needed to ensure the safety and quality of public services.

This research aims at developing a defect-based condition assessment model of railway infrastructure. This model attempts to cover the structural and geometrical defects associated with the different components of railway infrastructure. The defects of each component are identified and examined through literature and by experts in the field. Two main sets of input are used to develop the model: (1) the relative weights of the importance of components, defects and their categories, and (2) defects severities. To obtain the relative importance weights, the Analytic Network Process (ANP) technique is adopted, considering the interdependencies between the components and their defects. Fuzzy logic is used to unify all the different defect criteria and to translate the linguistic condition assessment grading scale to a numerical score. Furthermore, the weighted sum mean is used to integrate both the weights and severities to determine the conditions and to evaluate the overall condition of the railway infrastructure. The required data for the present research is collected from railway condition classification manuals, literature and questionnaires distributed to professionals across Canada. The fruit of this fusion is also presented in a user-friendly automated tool using EXCEL. The developed model gives a detailed condition of the railway infrastructure by representing a three-level condition state, starting with representing the condition of the individual defect categories of components, the condition of the components themselves and an overall condition that describes the railway infrastructure. The developed model is implemented in two case studies from Ontario, Canada. The model output results for the case studies and the experts' decision are compared, with similar results, indicating the reliability of the developed model. This model helps in minimizing the inaccuracy of the railway condition assessment through the application of severity, uncertainty mitigation and robust aggregation. It also benefits asset managers by providing the detailed condition of railway components, defect categories and overall condition for maintenance, rehabilitation and budget allocation purposes.

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CHAPTER I: INTRODUCTION

1.1 Overview

A solid infrastructure contributes to the improvement of economy and the development of civilizations. As part of city infrastructure, railways play a pivotal role in the transportation of both passenger and goods. Besides, railways are one of the most economical modes of transportations due to their energy efficiency. Railway infrastructure is a collection of different components from different types of materials such as rails, sleepers (ties), ballast, insulated rail joints and rail connections such as tie plates and anchors. Railway infrastructure is always under continuous loading, high-speed trains, severe weather condition, etc. These factors are liable to defects, which can gradually propagate and cause major failures in the railway system – leading to safety concerns, delays and economic losses. According to the United States Federal Railroad Administration Office of Safety Analysis, track defects are the second major cause of accidents on railways in the US. The first major cause of railway accidents is attributed to human error (FRA, 2005). The poor management decisions about rail accidents, caused by the lack of rail inspection, are significant, are not reported by FRA, but only by the National Transportation Safety Board (NTSB). Therefore, railway infrastructure should be always monitored and maintained to avoid major problems. Railway infrastructure maintenance is costly given that it is equipment-oriented. Besides, the continuous demand for higher speed trains and heavier axle loads and tonnage makes it even more challenging to keep the tracks in good condition – calling for building new practices.

A wide range of railway infrastructure inspection techniques has been used to investigate the condition of the track. The common practice for conducting railway infrastructure investigation nowadays is using the ultrasonic, track recording cars and laser scanners. The main inspection technique used in railways is visual inspections done by experts to assess the track condition. Condition assessment is a necessary part of asset management and it is of paramount importance to guarantee the accuracy, credibility and efficiency of the assessment as decisions are taken accordingly. Most railway infrastructure condition assessment techniques available in the market are limited either in terms of components or techniques, resulting in an incomplete representation of the railway infrastructure condition. Therefore, there is a need for a comprehensive, robust, and standardized railway infrastructure condition assessment model that represents the effect of the defects in an objective and credible manner.

1.2 Problem Statement

Railway Infrastructure had a GPA of C+ stated by the ASCE report card issued in 2013 (Herrmann and Andrew W 2013). Railways are experiencing an increasing demand, as both an energy-efficient freight transportation option and a viable city-to-city passenger service. Railways transport 43% of the US intercity freight and about one-third of U.S. exports (e.g., wheat and coal). Railroad freight tonnage growth is estimated to increase up to 22% by 2035, rising from 12.5 billion tons to 15.3 billion tons. Passenger railways have also an increasing demand, as the 2012 statistics shows an increase of 20% in the number of passengers since 2000, with an annual increase of 468 million passengers. Maintaining adequate infrastructure conditions to keep up with the expanding passenger and freight needs is a challenge in creating a competitive railway transportation system. Since 1980s, $500 billion have been spent on railway infrastructure. Capital investment includes maintaining, upgrading and adding tracks to the existing infrastructure (Herrmann and Andrew W 2013). Railway infrastructure is a mix of various components, each made of different types of material. A large number of defects however are associated with those various components. The condition assessment models are limited. Some assess railway track geometry condition individually and a few evaluate the structural condition of the tracks. They exclusively use the visual inspection evaluation of the track and are limited to certain types of tracks (Sadeghi and Askarinejad 2011). A lot of inspection technologies are used for the railway infrastructure inspection. They are however expensive and not well interpreted, making track assessment a hard and time-consuming process. Different variables such as train speeds, axle load, etc. affect the integrity of the railway infrastructure. Defect measurements and assessment criteria vary as well due to the different nature and types of material of the railway infrastructure components.

1.3 Research Objectives

The main objective of this research is to create a comprehensive railway assessment model that tackles uncertainty in the other models. The sub-objectives can be summarized as follows:

- Identify the condition assessment criteria of various railway components.
- Analyze the factors that affect the railway infrastructure deterioration.
- Develop a defect-based condition assessment model for railway infrastructure.
- Build a condition grading scale for all the railway components.
- Establish an automated tool for the developed railway infrastructure condition assessment model.

1.4 Research Methodology

The aim of this research is to create a comprehensive railway infrastructure condition assessment model that covers the limitations of the previously developed models. To develop this model, the literature on the previously developed models, condition assessment manuals, experts' opinions, available mathematical tools and decision-making methods have been reviewed. Figure 1.1 represents the research methodology flow chart. In terms of thesis organization, this research starts with literature review, studies the collected data, then goes through the model development and finalizes its outcome with the credibility testing of the developed model.

The following steps describe the research methodology in details:

- The work done on railway infrastructure condition assessment are reviewed.
- The different defects, defect categories and components that occur in railway infrastructure are determined.
- A hierarchy of the defects and their categories with respect to their components are described.
- The severity levels and the condition assessment grading scales are defined.
- The relative weights of various components, defect categories and defects are determined using the Analytical Network Process (ANP).
- Aggregating the severities and the weights for the components, defects categories and defects to define the condition using Weighted Sum Mean (WSM) Technique
- A detailed condition assessment model that would tie condition scores to protective and proactive actions is developed.

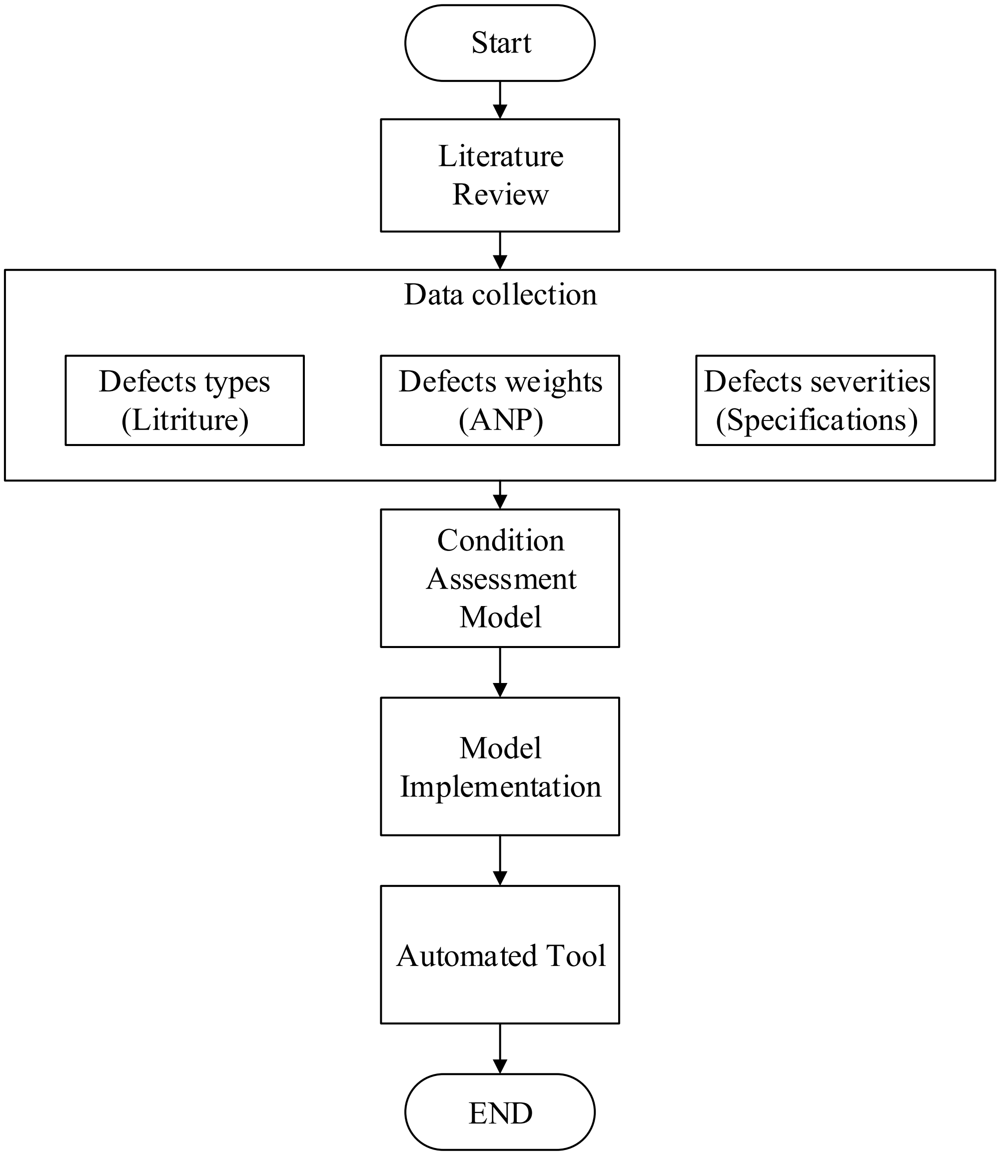


Figure 1-1: Research Methodology Flow Chart

Data were collected from various manuals for defect types and categories determination and a survey was developed and distributed to gather experts' opinions for the relative importance weights of the defects, defect categories and the components. The developed tool was applied to two case studies provided by Canarail Company, the results of the implementation were compared with those of the provided cases. In conclusion, an advanced spreadsheet was developed to visualize the model capabilities and create a user-friendly interface.

1.5 Thesis Organization

This thesis consists of six chapters, best summarized as follows:

Chapter I introduces the thesis topic with an overview of the subject. It discusses the importance of railway history, maintenance, statistics, inspection techniques and available practices. Then, the problem is stated and the research objectives are set. Moreover, a brief workflow of the research is provided to show where the research is heading.

Chapter II includes a summary of the reviewed literature, serving as a background to build this model. It reviews the main inspection technologies used in the condition assessment of the railway infrastructure as well as the manuals used in railway asset management. Moreover, it reviews the previous research in the field of railway condition assessment. Finally, it summarizes the multi-criteria decision making (MCDM) techniques to develop the model.

Chapter III provides a detailed explanation of the research model. The railway infrastructure components, defects and their categories are discussed. After that, a verified defect hierarchy is created and presented. Then, the fuzzy membership model to transform the linguistic assessment into a numerical one is presented. The condition assessment is defined using the Australian standards. Additionally, the Analytic Network Process in collaboration with the Weighted Sum Model Approach is used for aggregation purposes and to determine a crisp value that represents the whole asset.

Chapter IV delivers the data collection methodology. Three data types are collected for this research: 1. Defect types, collected by using the existing manuals; 2. Components and defect weights, collected through a survey (conducted both on-line and in hard copy and distributed to experts); 3. Defect severities, collected from available manuals.

Chapter V illustrates the model development and the implementation of different adopted techniques. Firstly, the model hierarchy is presented and the main two sets of input, the weights and the severities are defined. Then, the aggregation and the model development are provided. Finally, two case studies are used to validate the developed model.

Chapter VI describes the developed automated tool. It also visualizes the features and capabilities of the automated tool in terms of input and output. Finally, it contains some screenshots of the user-friendly automated tool and some other visualization reports issued by the automated tool.

Chapter VII wraps up the thesis with research conclusions and outcomes. In addition, it summarizes the main research contributions to both industry and academic fields. Finally, it sorts out the research limitations and provides some recommendations as a direction for future researchers.

CHAPTER II: LITERATURE REVIEW

2.1 Overview

This chapter summarizes the extensive literature review for railway asset management. The main inspection techniques used in the field of railway condition assessment are first highlighted. The main railway infrastructure manuals and specifications are reviewed for a better understanding of railway system. This chapter also summarizes the previous similar researches and the Multi-Criteria Decision Making techniques employed in the model development.

2.2 Railway Infrastructure Inspection Techniques

Several inspection techniques are used in condition assessment, each with its usages, advantages, disadvantages and technical challenges. Railway infrastructures are a mix of different components from different materials, requiring different technologies to asses each. Most of the railway inspections are visual inspections done by experts. This technique is expensive and time-consuming. Along with visual inspection, other techniques such as ultrasonic and laser technologies are used.

2.2.1 Visual Inspection

Visual inspection is one of the most used techniques today. Visual inspection is done by experts while walking along the tracks, searching for defects and recording them in inspection sheets. This method costs a lot of money and time. An average of 10 km of track per day is inspected by this technique. (Esvald 2001)

2.2.2 Camera Inspection

The idea of automated visual systems is based on the use of high-speed cameras capable of gathering video images of the railway infrastructure as they move over it. The captured images are analyzed automatically by a special image analysis software. Software analysis is done by the identification of components or defects detected by cross-correlation techniques while the data are classified in a supervised learning scheme. The speed of operation can vary from 60 km/h to 320 km/h, depending on the nature of the inspection. The camera inspection does not gather any internal defects (Barragan et al. 2011).

2.2.3 Track Geometry Cars

Track geometry defects are the main reason for high dynamic forces developing between the train and the rails. A track geometry car, also known as a track recording car, is an automated track inspection vehicle to inspect the track for any geometrical defects without obstructing normal railroad operations. Some of the measured parameters are position, curvature, gauge, alignment of the track and cross-level variation. The cars use a variety of sensors and measuring systems to create a profile of the track with the corresponding defects. Track recording cars can speed up to 200 km/h. (Grassie 2008)

2.2.4 Ultrasonic

Ultrasonic inspection was introduced to railway industry in 1927 by Dr. Elmer Sperry who built a massive rail inspection car for the American Railway Association. Ultrasonic works by transmitting a beam of ultrasonic energy into the rails. The reflected energy from the transmitted ultrasonic beam is then collected by transducers. The amplitude of the collected reflections can provide information regarding the state of the rails. Ultrasonic shows high accuracy of 90-95%. The speeds of up to 65km/h, however, are operated at 45km/h for safety and accuracy reasons.

This technique has limitations in highly cold weather conditions when ice interferes with the testing (Seringlion 2005). Heavy lubrication can affect results by producing an intervening interface (Esvald 2001) (Ph Papaelias et al. 2008)

2.2.5 LIDAR

LIDAR technology has been applied to the railway industry to measure and map the surface of the track and the ballast profile in particular. LIDAR (Light Detection and Ranging or Laser Imaging Detection and Ranging) technology uses optical remote sensing technology that measures the distance or other properties of targets by using laser light and analyzing the reflected light. Georgetown Rail Equipment Company (GREX) created the BallastSaver system, which is a LIDA- based track inspection system inspecting the railway infrastructure at a speed up to 20 mph and calculating ballast deficiencies along tracks of any desired length. (Zarembski 2013)

2.2.6 Ground Penetrating Radar (GPR)

GPR technique has been used in railways to inspect the Ballast, which uses radar pulses to image the substructure of the track (Ballast) and to map the bottom of the ballast and top of the subgrade sections of the track structure. The GPR assesses the foul ballast conditions and drainage problems hidden beneath the ballast surface as well as air voids, water inclusions and other cases of inhomogeneity (Esvald 2001). GPR antennas are attached to hi-rail cars and can assess tracks with speeds up to 180km/hr.

2.2.7 Laser Crack Measurement System (LCMS)

Laser Crack Measurement System (LCMS) Inspection Technique uses two high-performance 3D laser profilers that can measure complete transverse railway infrastructure profiles with 1mm resolution at high speeds. LCMS is economical and can be readily mounted on a hi-rail vehicle owned by every rail transit agency (Metari 2013). Based on a 3D map generated by LCMS, the rail gauge can be measured, detecting missing or broken fasteners and identifying cracks in concrete ties.

2.3 Railway Infrastructure Manuals

The inspection of railway infrastructure is a primary task in the process of condition assessment of the assets and planning maintenance programs. Condition assessment is used in the decision-making process and in setting maintenance and rehabilitation to extend the service life of the assets. Therefore, several manuals and codes have been generated by different countries and companies to attain this goal. Manuals describe the inspection methods, defects, defect limits and safety standards that should be taken into consideration for maintaining the safety of the goods and passengers. The manuals such as the American Railway Engineering and Maintenance-Of-Way Association (AREMA) (AREMA 2010), Transport Canada Track Safety Regulations (Transport Canada 2012), the US Federal Railway Administration (FRA) (Office of Railroad Safety 2014), and RailCorp Engineering Manual — Track from Australia have been carefully reviewed (Wilson, 2011).

2.3.1 AREMA

American Railway Engineering and Maintenance-Of-Way Association (AREMA Manual) consists of data, plans, principles and economic practices of engineering, design and construction of railways (AREMA 2010). This manual is developed by AREMA technical committees in the US. The AREMA Manual cannot be used as a maintenance manual since the development of standards or criteria for the maintenance of railways, roads, tracks and structures has always been considered the prerogative of individual railways, based on the nature and characteristics of their plants and operations as well as the specific characteristics of the geographical region(s) where they operate.

2.3.2 FRA

Federal Railroad Administration Manual developed by the Office of Railroad Safety at the US Department of Transportation consists of design aspects, inspection techniques and defects that occur; it also includes the safety standards of railways (Office of Railroad Safety 2014). The manual consists of minimum safety standards and cannot be used for maintenance issues.

2.3.3 Canada Track Safety Standards

Transport Canada Track Safety Manual includes the safety standards of the tracks, the defects that occur in the railway infrastructure and the inspection techniques approved by the Ministry of Transport, Infrastructure and Communities. The manual describes the minimum safety standards that describe the maximum severity levels for the defects. This manual cannot be used for maintenance purposes (Transport Canada 2012).

2.3.4 RailCorp Engineering Manual

RailCorp in Australia developed a collection of manuals for the different components, inspection technique defects, maintenance techniques and designs for railway infrastructure. The different manuals are available online under the name of TMC manuals. These manuals are adopted for and are mostly used in this research to define the defects and the defect severities. The two most used manuals are TMC 203 Track Inspection (Wilson 2013) and TMC 224 Rail Defects and Testing (Wilson, 2011). TMC 203 Track Inspection consists of requirements, processes and guidelines for the management of track assets and inspection activities. It also provides operating limits for track condition measurements and required mandatory actions when the limits are reached. The TMC 224 Rail Defects and Testing manual describes the rail defects, rail defect limitations and inspection techniques for the rail assessments.

2.4 Previous Research on Railway Infrastructure

Previous researches have been reviewed for a better understanding of the asset management of railway infrastructure, condition assessment, maintenance planning, etc. The following two works summarize the researches on condition assessment from the structural point of view, the assessment of the components, rails, sleepers, ballast, etc. Sadeghi and Askarinejad (2011) have developed a quality index to assess the structural condition of the track based on the visual inspection technique. The tracks are divided into four components, i.e. rails, ballast, sleepers and fasteners. The weighted deduction density model was adopted to develop the quality index for each component of the track. So, four indices are developed: rail quality index (RQI), ballast quality index (BQI), sleepers quality index (SQI) and fasteners quality index (FQI); and the overall condition is track quality index (TQI). The indices are based on the defects and their severities. Table 2-1 illustrates the three severity levels (low, moderate and high) and their descriptions used in the indices, where low represents a good track condition with minimum defects, moderate represents defects that may or may not cause any operation restrictions or delays and high represents defects that cause operating restrictions on the track, preventing train operation and causing safety concerns. To organize the maintenance actions, the track line is divided into management sections and the management sections are further divided into segments to aid in the evaluation of structural conditions by the visual inspection of the selected segments (Sadeghi and Askarinejad 2011). The report developed by the US Army for railway infrastructure condition assessment is a development of condition indices for low volume railroad tracks. Table 2-2 illustrates the scale used in all the indices where the scale ranges from

0 to 100 and is divided into seven condition categories from excellent (85-100%) to failed level (0-10%). The excellent level is for very few defect presence, when the track function is not impaired and no immediate work action is required, but routine or preventive maintenance could be scheduled for accomplishment. The failed level shows extreme deterioration throughout nearly all or the entire track, when track is no longer functional and major repair, complete restoration or total reconstruction is required. Several indices are developed to describe the condition of each component in the railway infrastructure. Weighted Deduct-Density Model has been utilized to develop the following indices: Rail and Joints Condition Index (RJCI), Tie Condition Index (TCI), Ballast and Subgrade Condition Index (BSCI) and the aggregated condition index of the components indices is Track Structure condition Index (TSCI), the TSCI was developed using regression technique (Uzarski 1993).

Table 2-1 Severity Levels (Sadeghi and Askarinejad 2011)

Severity level	Description
Low	Distresses that do not affect train operation
Moderate	Distresses that may or may not cause an operating restriction on the track
High	Distresses that cause operating restrictions on the track and may prevent train operation

Table 2-2 Condition Assessment Scale for Uzarski 1993

Category	index	Condition Description
Excellent	100 - 85	Very few defects. Track function is not impaired. No immediate work action is required, but routine or preventive maintenance could be scheduled for accomplishment.
Very Good	70 - 85	Minor deterioration. Track function is not impaired. No immediate work action is required. But, routine or preventive maintenance could be scheduled for accomplishment.
Good	55 - 70	Moderate deterioration. Track function may be somewhat impaired. Routine maintenance or minor repair may be required.
Fair	40 - 55	Significant deterioration. Track function is impaired, but not seriously. Routine maintenance or minor repair is required.
Poor	25 - 40	Severe deterioration over a small percentage of the track. Less severe deterioration may be present in other portions of the track. Track function is seriously impaired. Major repair is required.
Very Poor	10 - 25	Critical deterioration has occurred over a large percentage or portion of the track. Less severe deterioration may be present in other portions of the track. Track is barely functional. Major repair or less than total reconstruction is required.
Failed	0 -10	Extreme deterioration has occurred throughout nearly all or the entire track. Track is no longer functional. Major repair, complete restoration, or total reconstruction is required.

Here, the condition assessment is discussed from a geometrical point of view. Madejski and Grabczyk (2002) have developed the five-parameter defectiveness (W_{5}), a parameter to assess the geometrical condition of the track. The parameter is a result of the aggregation of the 5 parameters, each representing one of the five geometrical defects, i.e. twist, horizontal deviation, gauge, vertical alignment and the cross level variation defectives. Each parameter is a ratio of the sum of the length when the acceptable limits for the defects are exceeded by the total length of the section. The evaluation data can be gathered by the geometry track measurements done by the manual equipments, microprocessor-based portable instruments and geometry recording cars (Madejski and Grabczyk 2002). Indian Railway defines the assessment of the geometrical condition of the track by the Track Geometry Index (TGI), using the standard deviation of the geometrical defects (Mundrey 2003). Polish Railways highlights the frequency of track inspection, using the geometry cars. It states that the inspection should take place as minimum as twice a year and the frequency changes with the degree of curvature. For example, curves with a radius less than 350m should be inspected at least three times a year. Also, Polish Railways developed a synthetic track quality coefficient (J) to assess the geometry condition. The standard deviation is firstly used as a basic measurement for different geometry defects and the J-coefficient is a result of the average value of the standard deviations of the defects (Madejski and Grabczyk 2002). Swedish National Railway has developed a quality Q index to define the geometry condition of the track. The standard deviation of the left and right profiles of the track and the geometry defects are used to assess these components. The condition is defined by dividing the standard deviation of the existing condition over the allowable value of the standard deviation based on track categories (Anderson 2002). Sadeghi and Askarinejad (2012) have developed a methodology to correlate between the tracks' structural conditions and the data obtained from the automated inspections such as the track recording cars used to inspect the track geometry condition. The neural network is employed to explore relationships between the geometry data and the track structural defects to develop a model that predicts track structural conditions by using the geometry recording cars without the need for visual inspection to save both time and economic losses (Sadeghi and Askarinejad 2012). Ferreira and Murray (1997) highlight the main causes of railway infrastructure deterioration, i.e. dynamic loads, train speed, axle loads and environmental factors. They also discuss maintenance decision support systems and maintenance optimization techniques for railway infrastructure (Ferreira and Murray 1997).

Here, some of the researches to enhance and optimize the use of inspection technologies are reviewed. Li-jun (2009) discusses GPR technology used in the substructure assessments (Ballast and Subgrade) of railway infrastructure. GPR can be utilized to find borders between the ballast and the subgrade and it assesses contaminated ballast with fine materials (fouling), moisture content and subgrade conditions, depending on the frequency of the antenna and data dispensation techniques. According to Li-jun, the overall excellence of the data gathered by the 2 GHz antennas is more accurate than that of the 400 MHz one. The higher the moisture content of the ballast, the better for GPR to identify the fouled ballast; and the sampling interval approximately has no effect on the quality of the GPR data collected when it changes in a small range (Li-jun 2009). Liu et al. (2014) address the development of an analytical model to talk about the trade-offs between the various factors related to rail defect inspection frequency, to maximize railway safety and productivity. The results show that the ideal inspection frequency varies with different reasons such as traffic density, rail age, inspection technology reliability and other factors. Liu et al. highlight the main causes of railway accidents, i.e. broken rails. They have also developed models to calculate different costs associated with broken rails, i.e. the costs of inspection, maintenance and derailments (Liu et al. 2014). Figure 2-1 illustrates the main causes of broken rails as the main cause of railway accidents (Liu et al. 2014). The main causes have been found by analyzing the defects for two time intervals: (2001-2005) and (2006-2010). The analysis gives similar results for the two time intervals, showing that the main cause of this major defect is the transverse/compound fissure, followed by the fractures caused by surface defects and so on (Figure 2-1). Figure 2-2 is about the main causes of railway accidents and derailments, where the main accident causes from 2001 to 2010 have been collected and compared. Two of the main causes for accidents are the broken rails and the track geometry defects. These two defects are related to the infrastructure defects – i.e. the main scope of this research.

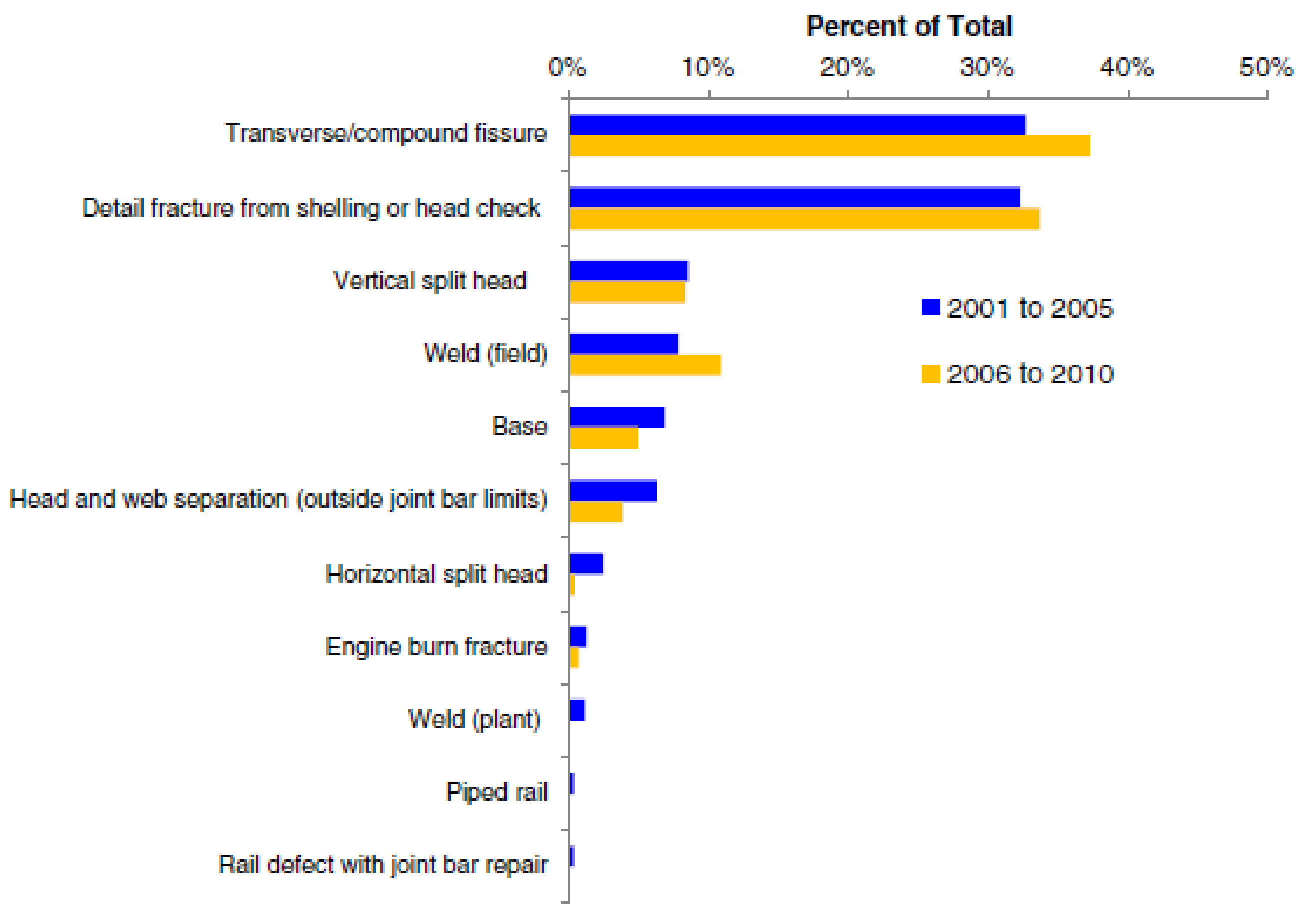


Figure 2-1 Broken Rail Causes (Liu et al. 2014)

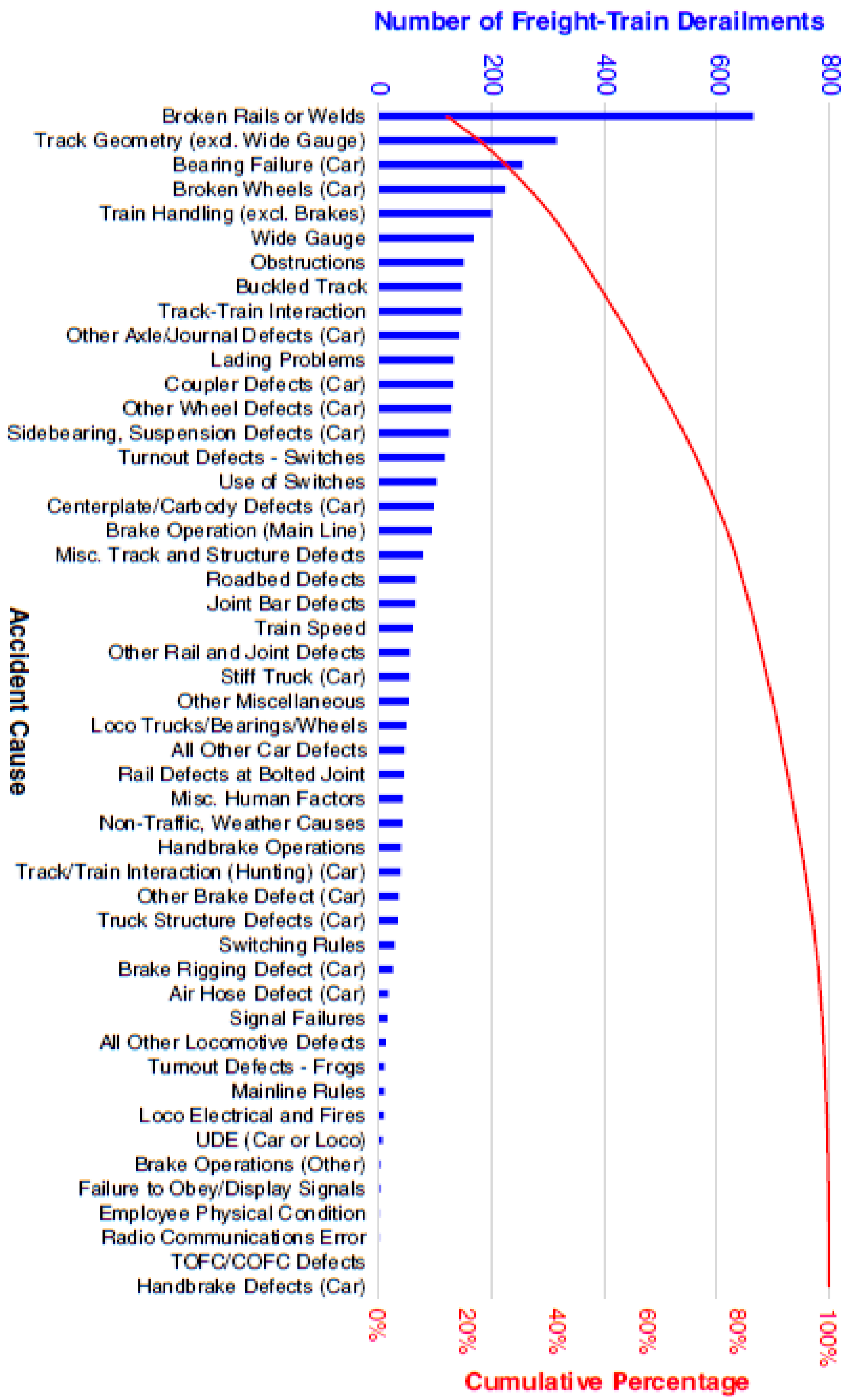


Figure 2-2 Frequency of accident cause and train derailments, 2001–2010 (Liu et al. 2014)

The researches reviewed below deal with various deterioration models that predict the degradation of railway infrastructure. Sadeghi and Askarinejad (2010) have developed a deterioration model that has two formats. One model is developed to predict the geometry degradation of the track and the other is developed to predict the structural degradation of the track. The data have been collected and analyzed for over two years, for approximately 100 km of railway line. The geometric data are collected by the track recording cars and the structural defects are collected by the visual inspections. The main parameters that influence the chosen track degradation are the axle loads, track maintenance status, speed and track quality. As the analysis shows, the geometry conditions of the track have a higher rate of degradation compared with the structural condition of the track and the tracks in bridges, curve-bridges and turnouts deteriorate at a higher rate, when compared with straight lines. The collected data in this study are limited to a speed of 100 km/h while data on materials and environmental factors are not available. The structural models are also limited to the visual inspection (Sadeghi and Askarinejad 2010). Zhang et al. (2000) have developed a deterioration model to predict the structural condition of the track. The model uses different methodologies to predict railway infrastructure deterioration by using an integrated track degradation model (ITDM) via mechanistic techniques to predict track degradation. The model is a combination of sub-models that predict single-part deteriorations i.e. rails, sleepers and ballast. The rail model is developed to predict wear defects in the rails. The axle loads, the degree of curvature and the hardness of rail material are chosen as the main factors that affect rail wear. The sleeper model defines deterioration by the damage intensity factor, the factor that is based on the loading cycles and environmental factors. The ballast model predicts the settlement that occurs on the track. The model assumption is that the track modulus is a key parameter in predicting track behavior under passing traffic, affecting track deflections calculations (Zhang et al. 2000).

2.5 Multi-Criteria Decision-making

In infrastructure asset management, a lot of multi-criteria decision-making techniques are used for a robust decision. The common uses of the decision-making techniques are to combine technical information with experts' opinions. These techniques combine data and weights of several alternatives by aggregating the results of each to reach a single index that would represent the condition of the asset (Kabir et al. 2014).

2.5.1 The Analytic Network Process

The Analytic Network Process (ANP) technique was developed by Saaty in 1996 as a development of the Analytic Hierarchy Process (AHP) also developed by Saaty in 1980s (Görener 2012). The AHP is a multi-decision making technique that uses a pairwise comparison matrix to result in ratio scales and therefore priorities based on the decision-maker's judgments (Büyükyazıcı and Sucu 2003) who provides a hierarchical representation of complicated decision-making problems. The Analytic Network Process (ANP) is a generalization of AHP, accounting for interdependencies and interactions between criteria and sub-criteria in which a hierarchical structure is not a must.

In AHP/ANP, pairwise comparisons between different elements or criteria in the same group are done by experts' opinions. The degree of importance of one factor over the other with respect to a major criterion or a common group is done by judgments from experts or decision-makers. The ANP method works by organizing the different elements or criteria in hierarchies or feedback networks. ANP then performs pairwise comparisons between the different components of the problem to define the relative importance weights. After that, an unweighted supermatrix is created by including the relative importance weight for the different elements and their criteria. ANP is an extension of the AHP to include the weighted supermatrix, considering the interdependencies among different elements in the network. Finally, the developed weighted supermatrix is multiplied by itself until the limit supermatrix is reached where the final local priorities corresponding to the global ones are attained (Yang et al. 2008). The pairwise comparison is conducted by distributing a questionnaire. Table 2-3 illustrates Saaty's (1-9) scale the questionnaire is developed based on. The scale is 1 to 9 where each number represents a comparison level. So, 1 represents an equal importance and 9 represents an extreme importance. The odd numbers represent a level and the even numbers represent an intermediate value.

Table 2-3: Pairwise Comparison - Saaty's Fundamental Scale

Importance	Degree of Importance	Explanation
1	Equal Importance	Two attributes with equal contribution to the objective
3	Moderate Importance	Judgment slightly favors one activity over the other
5	Strong Importance	Judgment strongly favors one activity over the other
7	Very Strong Importance	An activity is favored very strongly over another; its dominance is demonstrated in practice
9	Extreme Importance	The evidence favoring one activity over the other is of the highest possible order of affirmation.
2,4,6,8	Intermediate values that signify (Weak, Moderate Plus, Strong Plus, and (Very, Very Strong).	
Reciprocals	If activity *i* is given, one of the above numbers representing its importance over another activity *j*, then *j* has the reciprocal value when compared with *i*.	

In performing the pairwise comparison, the reciprocal property in AHP/ANP states that if an element x is given an importance of "j" when compared to element y, then element y can be given an importance of 1/j when compared to element x with respect to a common property. In performing the pairwise comparisons, it is important to check for the consistency property through calculating the consistency index (CI) and then the consistency ratio (CR) to test the judgments. The pairwise comparison matrix is said to be consistent if CR is <0.1.

$$CR = \frac{CI}{Random\ Index} \quad \text{.......... (1)}$$

$$\mathrm{CI} = \frac{\lambda - n}{n - 1} \quad \text{.......... (2)}$$

where λ is the eigenvalue of the pairwise comparison matrix and n is the matrix size. Table 2-4 shows the average random index values recommended by Saaty, where the random index is a number related to the size of the matrix. For example, for the matrix with a size of 4, the related random index is 0.89.

Table 2-4: Average random consistency index (R.I.) (Saaty et al. 2012)

N	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Random consistency index (R.I.)	0	0	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49

2.5.2 The Fuzzy Set Theory

An extensive variety of real life issues should be solved in an objective manner for trustworthy results. Such issues, for the most part, include physical procedures that are accompanied by ambiguity. The fuzzy set theory developed by Zadeh (1965) as a mathematical representation deals with uncertainties that are not of statistical nature. Since its development, fuzzy decision-making has been applied to many fields such as civil engineering (Salah 2012).

(i) Fuzzy Relations

In an arrangement of data, a traditional set is characterized as one that has certain limits without uncertainty. Meanwhile, the fuzzy set, introduced by Zadeh (1965), is defined as a set with ambiguous boundaries due to its uncertain properties. The transition of a component in an established set is very much characterized. However, the transition of a component in a fuzzy set is through a membership with a defined function that would depict the uncertainty in the component's properties. In a fuzzy set, the same component might be a member of another fuzzy set in a similar universe since there is fragmented data, unlike the classical set in which the components would have a full membership, i.e. 0 or 1. Some of the standard fuzzy operations are the combination, intersection and completion of the fuzzy sets.

(ii) Fuzzification and Defuzzification

Fuzzification and defuzzification are two major procedures related to the use of fuzzy sets. Fuzzification is defined as the process of translating available data from linguistic terms (e.g. high, low, very low, etc.) into membership functions (Wong and So 1995). However, defuzzification is defined as the procedure where the aggregated output or the overall membership functions are translated back into a crisp (non-fuzzy) value, which is the opposite of fuzzification (Mamdani 1974). Figure 2-3 represents the output of a fuzzy procedure; the output is the combination of two or more fuzzy memberships. For example, suppose that a fuzzy output comprises of two components: (1) a trapezoidal membership function shape and (2) a triangular membership function shape. The combination of these two membership functions is $C=C1\cup C2$. This combination uses the maximum operator as the outer envelope of the combination of the two shapes. Also, the output fuzzy membership can be the union of more than two membership functions with shapes other than triangular and trapezoidal but the union procedure is the same (Ross 2009). After defuzzification, a fuzzy number can be represented by a crisp value.

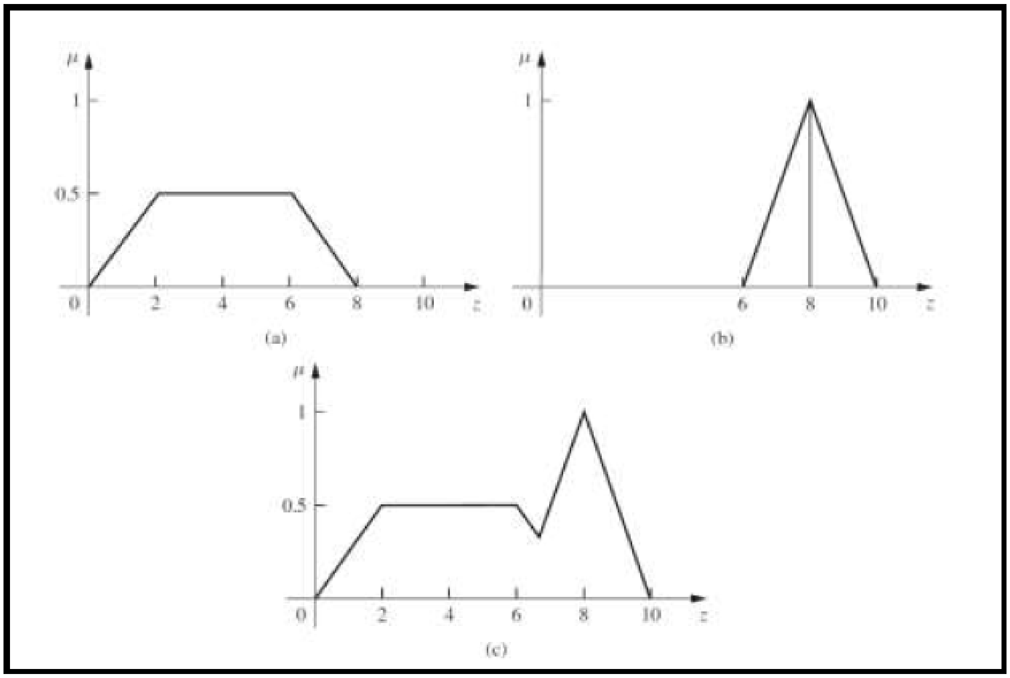


Figure 2-3: Typical Fuzzy Process Output: (A) First Part of Fuzzy Output; (B) Second Part of Fuzzy Output; And (C) Union of Both Components (Ross, 2009).

2.5.3 Weighted Sum Model

The weighted sum model (WSM) is one of the best known and simplest multi-criteria decision analysis (MCDA)/ multi-criteria decision-making technique model (Florian Helff 2016). WSM is mostly used in multi-objective optimization problems. It works by combining different objectives and weights related to different alternatives to create a single value or a score for each alternative to make them comparable. WSM uses the formulas below. In these formulas, the WSM-score for an alternative Ai denoted as Ai WSM−score is calculated by adding the multiplications of a weight W_j with its corresponding value aij. This value can be any type of value, a cost or a severity for a defect. The best alternative will be chosen based on its WSM score; the highest WSM score (A∗ WSM−score) represents the best alternative.

$$A_i^{WSM-score} = \sum_{j=1}^{n} W_j a_{ij} \quad (1)$$

$$A_*^{WSM-score} = max_i \sum_{j=1}^{n} W_j a_{ij} \quad (2)$$

2.6 Summary and Limitations of Previous Research Works

So far, the various inspection techniques for railway infrastructure inspection have been discussed. The major manuals for railway asset management and condition assessment are also reviewed. Moreover, this chapter has summarized the previous research on the condition assessment of railway infrastructure. It has also referred to several MCDM tools including the fuzzy set theory, the analytic network process and the weighted sum model, in line with what this research aims to achieve.

In conclusion, most of the available inspection techniques are assessing individual components or they assess a certain type of defects and they use expertise and human judgment. Therefore, it is important to define a condition assessment model that would account for these limitations and to incorporate the different inspection techniques. Reviewing the different MCDM techniques shows that the fuzzy synthetic evaluation is an important technique that can be used to uniform and translate all the different defect severities measuring criteria. Also, the Analytic Network Process technique is used to determine the weights of different components and defects. Moreover, the weighted sum model technique has been utilized in many research works and has been validated. Therefore, it is used in this research as an aggregation tool.

After reviewing the previous condition assessment models and previous academic research, many limitations have been encountered with regards to the condition assessment of railway infrastructure. Most of the current models assess the track geometry condition, which is a small part of the various defects and components of the railway infrastructure, relying on one inspection technique, which is the track recording car. Moreover, the rest of the condition assessment models are limited to a certain component or a certain type of a track. Some models use one inspection technique such as GPR to assess the substructure of the tracks or they only use the ultrasonic to assess only the rail. None of the reviewed works take into consideration the different speed levels or classes of the railway tracks.

CHAPTER III: RESEARCH METHODOLOGY

3.1 Overview

This chapter provides an overview of the research methodology as shown in Figure 3-1. It consists of the flow chart of the research as well as the used techniques and data resources. The first type of data in this research is the defects types and their nature and the second type of data is the defect severities. The third type is the weights of these defects, the components and the defect categories. This chapter also discusses the model development. The originality of this work is portrayed in the objective manner of classifying defects and in minimizing uncertainty through aggregation. Due to the importance of railway transportation in the family of infrastructures, a comprehensive knowledge of the defects is required for a reliable assessment algorithm. Therefore, this research explores the defects corresponding to all the railway infrastructure components in an objective manner to address the subjectivity and uncertainty in the current condition assessment models.

In this research, railway infrastructure is divided into five main components. It comprises of the Rails, Sleepers (Ties), Ballast, Track Geometry and the Insulated Rail Joints. The defects in each component are classified into certain categories, which are created based on the nature of the defects. Consequently, the relative importance weights of these components, defect categories and defects are obtained by delivering online and hard copy surveys to experts and professionals in this area. After obtaining the weights, the defect severities are fuzzified to uniform the different classifications of defect severities. Finally, both the weights and the severities are aggregated using the Weighted Sum Mean Technique to result in the desired condition. This model is finally interpreted into an automated tool.

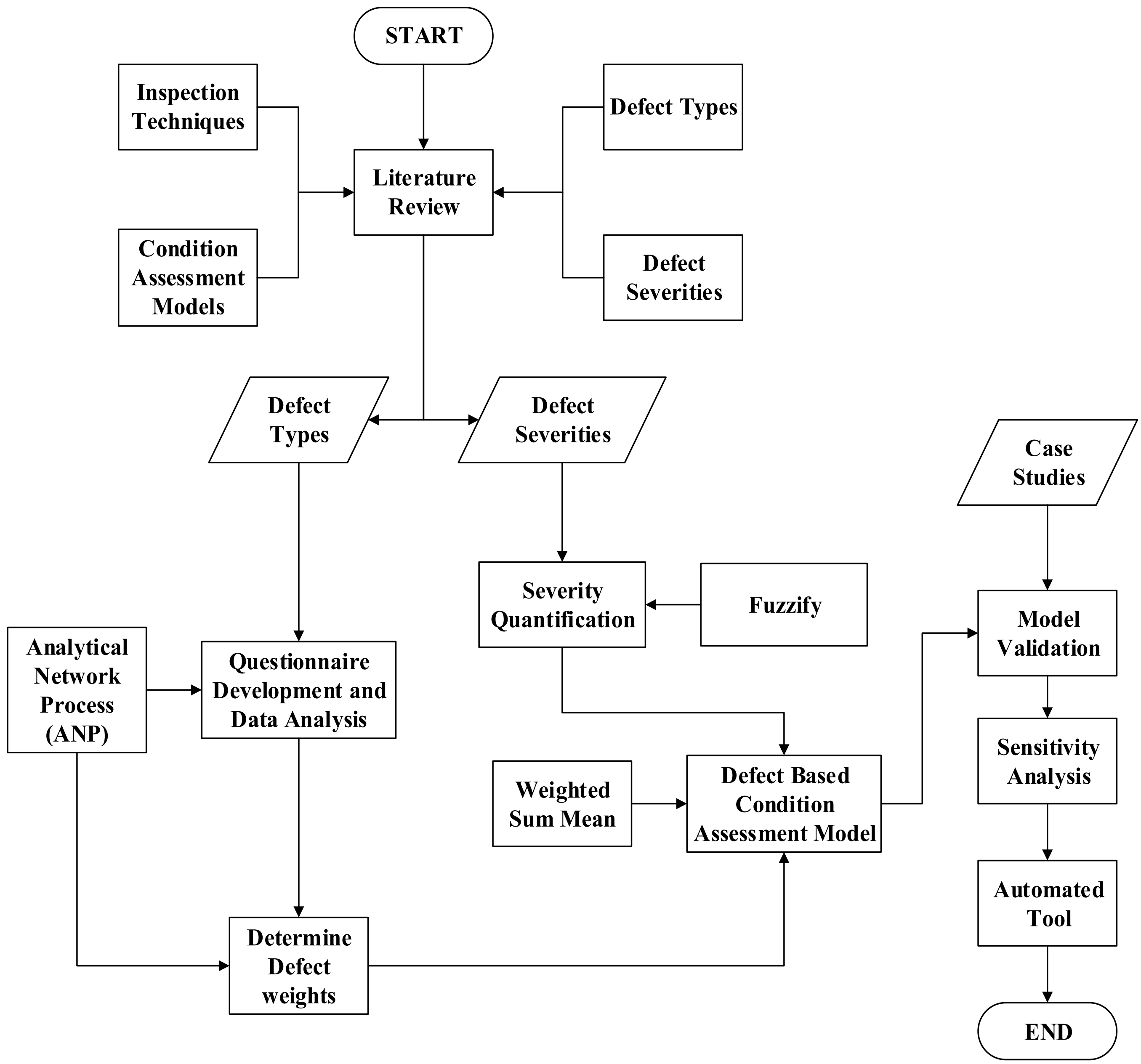


Figure 3-1: Research Methodology Flow Chart

3.2 Data Collection

The first type of collected data is the defects type and their nature. Manuals, books and research papers are used to collect all the defects encountered in railway infrastructure. A collection of 90 different defects associated with the different components is provided. These defects have been sent to experts to summarize them and choose the main defects. A collection of 35 defects is used in building the model. The second data type is the defect severities, for which online and print manuals, advised by professionals, are reviewed. The third data type is the defect weights, found based on a questionnaire. This questionnaire has been distributed to engineers in Canada. Moreover, case studies in the form of inspection sheets are provided by Canarail, the Canadian-based company.

3.3 Model Development

The developed model contains three sub-models: Analytic Network Process Model (weights), Fuzzy Synthetic Evaluation Model (severity) and Weighted Sum Mean Model (aggregation). To build the model, the railway infrastructure is divided into five components (Rails, Sleepers, Ballast, Track Geometry and Insulated Rail Joint) and the defects associated with these components are categorized based on the similarities of the defects. The standard Fuzzy Synthetic Evaluation that comprises both the fuzzification and the defuzzification is adopted to uniform all the different defect criteria and to translate the linguistic grading scale into numerical values. The weighted sum mean model is used to aggregate the weights and the severities, in order to find the desired goals of this research, i.e. to find the condition.

3.3.1 Weight Determination via the Analytic Network Process (ANP)

This model is adopted to obtain the weights corresponding to the components, the defects categories and the defects. The goal is defined as the railway infrastructure in which its overall condition will be affected by the condition of defects and components. After defining all the defects and the hierarchy, pairwise comparisons are built in three directions to consider the interdependencies of the following criteria:

- Between the sub-criteria: Defects.
- Between the main criteria: Components
- Between the main criteria and the goal: Components and the Railway Infrastructure.

The steps below describe the procedure of ANP to find the weights for defect types, their categories and components.

1. Both online and paper questionnaires are developed based on Saaty's (1-9) scale shown in Table 2-3.
2. The questionnaire is distributed to collect experts' opinions.
3. Each questionnaire is analyzed individually to find the weights corresponding to it, using the "SuperDecisions" software.
4. An average value is taken in all the questionnaires to find the weights.

3.3.2 Defect Severity Quantification

The defect severities grading scale along with the defect severities used in this research have been adopted from an Australian manual called Track Inspection TMC 203 (Wilson 2013) and TMC 224 Rail Defects and Testing (Wilson 2011). A six level condition grading scale is defined to describe the different levels of the defect severities. Each level has its own planning time for the inspection and the maintenance action. Table 3-1 describes the six levels of defect severities from normal where the track is in good condition and no maintenance is needed to emergency 1 where the track is in its worst condition and maintenance is needed before the next train passage. Each level is described and an inspection and maintenance time is recommended.

Table 3-1: Railway Track Defects Severity Levels (TMC 203)

Response Category	**Inspect and verify response**	**Action**
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

Fuzzy membership functions of defect indicators are applied in this model to uniform the different defect criteria and to translate the linguistic condition assessment grading scales into numerical values. This model is developed through the following steps:

1. Condition assessment grades (severity) are defined as fuzzy sets (subsets of the universe).
2. Defect severities are deduced from the Australian manuals.

3. Severity quantification is done based on the analysis of the defect severities.
4. The severities are fuzzified based on their common property.
5. Triangular membership function has been used and the upper and lower boundaries of each subset are known.
6. Fuzzy membership functions are applied to all defects and the six severity levels.

3.3.3 Condition Assessment Model

The model is developed by the fuzzy synthetic evaluation technique that includes fuzzification, aggregation and defuzzification. After defining the two main input sets, which are the weights and defects severities, the WSM approach is adopted to aggregate these two input sets to find the desired condition. The WSM approach is applied to find the condition, using the following steps:

1. The corresponding weights and severities for each defect are collected and organized.
2. The first level of the condition is the defect condition, created as a result of multiplication of the defect weight and its own severity using equation 1. There will be 35 conditions related to the 35 defects.

   $$C_i = W_i * S_i \quad \text{.....} (1)$$

   where C_i is defect i condition, Wi is the weight of defect i and S_i is defect i severity.
3. The second step is repeated for all defects to calculate each condition.
4. The second level of condition is the defect category condition. It is a result of aggregating all the defect conditions that are in the same category. Equation 2 represents the mathematical formulation representing the aggregation step. The weight of each defect is multiplied by its severity, divided by the maximum severity the defect reaches.

$$C_c = \sum_{i=1}^{n} W_i \ * \ \frac{S_i}{S_{imax}} \quad \ldots\ldots \text{(2)}$$

where C_c is the defect category condition, Wi is the weight of defect i, S_i is defect i severity, S_{imax} is the maximum severity level defect i reaches and n is the number of defects for one defect category.

5. Step 4 is repeated for all defect categories to find their corresponding condition.
6. The component condition is a result of aggregation of each component's defect category condition. Equation 3 represents the mathematical formulation representing the component condition. The weight of the defect category is multiplied by its condition from the previous step.

$$C_p = \sum_{j=1}^{m} W_j \ * \ C_{cj} \quad \ldots\ldots \text{(3)}$$

where C_p is component condition, W_j is the weight of defect category j, C_{cj} is defect category j condition and m is the number of defect categories.

7. The final level of condition is the overall infrastructure condition. The infrastructure condition is a result of aggregation of the component condition. Equation 4 illustrates the aggregation step. The weight of components is multiplied by their corresponding condition found before.

$$C_I = \sum_{k=1}^{L} W_k \ * \ C_{p_k} \quad \ldots\ldots \text{(4)}$$

where C_I is the infrastructure condition, C_{pk} is component k condition, W_k is the weight of component k and L is the number of components, i.e. 5 components.

3.3.4 Model Testing

Model testing is a major step in model development. Model testing is done to check the integrity of the developed model. Therefore, two case studies have been used. The data is provided in excel files of field inspection reports, done by experts using visual inspection techniques. The case studies are segments of railway tracks with different speed levels. The data is provided by Canarail Company in Montreal, Canada. The case studies are implemented in the model and the results are compared with those of the original decision.

3.4 Railway Condition Assessment Automated Tool

The railway infrastructure condition assessment automated tool consists of six different speed levels of the track to assess the condition of the railway infrastructure for all of its classes. Each speed level has its own spreadsheet since the severities of the defects change with the speed. Each spreadsheet includes all the components, defects and defect categories. The overall condition is based on the five components. The developed spreadsheet is a user-friendly interface that helps the user obtain the respective conditions through incorporating the defects obtained from the inspection sheets done by the inspectors or the inspection technologies. The automated tool is developed through Microsoft Excel in which the fuzzy membership functions of each defect, the ANP weights and the severities driven from the specifications, the WSM aggregation technique and the defuzzification approach are all incorporated into this model. The spreadsheet gives a detailed condition, overall condition, defect category condition and component condition, helping decision- makers in the process of planning for maintenance and rehabilitation.

3.5 Summary

This chapter has elaborated the research methodology used to build the condition assessment model for railway infrastructure. In brief, the model development goes through several stages. Starting with the collection and categorization of defects types, the components are studied in terms of their nature, their material and the factors affecting their life cycle. Then, the condition grading scale and defect severities (S) are defined. Moreover, the analytic network process model is adopted to find the defects, defect categories and component weights (W). ANP is also used for the interdependency of the sub-criteria and the main criteria, the interdependency of the main criteria themselves and the interdependency of the main criteria with respect to the goal. Furthermore, fuzzy synthetic evaluation is utilized to uniform the different criteria of the defects and to translate the linguistic condition rating systems into numerical values. Consequently, the Weighted Sum Mean approach is used to aggregate the defect weights W and the defect severities S to find the railway infrastructure condition.

CHAPTER IV: DATA COLLECTION

4.1 Introduction

This research has so far reviewed several sources to give a better understanding of railway infrastructure. A number of railway infrastructure condition assessment manuals are studied to elaborate on different ways of railway infrastructure condition assessment. Also, several previous researches are reviewed to help in developing this model. Figure 4-1 illustrates the types of the collected data to build this model. The data is divided into three types (defect types, categories and components, defect weights and defect severities). The following sections discuss the collected data in details.

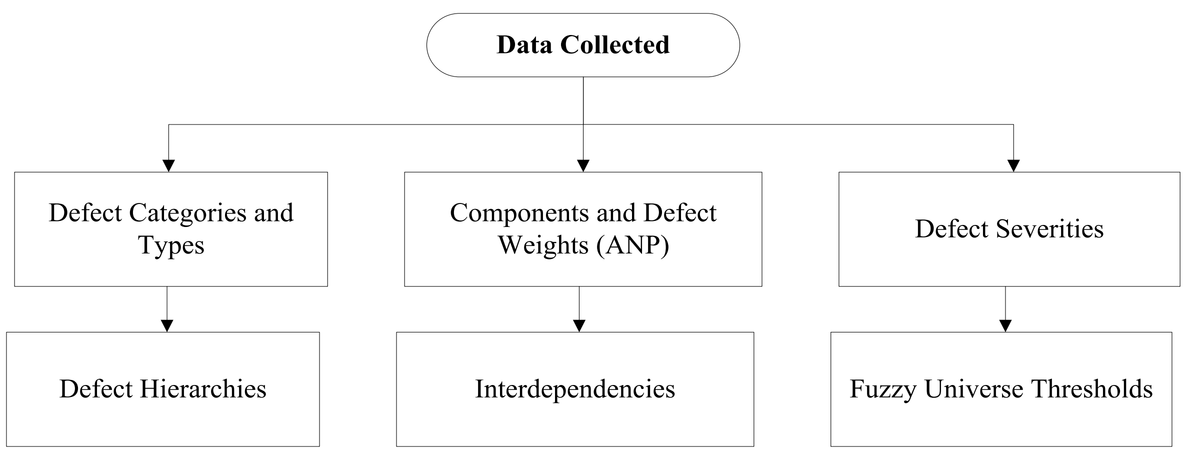


Figure 4-1: Types of Data Collected

4.2 Components, Defect Categories and Defects

This section presents the different components, defect categories and defects related to railway infrastructure, based on the reviewed literature. Over ninety different defects have been encountered, summarized to thirty-five defects based on experts' opinions on the main defects that inflict railway infrastructure. Railway infrastructure is composed of five main components, i.e. rails, sleepers (ties), ballast, track geometry and insulated rail joints. Their defects are categorized in form of a comprehensive hierarchy to represent railway infrastructure.

4.2.1 Rail Defects

The rail defects are divided into three main categories, rail internal defects, surface defects and rail wear defects.

I. **Rail internal defects**

   Table 4-1 lists the main rail internal defects with a brief description for each. The internal defects in a rail segment are used to interpret the rails' physical condition and their severity. Examples are broken rails as one of the most railway accident causes, compound fissures as progressive fractures in the rails head, defective welds representing the defects in the weld areas for continuous welded tracks, foot and web separations, head and web separations and the rail cracks that propagates and can deform into severe defects if not maintained properly.

II. **Surface defects**

   Table 4-2 lists the main rail surface defects along with a brief description for each. The surface defects in a rail segment are used to interpret the rails surface condition and their severity. Examples are fish scaling, spalling as the cracking and chipping of the rail surface, rail contact fatigue as thin cracks appearing at the gauge corner of the rail, rail corrosion and wheel burns.

Table 4-1: Rail Internal Defects (AREMA, 2010) (Kumar 2006) (Wilson, TMC 203 Track Inspection, 2013) (Wilson, TMC 224 Rail Defects and Testing, 2011)

Defect	Definition
Broken rail	A lateral break in the rail.
Compound Fissure	A progressive fracture in the rail head that originates as a horizontal separation turning up and down or in both directions, to form a transverse separation substantially at right angles to the running surface. Compound fissures may include multiple horizontal or vertical planes.
Defective Welds	A field or plant weld containing any discontinuities or pockets.
Foot and Web separation	A crack that occurs in the foot and web fillet area; it is a progressive crack along the fillet.
Head and Web separation	A progressive fracture, longitudinally separating the head from the web of the rail at the head fillet area.
Rail cracks	Cracks that propagate in the rails, as hidden most of the time.

Table 4-2: Rail Surface Defects (AREMA, 2010) (Kumar 2006) (Wilson, TMC 203 Track Inspection, 2013) (Wilson, TMC 224 Rail Defects and Testing, 2011) (RailCorp 2012)

Defect	Definition
Fish Scaling; Spalling	Cracking and chipping of the rail surface; spalling is a progression of head checking and flaking.
Rail Contact fatigue	Thin cracks appearing at the gauge corner of the rail, appearing most often on the outer rails of curves and sometimes on tangent rails but infrequently on low rails.
Rail Corrosion	Corrosion is the disintegration of the rail starting at the surface, from chemical decay, mainly oxidation (rusting). As it progresses, it often forms irregular pits and cavities, or it develops cracks in the rail web or the base.
Wheel Burns	Defects that form on the running surface of the rails.

III. **Rail Wear Defects**

Table 4-3 lists the main rail wear defects along with a brief description for each. Three main defects are curve wear, tangent wear and head loss percentage. The rail wear defects in a rails segment are used to interpret the rail wear condition and its severity. Rail wear is one of the most common defects in rails, needing continuous lubrication to avoid these defects. Rail wear defects can be resolved by rail grinding technology.

Table 4-3: Rail Wear Defects (AREMA, 2010) (Wilson, TMC 203 Track Inspection, 2013) (Wilson, TMC 224 Rail Defects and Testing, 2011) (RailCorp 2012)

Defect	Definition
Head Loss Max %	Percentage loss of the head part of the rail due to the grinding or the movement of the train
Curve Wear	Separation or cutting of the rail due to friction and abnormal heavy loads
Tangent Wear	Separation or cutting of the rail due to friction and abnormal heavy loads

4.2.2 Sleeper (Tie) Defects

The sleeper defects are divided into two main categories: Sleeper Condition Defects and Sleepers Component Defects. The sleeper condition defects are divided based on the nature of the sleepers, concrete sleepers and timber sleepers.

I. **Sleeper Condition Defects**

Table 4-4 lists the main sleeper condition defects for both concrete and timber sleepers along with a brief description for each. The sleeper condition defects are used to interpret the sleeper conditions and their severity. Based on the sleeper condition defects, the nature of the sleepers are divided into two groups: concrete sleepers and timber sleepers. The concrete sleeper defects are called general sleeper defects because the timber sleeper defects can be described by the concrete defects, such as spacing defects. According to the timber sleeper defects specifications, when the sleeper defects reach a certain percentage, the specifications refers to the concrete sleepers defects of clusters of consecutive ineffective sleepers. The main sleeper in the cluster of consecutive ineffective sleepers is that a number of sleepers are not in a good condition and they are not supporting the rails properly.

II. Sleeper Components Defects

Table 4-5 illustrates the sleeper component defects with a brief description for each. The sleeper component defects describe the condition of the sleeper components connected to the rails such as insulators, pads and bolts. Defects such as squeezed, missing or failed insulators are caused by continuous loading, worn sleeper pads and their higher dynamic loads, loose or missing bolts, etc.

Table 4-4: Sleeper Condition Defects (AREMA, 2010) (Wilson, 2013) (Zakeri and Rezvani 2012)

Sleeper Type	Defects	Definition
General sleepers defects	**Consecutive Missing Sleepers**	Defective sleepers in a row
	Spacing	Spacing deviation between sleepers
	Clusters of Consecutive Ineffective Sleepers	Ineffective sleepers not functioning their proposed [what?]
Timber sleepers defects	**Ineffective Timber Sleepers at Joints**	Defective sleepers at joints areas
	General Condition Description Timber Sleepers	The percentage of defective sleepers

Table 4-5: Sleeper Components Defects (AREMA, 2010) (Wilson, TMC 203 Track Inspection, 2013) (Zakeri and Rezvani 2012)

Defects	Definition
Squeezed out missing or failed insulators	Insulation failed due to continues loading; the failure could be that the insulation materials are squeezed between the steel components of the insulation system or could be missing.
Severely worn sleeper pads	Becoming worn with time, due to the continuous loading, and increases the dynamic loading
Loose or Ineffective Fish Bolts	Shear failure of bolts caused by electrolysis/corrosion; due to corrosion and electrolysis within a few months of installation, i.e. when the insulator sleeve breaks due to shear failure and corrosion
Swage Fastenings at Fish-Plated Joint	Becoming loose with time, due to the continues loading, increasing the dynamic loading

4.2.3 Ballast Defects

The ballast defects are divided into two main categories: Ballast profile and drainage.

I. **Ballast Profile**

Table 4-5 illustrates ballast profile defects with a brief description for each. Ballast profile defects are used to interpret the ballast amount, their profile condition and their severity. Two ballast profile defects have been chosen here, the ballast deficiency that signifies insufficient amounts of ballast that causes geometry-related issues. Excess ballast also signifies extra amounts of ballast that might interfere with the passing trains and can cause issues for the signaling devices.

II. **Drainage**

Table 4-6 explains the main two defects that cause drainage blockage. Drainage defects in a ballast are used to interpret the ballast drainage property conditions and their severity. There are two main causes for ballast drainage blockage: One is the fouling that shows ballast blockage caused by fine materials filling the voids. The other is vegetation growth in the ballast system, which blocks the voids and trap water in the tracks.

Table 4-5: Ballast Profile Defects (Sadeghi and Askarinejad 2010) (Esvald, 2001)

Defects	Definition
Ballast deficiency	Loose ballast from the track, causing geometry defects and poor sleeper support by the ballast, e.g. cracking of sleepers and bearers, excessive vertical sleeper movement or track pumping
Excess Ballast	Too much ballast on track; ballast can foul the signaling equipment, especially at points and train stops. It can also foul rolling stock and cause tripping of trains track sections where the ballast profile may interfere with the operation of infrastructure (e.g. signals or switches) or rolling stock.

Table 4-6: Drainage Defects (Lim 2004) (Esvald 2001)

Defects	Definition
Fouling	Fine material fills the voids between the ballast particles, causing lake of drainage in the track; this will trap water in the track.
Vegetation Growth	When found in the ballast area, it indicates fouled ballast and result in poor drainage.

4.2.4 Track Geometry Defects

Table 4-7 explains five geometry defects, i.e. gauge, twist, cross-level variation and horizontal and vertical alignment deviation. Geometry defects, with their unified nature, fall into one category. Geometry defects are one of the main concerns in the railway industry since they are the second main cause of railway accidents (Liu, et al. 2014). Gauge is the distance between the rails and the horizontal and vertical alignments are the profile of the track, twist and cross-level variations, showing the difference in the level of the two rails.

Table 4-7: Geometry Defects (Esvald, 2001) (AREMA, 2010) (Canada, 2012)

Defects	**Definition**
Gauge	Distance measured between the two parallel rails; gauge is measured between points on the gauge face (or inside) of the rails, 16 mm below the top.
Horizontal alignment	Position of the track or rail in the horizontal plane; it is expressed as being tangent or curved alignment and is measured in a straight track by stretching a 62’ string between two points along the gauge corner of the rail.
Top (vertical alignment)	Is the track layout on the vertical plane? This can be thought of as the elevation view, i.e. the side view of the track to show track elevation. In track geometry, the vertical layout involves concepts such as cross-level, cant and gradient.
Cross-level variation	Difference in the level of the two rails at a single point along the track.
Twist	Variation in actual track cross-level (i.e. the difference in the level of the two rails) over a defined length; the twist is to be assessed by two criteria. The short twist is measured over 2 m and the long twist is measured over 14 m.

4.2.5 Insulated Rail Joints Defects

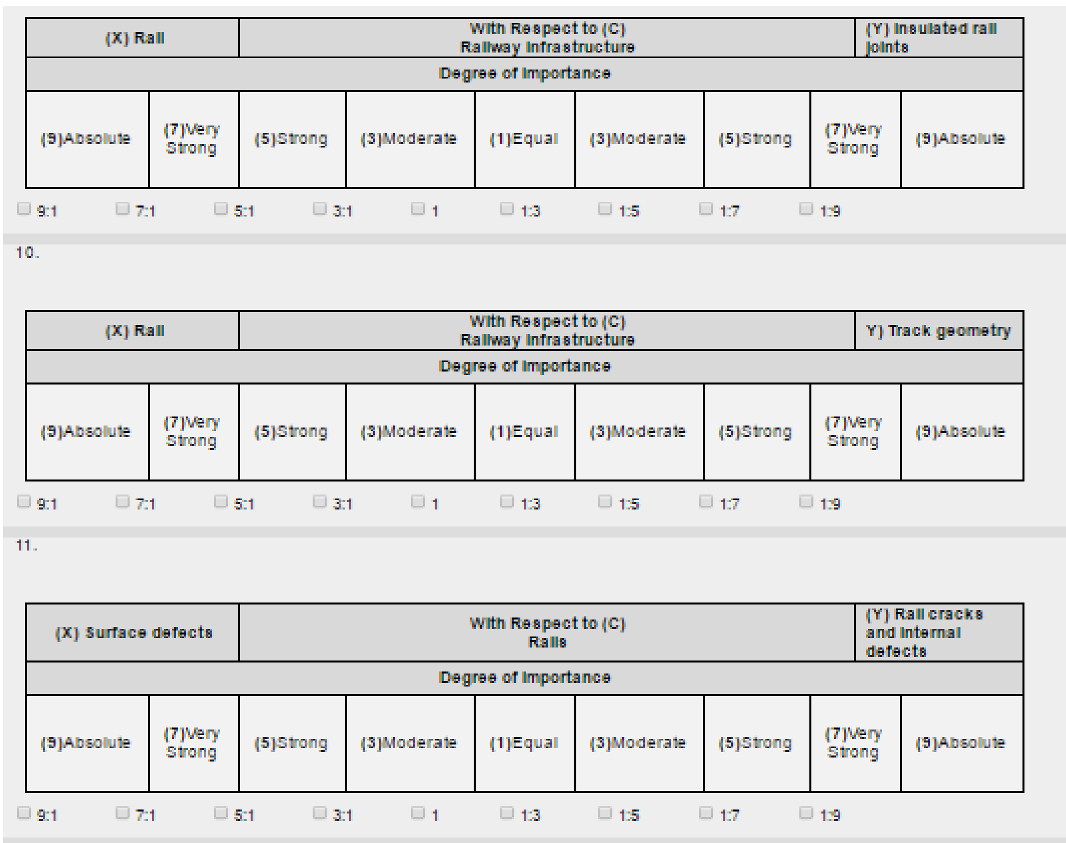
Table 4-8 illustrates the defects in insulated rail joints with a description of each. The insulated rail joints, with their unified nature, fall into one category. The insulated rail joint is an important component in signaling train movements to ensure safety in railway crossings. Four main defects in this component have been encountered: Loss or failure of the insulated materials, causing signaling failures; joint gap movement; ineffective drainage around the joint, causing water trapping; and rail head flow around the joints causing a gap between the two connected rails.

Table 4-8: Insulated Rail Joints Defects (Wilson, 2013)

Defects	Definition
Loss or failure of insulation material	Insulation material visibly cracked or disintegrated; components fail to insulate (generally causing signal failure)
Joint Gap Movement	Insulation key being squeezed out; joint pulling apart -visible gap at insulation key, joint pulling apart -bent bolts
Ineffective Drainage around Joint	Water lying in joint vicinity, water contacting a rail foot near joints
Railhead flow across joint Rail	Flow on either rail with potentials to provide a gap between rail ends

4.3 Weight Data Collection

This research has adopted the analytic network process to find the components, defect categories and defect weights. This process has been specifically chosen to account for the interdependency of sub-criteria (defects), criteria (defect categories and defects) and each other. A questionnaire has been developed and distributed first, both in hard copy and online. The online questionnaire has been developed based on "http://www.surveyexpression.com" – the website that allows the user to build and distribute questionnaires. The site provides a detailed analysis of the filled questionnaires. Both surveys consist of six parts with a total of 66 questions. The general question is as follows: What is the relative importance of element (X) over an element (Y) with respect to element (C). The first part in the survey is a general pairwise comparison of the components and defect categories with respect to the set goal. The second part is a pairwise comparison of the rails defect categories and defects. The third part is a pairwise comparison of the sleepers defect categories and defects. The fourth part is a pairwise comparison of the ballast defect categories and defects. The fifth part is a pairwise comparison of the track geometry defects. The final part is a pairwise comparison of the insulated rail joints defects. Figure 4.2 shows a sample of the online survey with part of the comparison between the components. The full hard copy survey can be found in Appendix A.



(X) Rail		With Respect to (C) Railway Infrastructure						(Y) Insulated rail joints
Degree of Importance								
(9)Absolute	(7)Very Strong	(5)Strong	(3)Moderate	(1)Equal	(3)Moderate	(5)Strong	(7)Very Strong	(9)Absolute

☐ 9:1 ☐ 7:1 ☐ 5:1 ☐ 3:1 ☐ 1 ☐ 1:3 ☐ 1:5 ☐ 1:7 ☐ 1:9

10.

(X) Rail		With Respect to (C) Railway Infrastructure						Y) Track geometry
Degree of Importance								
(9)Absolute	(7)Very Strong	(5)Strong	(3)Moderate	(1)Equal	(3)Moderate	(5)Strong	(7)Very Strong	(9)Absolute

☐ 9:1 ☐ 7:1 ☐ 5:1 ☐ 3:1 ☐ 1 ☐ 1:3 ☐ 1:5 ☐ 1:7 ☐ 1:9

11.

(X) Surface defects		With Respect to (C) Rails						(Y) Rail cracks and internal defects
Degree of Importance								
(9)Absolute	(7)Very Strong	(5)Strong	(3)Moderate	(1)Equal	(3)Moderate	(5)Strong	(7)Very Strong	(9)Absolute

☐ 9:1 ☐ 7:1 ☐ 5:1 ☐ 3:1 ☐ 1 ☐ 1:3 ☐ 1:5 ☐ 1:7 ☐ 1:9

Figure 4-2 Online Survey Sample

4.3.1 Questionnaire Response Statistics

Table 4-9 shows the statistics based on the survey given to more than 50 experts, managers and engineers in railway engineering and construction in Canada. Fifteen questionnaires are collected, one is neglected due to giving the same answer for all the questions and the majority has been filled by engineers with varying years of experience in the field. Figure 4-3 shows the distribution of respondents' number of years of experience, where 64% of the questionnaires are filled by engineers with more than 20 years of experience – providing more reliable results. 14% of the questionnaires are from respondents with 6-10 years, 7% with 11-16 years and 15% with less than 5 years of engineering experience.

Table 4-9: Questionnaire Statistics

Survey	Numbers
Sent	>50
Received	15
Discarded	1
Considered	14

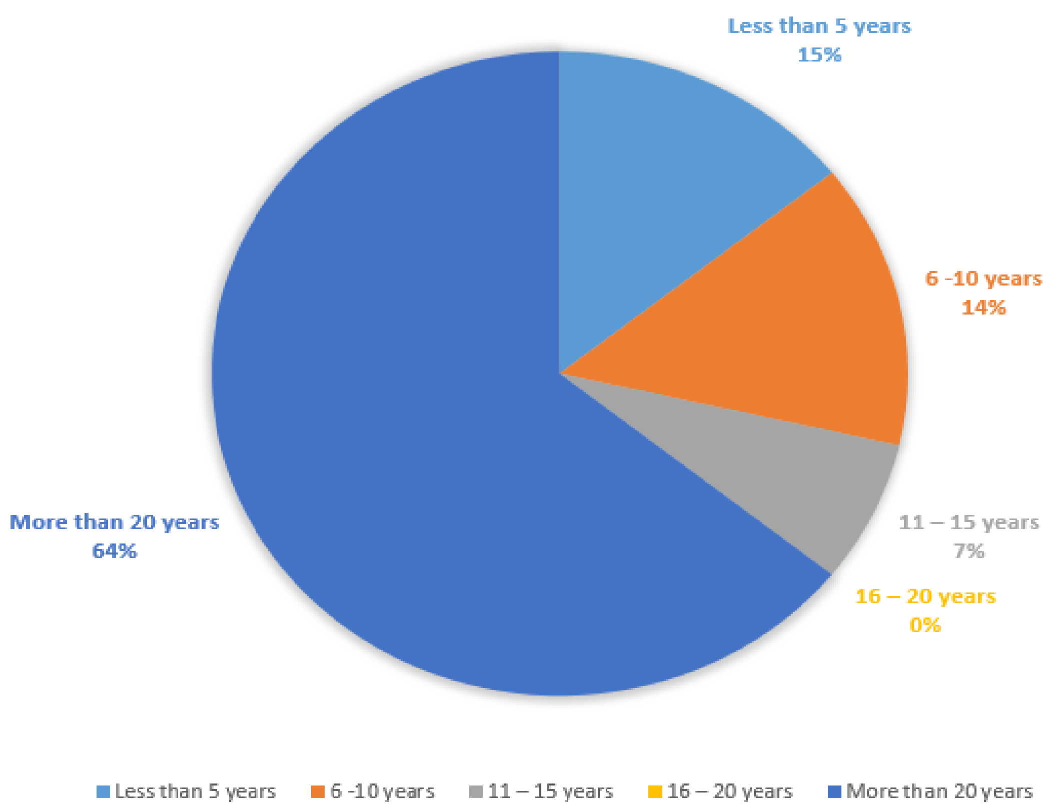


Figure 4-3 Years of Experience of Respondents Distribution

4.3.2 Questionnaire Analysis

To analyze the surveys, the responses are checked for the credibility of the questionnaires and for being used in the process of weight determination. The responses to 66 questions are reviewed and their corresponding statistics are provided. The questions are based on pairwise comparisons, as mentioned earlier and the comparisons are between two components or two defect categories or defects. They have two sides: Whether element X is more important than element Y or element Y is more important than element X. 95% of the questions are one-sided. An average of 76% of the responses to the same question is one sided, meaning that the answers to the same question has the same point of view when it comes to which element is more important than the other. Table 4-10 illustrates an example for the questions as well as their response statistics. The example question compares the sleeper component (X) to the insulated rail joint component (Y) with respect to ballast (C). 85.8% of the responses take the side of the sleepers and the majority says that the ballast is more important than the insulated rail joints.

Table 4-10 Sleepers to Insulated Rail Joints Comparison Statistics

Comparison elements	(X) SLEEPERS		WITH RESPECT TO (C) BALLAST					(Y) INSULATED RAIL JOINTS	
DOI	DEGREE OF IMPORTANCE								
DOI #	9	7	5	3	1	3	5	7	9
# Of Ques	1	1	6	3	1	0	1	1	0
% Of Ques	7.1%	7.1%	43%	21.5%	7.1%	0	7.1%	7.1%	0

4.4 Defect Severities

Different sources have been carefully reviewed to define defect severities. These sources have been advised by experts such as the Transport Canada Track Safety Regulations (Transport Canada 2012) and the US Federal Railway Administration (FRA) Regulations (Office of

Railroad Safety 2014). Neither of these Canadian and American manuals are useful for this research. The FRA and Transport Canada establish the minimum safety standards for various classes of track. They are commonly referred to as URGENT limits. If and when a track section reaches these limits, the operating railway is obligated to implement the appropriate corrective action immediately to protect rail traffic. These manuals cannot be used as a maintenance manual since the development of standards or criteria for the maintenance of railways, track and structures has always been the prerogative of individual railways, based on the nature and characteristics of their plant and operations and the specific characteristics of the geographical region or regions through which they operate. Therefore, each major railway company in Canada uses their own standards.

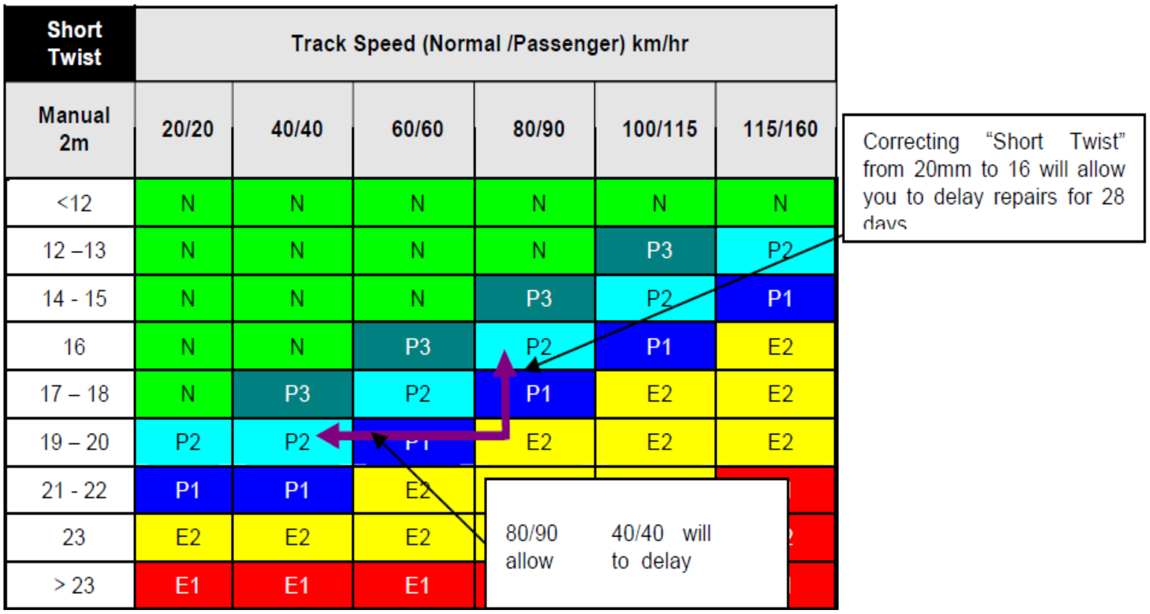
The Canadian companies' specifications for defect severities use three levels of severity where the first is the priority level followed by the near urgent. The maximum severity level is urgent, when the urgent level is the same as the urgent limits from transport Canada. This research does not use Canadian maintenance manuals for confidentiality reasons. Besides, several other condition assessment scales have been mentioned earlier in section 2.4, i.e. previous research works on railway infrastructure.

Two online Australian manuals are used in this research to define the desired severities. Developed by RailCorp Engineering, they are TMC 203 Track Inspection (Wilson 2013) and TMC 224 Rail Defects and Testing (Wilson 2011). Table 4-11 illustrates the six level condition grading scale developed by Railcorp and used in this research. The best track condition is defined as normal and represents the first severity level and the worst condition is defined as emergency one (E1) condition where maintenance is required before the passage of the next train. Each level of the condition grading scale recommends an inspection and variation time along with the required maintenance

The severity of the railway infrastructure defects changes with the speed level of the track. It means that the same defect can be more dangerous when the speed of the track is higher. So, six-speed levels are taken into consideration. Different defects have different criteria and different ways of measurement. Some defects reach more severe levels than others. As an example, broken rails reach emergency 1 level while ballast fouling reaches priority 1 level. To uniform the different defect severities, defuzzification technique is adopted as mentioned in Chapter 3. Figure 4-4 illustrates an example for the short twist defect severities when severities are divided by the six levels of condition grading scale, marked by their color codes. It shows how the defect severities change with speed and how to determine the exact condition based on the collected data.

Table 4-11: Railway Track Defects Severity levels (TMC 203)

Response Category	Inspect and verify response	Action
Emergency 1 (E1)	Prior to passage of next train	Prior to passage of next train
Emergency 2 (E2)	Within 2 hrs or before the next train, whichever is the greater	Within 24 hrs
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



Short Twist	Track Speed (Normal /Passenger) km/hr					
Manual 2m	20/20	40/40	60/60	80/90	100/115	115/160
<12	N	N	N	N	N	N
12 –13	N	N	N	N	P3	P2
14 - 15	N	N	N	P3	P2	P1
16	N	N	P3	P2	P1	E2
17 – 18	N	P3	P2	P1	E2	E2
19 – 20	P2	P2	P1	E2	E2	E2
21 - 22	P1	P1	E2	[illegible]	[illegible]	[illegible]
23	E2	E2	E2	[illegible]	[illegible]	[illegible]
> 23	E1	E1	E1	[illegible]	[illegible]	[illegible]

Figure 4-4: Twist Defect Severity (TMC 203)

4.5 Case Studies

Model implementation and validation is a major step in the model development process. Validation is the step where model credibility and reliability are checked. In this important step, case studies of the existing railway infrastructure inspection sheets or data are provided by means of inspection technologies along with the experts’ analyses and the final decision. For desired case studies, the railway industry in Canada has been contacted and two case studies have been provided by Canarail Company in Montreal, Quebec.

4.5.1 Case Study 1

The first case study is a class 1 track with a 20 km/h speed limit with 65 km of the existing track located in Ontario, Canada. The inspection is done by experts and the inspection sheets and the final decision are provided. The track has a lot of fouled ballast and a high percentage of the wooden sleepers are defective. The final decision is a sleeper rehabilitation program. Pictures in figure 4-5 describe different components of different milepost tracks. While (A) describes a tangent part of the track showing the main components, (B) shows fouled ballast and (C) prescribes some defective sleepers.

Figure 4-5 Case 1 photos of Different Segments (A) Tangent Part of the Track (B) Fouled Ballast (C) Defective Sleepers

4.5.2 Case Study 2

The second case study is a class 5 track with a 150 km/h speed limit with 25 km of tracks also located in Ontario, Canada. The inspection is done by experts and the inspection sheets and the final decision are provided. The track does not show any deficiencies and only a small percentage of the sleepers are defective. No maintenance plans are taken while the sleepers should be monitored. Pictures in figure 4-6 describe different components of different milepost tracks. (A) Describes a tangent part of the track that shows the main components, (B) shows railway switches and (C) prescribes excess ballast covering sleepers.

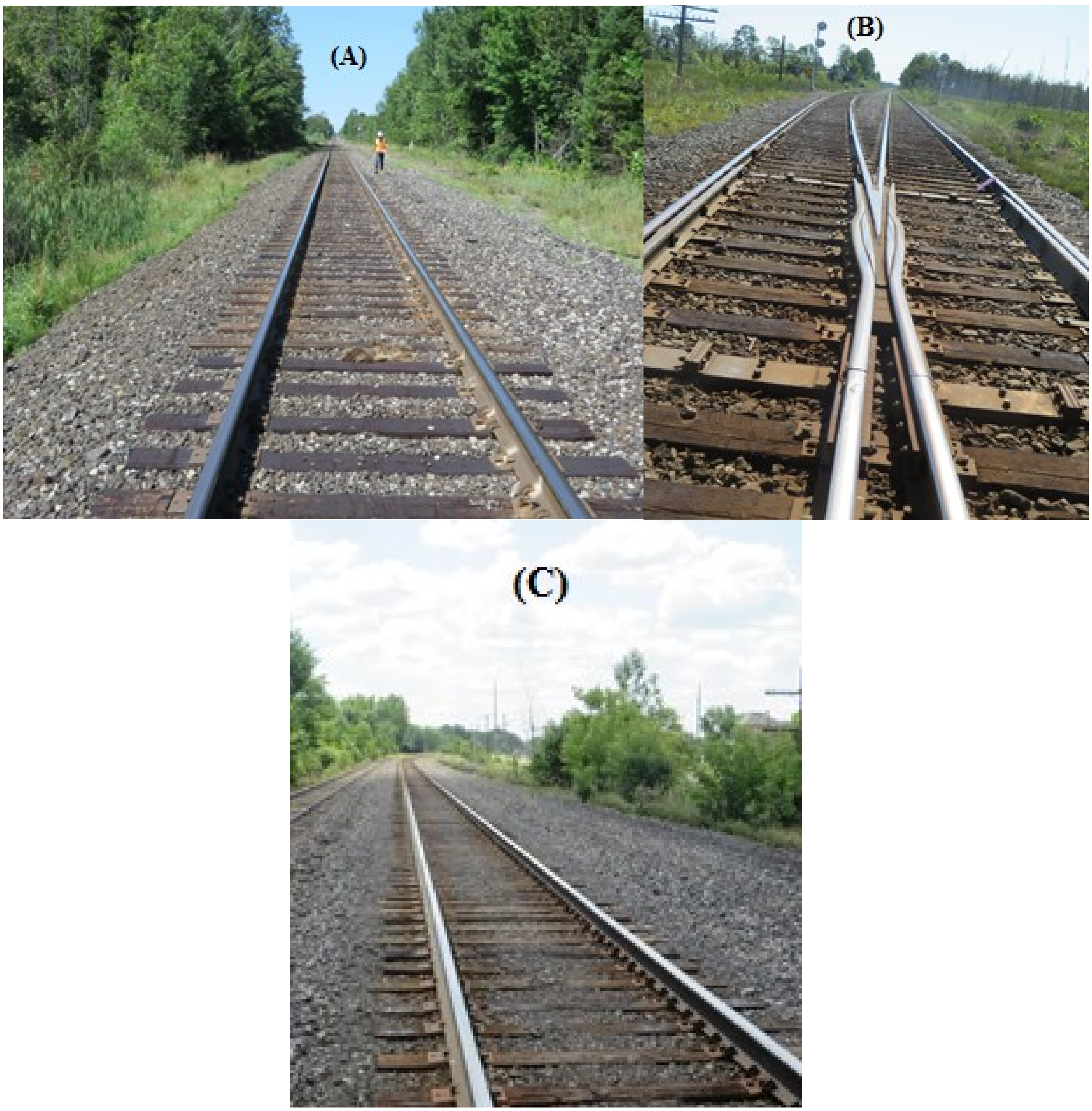


Figure 4-6 Case 2 Photos Describing Deferent Segment of The Track (A) Tangent Segment of the Track (B) Switch (C) Ballast Covering the Sleepers.

4.6 Summary

This chapter provides the data collection procedure in this research. The first type of the collected data is the components, defect categories and defects, investigated and well understood. The second type of the collected data is the surveys distributed among professionals for credible pairwise comparisons, to obtain the components, defect categories and defect weights. Moreover, various sources are reviewed to define the defect severities in the fuzzy set model. Finally, case studies are collected for the purpose of model implementation and testing.

CHAPTER V: MODEL DEVELOPMENT AND IMPLEMENTATION

5.1 Introduction

This chapter outlines the use of techniques explained in the previous ones to develop the defect-based condition assessment model through results, implementation and validation. Here, the constructed defect hierarchy of the railway infrastructure components and their defects are first presented. Then, the relative importance weights are discussed and analyzed. The relative weights include components, defect categories and defects. Additionally, the condition grading assessment scale and the defect severities are demonstrated. Furthermore, this chapter presents the fuzzy membership functions adopted to uniform the different defect criteria. Consequently, the aggregation process that uses weighted sum mean is explained through examples and the defuzzification process. Finally, this chapter discusses the implementation of the case studies as well as the model's verification and validation.

5.2 Model Hierarchies

To discuss the railway infrastructure and provide a hierarchy to apply the models mentioned beforehand, the model is divided into five main components, rails, sleepers (ties), ballast, track geometry and insulated rail joints – each with zero to three defect categories. Figure 5.1 describes a railway infrastructure hierarchy for the five main components with each component defect category, as an example, showing the sleeper component with its two defect categories, sleeper components and sleeper condition defects.

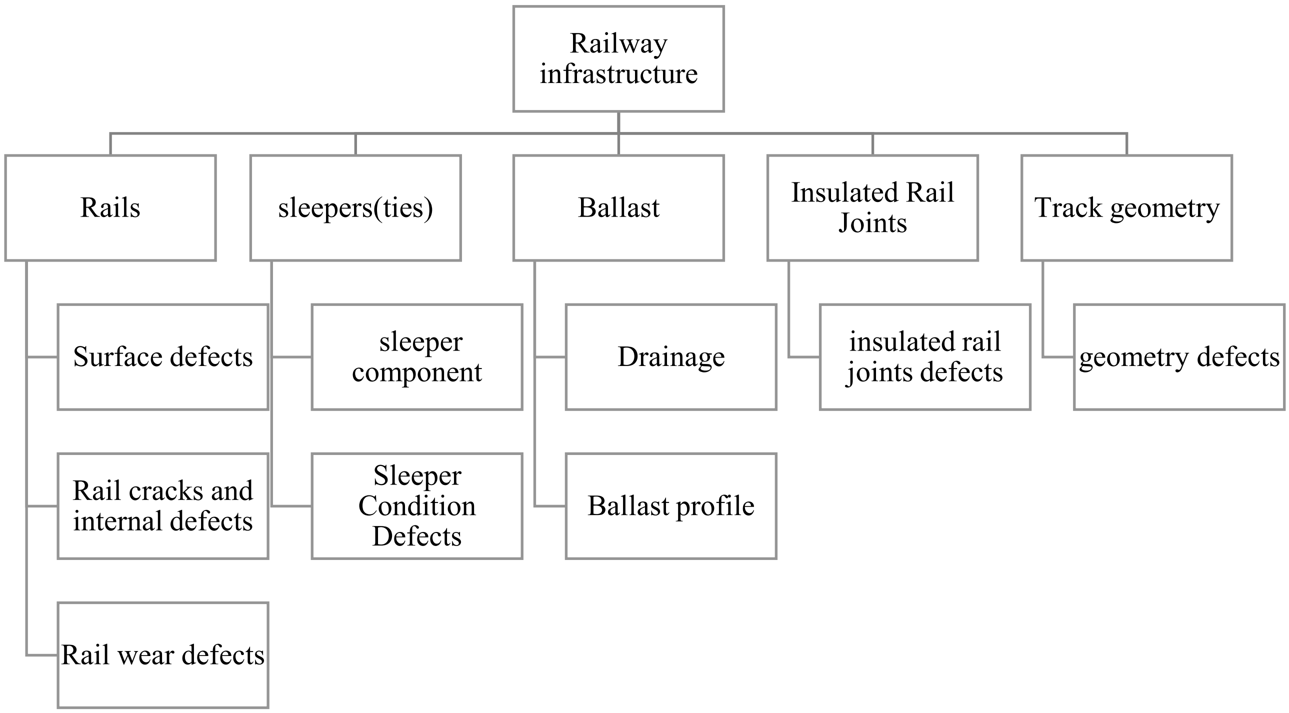


Figure 5-1: Railway Infrastructure Hierarchy

5.2.1 Railway Infrastructure Defects Hierarchy

Table 5-1 illustrates the railway infrastructure defect hierarchy that consists of the main five components – rails, sleepers, ballast, track geometry and insulated rail joints – as well as their defect categories and the corresponding defects of each. Several manuals are reviewed and professionals are consulted to define the main defects that occur in railway infrastructures. A summary of 35 defects has been chosen to build the desired defect-based condition assessment model. The two timber sleeper defects are not mentioned in the table below due to the similar nature and description of the concrete defects. Therefore, the concrete sleeper defects are used to describe the sleeper defects. A full and detailed description of the components, defect categories and defects can be found in chapter 4 on data collection.

Table 5-1 Railway Infrastructure Defects Hierarchy

Parts	Defects Categories	Defects
Rails	Surface defects	Fish Scaling; Spalling
		Rail Contact fatigue
		Rail Corrosion
		Wheel Burns
	Rail cracks and internal defects	Broken rail
		Compound Fissure
		Defective Welds
		Foot and Web separation
		Head and Web separation
		Rail cracks
	Rail wear	Head Loss Max %
		Curve Wear
		Tangent Wear
Ballast	Ballast Profile	Excess Ballast
		Ballast deficiency
	Drainage	Fouling
		Vegetation Growth
Sleepers (Ties)	Sleepers Condition Defects	Clusters of Consecutive Ineffective Sleepers
		Consecutive Missing Sleepers
		Spacing
	Sleepers Components Defects	Loose or Ineffective Fish Bolts
		Severely worn sleeper pads
		Squeezed out missing or failed insulators
		Swage Fastenings at Fish-Plated Joint
Geometry	Geometry	Gauge
		Horizontal alignment
		Top Vertical alignment
		Twist
		Cross-level variation
Insulated Rail Joints	Insulated Rail Joints	Loss or failure of insulation material
		Joint Gap Movement
		Ineffective Drainage around Joint
		Railhead flow across joint Rail

5.3 Weights (W)

This research adopts the Analytic Network Process (ANP) to compute the relative importance weights of the components, defect categories and defects using the previously mentioned defect hierarchies. This analysis takes fourteen surveys into account. Due to the large number of defects, “SUPER DECISIONS” software is employed to find the weights. Figure 5-3 shows the defect hierarchy built in “SUPER DECISIONS” software for the survey analysis. The hierarchy gathers the components, defect categories and defects. The answers from the fourteen questionnaires are the input for the “SUPER DECISIONS” software. The fourteen questionnaires are input individually into the software and the associated weight matrices are extracted. After extracting all the weights from the questionnaires, an average value of the weights (W) is used in the aggregation process.

Three levels of weights based on the three levels hierarchy are found. The first level is components weights, defect category weights and defect weights. Table 5-5 summarizes all the three level weights. The component weights analysis shows that the sleepers have the highest weight (27%) followed by track geometry (26%), ballast (18%), rails (16%) and insulated rail joints (13%) with the lowest weight among the components.

The rail defect weights show that the rail internal defects have the highest weight (41%). The surface defects with a weight of (35%) has the second highest and the wear defects (24%) has the lowest weight. This result is reasonable as the internal defects are a major cause of accidents. Moreover, in the internal defects category, broken rails are given the highest weight (26%). These results are logical since the broken rails are considered one of the worst kinds of defects.

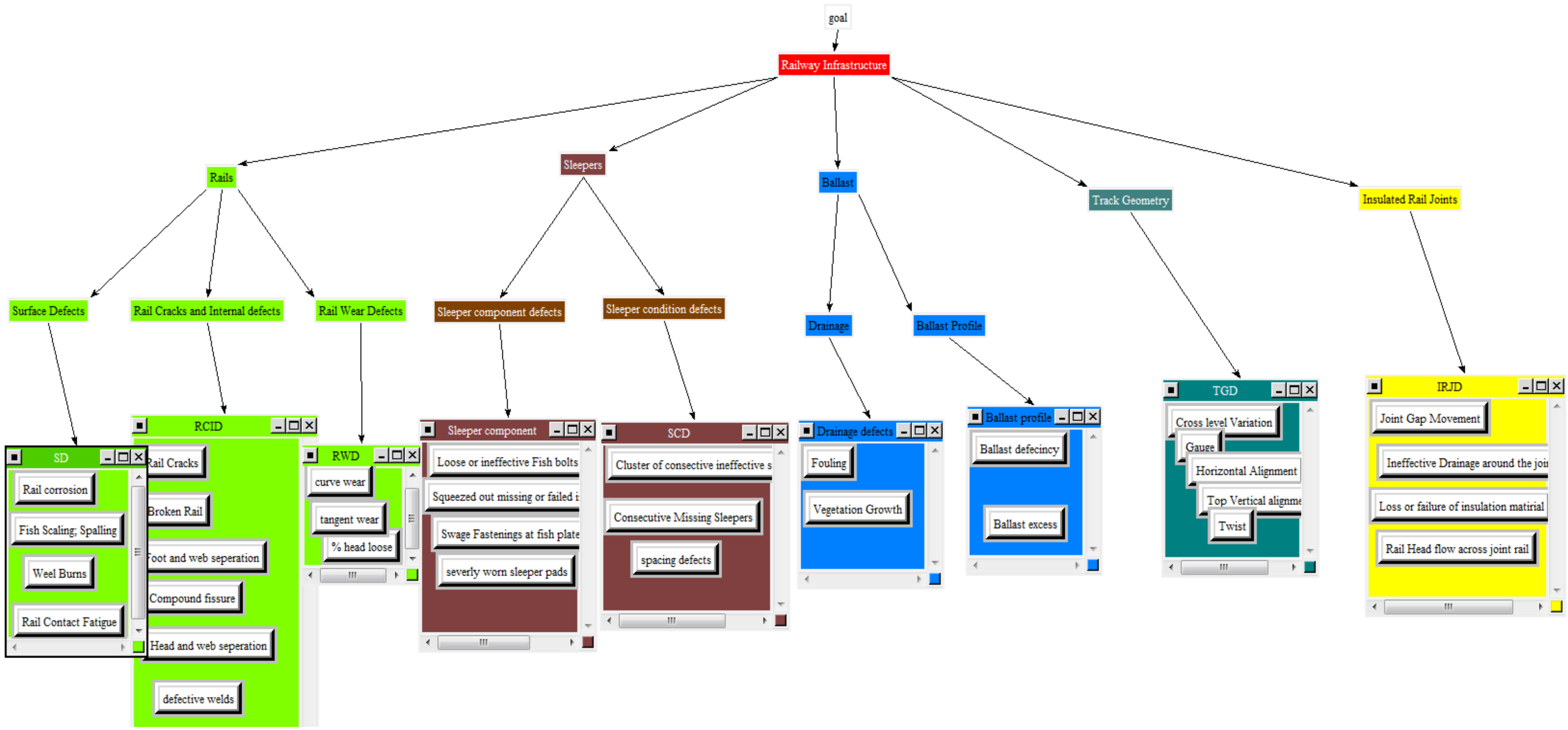


Figure 5-2: Super Decision Model Hierarchy

For surface defects, all defects have almost equal weights. On the other hand, the curve wear has the highest weight (53%). This is a reasonable result since the curve defects are more severe than the ones in the tangent areas.

The sleeper condition defects are given a relatively higher weight, i.e. (63%), than the sleeper component defects, i.e. (37%). Both the clusters of consecutive ineffective sleepers and the general condition describing timber sleepers are considered the same due to their common definition in terms of a defect. The first one is for concrete or it can describe the timber sleepers when the percentage of defective timber sleepers exceeds a certain level. The sleeper pads have the highest weight among the sleeper components, showing that the pads are the most important part in the connection between the rails and the sleepers.

As the results of the ballast weight extraction show, the drainage defects outweigh the ballast profile defects with a weight of 55%, compared to a 45% – which is not of a great difference. The fouling defect of 62% has a higher weight than the vegetation growth, showing that the fine materials are more effective than the vegetation in terms of blocking the drainage feature of the ballast. The analysis shows that the ballast deficiency of 79% outweighs the ballast excess of 21% in terms of ballast profile defects.

The twist defect has the highest weight among all the geometry defects. The joint gap movement has the highest weight among all the defects in the insulated rail joints.

Table 5-2 Weight Determination

Component	Wk	Defects Categories	Wj	Defects	Wi	Wi global
Rails	16%	Surface defects	35%	Fish Scaling; Spalling	28%	1.57%
				Rail Contact fatigue	21%	1.18%
				Rail Corrosion	24%	1.34%
				Wheel Burns	26%	1.46%
				Total (∑)	**100%**	**0%**
		Rail cracks and internal defects	41%	Broken rail	26%	1.71%
				Compound Fissure	15%	0.98%
				Defective Welds	8%	0.52%
				Foot and Web separation	18%	1.18%
				Head and Web separation	18%	1.18%
				Rail cracks	15%	0.98%
				Total (∑)	**100%**	**0%**
		Rail wear	24%	Head Loss Max %	32%	1.23%
				Curve Wear	53%	2.04%
				Tangent Wear	14%	0.54%
		Total (∑)	100%	**Total (∑)**	**100%**	**0%**
Ballast	18%	Ballast Profile	45%	Excess Ballast	21%	1.70%
				Ballast deficiency	79%	6.40%
				Total (∑)	**100%**	**0%**
		Drainage	55%	Fouling	62%	6.14%
				Vegetation Growth	38%	3.76%
		Total (∑)	100%	**Total (∑)**	**100%**	**0%**
Sleepers (Ties)	27%	Sleepers Condition Defects	63%	Clusters of Consecutive Ineffective Sleepers	52%	8.85%
				Consecutive Missing Sleepers	34%	5.78%
				Spacing	13%	2.21%
				Total (∑)	**100%**	**0%**
		Sleepers Components Defects	37%	Loose or Ineffective Fish Bolts	21%	2.10%
				Severely worn sleeper pads	45%	4.50%
				Squeezed out missing or failed insulators	20%	2.00%
				Swage Fastenings at Fish-Plated Joint	14%	1.40%
		Total (∑)	100%	**Total (∑)**	**100%**	**0%**
Geometry	26%	Geometry	100%	Gauge	27%	7.02%
				Horizontal alignment	15%	3.90%
				Top Vertical alignment	11%	2.86%
				Twist	32%	8.32%
				Cross-level variation	16%	4.16%
		Total (∑)	100%	**Total (∑)**	**100%**	**0%**
Insulated Rail Joints	13%	Insulated Rail Joints	100%	Loss or failure of insulation material	20%	2.60%
				Joint Gap Movement	45%	5.85%
				Ineffective Drainage around Joint	21%	2.73%
				Railhead flow across joint Rail	14%	1.82%
Total (∑)	**100%**	**Total (∑)**	100%	**Total (∑)**	**100%**	**100%**

5.4 Defect Severity (S)

Defect severity is the second main input in the model development. Defect severity is the degree of impact of a defect on a component or a system. Different sources have been reviewed to define defect severities, some sources have been found online and others have been advised by experts as previously mentioned in Chapter Four. The main sources to define the severities and the condition assessment grading scales are TMC 203 Track Inspection (Wilson 2013), TMC 224 Rail Defects and testing manuals (Wilson 2011) developed by Railcorp in Australia. Table 5-3 shows the assessment scale that consists of six severity levels, from normal level where the track is safe with no maintenance required to emergency 1 (E1) as the most severe level with a maintenance plan required before the next train passage. The assessment scale recommends both the appropriate inspection and action times for each severity level.

The defect severities for each defect are divided into the six levels of condition assessment scales, based on the defect's impact on the railway infrastructure. Different defects have different levels of impact, with some defects reaching emergency 1 severity level while other defects do not reach that level. Broken rail defect reaches emergency 1 level while ballast fouling reaches priority 1 level. The severity of defects changes with the speed level of the track, meaning that the same defect can have a higher level of impact when the speed of the track increases. The manuals define the six-speed levels with which the tracks operate. The severities are collected and organized for different defects and different speed levels. Table 5-4 and 5-5 below are an example of rail defect severity for two different speed levels. Rail defect severities are represented by the six levels of condition assessment grading scale as an example of the broken rail defect. If the spacing between the two parts of the broken rail is less than 50 mm, the condition is priority 1 and if the spacing is 100mm or greater, the condition is emergency 1.

Table 5-4 shows the defect severities of rail component for tracks with speed 20 km/h and Table 5-5 shows the defect severities of rail component for tracks with speed 40 km/h. All defect severities for the different speed levels can be found in Appendix B.

Table 5-3: Condition Assessment Scale (TMC 203)

Response Category	Inspect and verify response	Action
Emergency 1 (E1)	Prior to passage of next train	Prior to passage of next train
Emergency 2 (E2)	Within 2 hrs or before the next train, whichever is the greater	Within 24 hrs
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

Table 5-4: Rails Defects Severities at speed 20 km/hr

Parts	Defects Categories	Defects	N	P3	P2	P1	E2	E1
Rails	Surface defects	Fish Scaling; Spalling	No surface cracking in gauge corner or on rail head	Minor Spalling Present: Gauge Corner, and Top of rail head	Significant Spalling Present: Gauge Corner, and Top of rail head			
		Rail Contact fatigue	No visible cracking on rail head	Cracks visible	Cracks 1mm deep or TDS potentially hidden during ultrasonic testing	TDM potentially hidden during ultrasonic testing	TDL potentially hidden during ultrasonic testing	
		Rail Corrosion	>15	13-15		<13		
		Wheel Burns	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		
	Rail cracks and internal defects	Broken rail				0-50	51-100	>100
		Compound Fissure	4.9% or less		5% to 69.9%		70% to 99.9%	1
		Defective Welds		40 to 56	57 to 90		over 90	
		Foot and Web separation			20 to 40	41 to 75	76 to 150	Over 150
		Head and Web separation				20 to 75	76 to 200	over 200
		Rail cracks	<4	4 to 10	>10			
	Rail wear	Head Loss Max %				0.55		
		Curve Wear		52		48		
		Tangent Wear		32		26		

Table 5-5: Rails Defects Severities at speed 40 km/hr

Parts	Defects Categories	Defects	N	P3	P2	P1	E2	E1
Rails	Surface defects	Fish Scaling; Spalling	No surface cracking in gauge corner or on rail head	Minor Spalling Present: Gauge Corner, and Top of rail head	Significant Spalling Present: Gauge Corner, and Top of rail head			
		Rail Contact fatigue	No visible cracking on rail head	Cracks visible	Cracks 1mm deep or TDS potentially hidden during ultrasonic testing	TDM potentially hidden during ultrasonic testing		TDL potentially hidden during ultrasonic testing
		Rail Corrosion	>15	13-15		<13		
		Wheel Burns	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		
	Rail cracks and internal defects	Broken rail				0-50	51-100	>100
		Compound Fissure	4.9% or less		5% to 69.9%		70% to 99.9%	1
		Defective Welds		40 to56	57 to 90		over 90	
		Foot and Web separation				20 to 40	41 to 75	76 to 150
		Head and Web separation				20 to 75	76 to 200	over 200
		Rail cracks	<4	4 to 10	>10			
	Rail wear	Head Loss Max %				0.55		
		Curve Wear		52		48		
		Tangent Wear		26		32		

5.4.1 Severities Quantification

After collecting all defect severities and defining all different measuring criteria for different defects, this research uses the defuzzification technique to uniform all defect criteria and to translate the linguistic condition assessment grading scales into quantitative scores. The membership function used in the defuzzification process is the triangular membership function that fits the used data. Firstly, defuzzification is done on the six levels of severity, by defining them with a 0-10 grading scale. The grading scale for each level of severity is defined by analyzing the geometry and the ballast deficiency defects severity. The geometry defects and the ballast deficiency are chosen because these defects have numerical values describing their severities and cover all the defect severity levels using the weighted percentage technique. Table 5-6 is an example of the weighted percentage applied to the ballast deficiency to find the grading scale and the score for each level of severity. The severities are translated into a score from 1 to 10 by dividing the permissible limits for the severity level by the maximum permissible level. After finding each level grading scale, the mean value for each grading scale is used to define the score for each level. The weighted percentage is applied to all geometry defects and the ballast deficiency for all the six-speed levels.

Table 5-6: Weighted percentage of the ballast deficiency defect severity for track speed of 20km/h.

Severity Level	N	P3	P2	P1	E2	E1	Sum
Severity	0-4	4-8	8-12	12-14	14-17	17-19	
	4	4	4	2	3	2	19
	2.1	2.1	2.1	1.1	1.6	1.1	10
Grading scale	0-2.1	2.1-4.2	4.2-6.3	6.3-7.3	7.3-8.9	8.9-10	
score	1.05	3.15	5.25	6.8	16.2	9.45	

Table 5-7 shows the grading scale and the score of the six severity levels deduced from the weighted percentage analysis done on the defects. Where each level is given a grading scale and a score defined as the average value of the grading scale. i.e. the Normal N level were given a grading scale of 0 to 3 and the score that represent this level and will be used to define it is 1.5, were this value will be used in the aggregation process, and correspondingly the table shows the grading scale and the scores of all other levels in the same way. When the six severity levels with their corresponding numerical scores are defined, and since all defects are defined based on the same condition assessment levels of severity, these scores are distributed for all defects at all speed levels.

Table 5-7: Limits of the fuzzy process Severity Levels

Severity	grading scale	score
N	0 – 3	1.5
P3	3 – 5	4
P2	5 - 6.5	5.75
P1	6.5 – 8	7.25
E2	8 - 9.5	8.75
E1	9.5 - 10	9.75

5.5 Defect-based Condition Assessment Model

After collecting and quantifying the defect severities (S) and finding all the weights (W) for the components, defect categories and defects, the Weighted Sum Mean Technique is employed as a comprehensive aggregation method. As mentioned before, the model is divided into a hierarchy of components followed by defect categories and defects, to define and calculate the railway infrastructure condition. The aggregation process and its equations are explained in Chapter Three, the Condition Assessment Model section. The main equation is $C=W*S$ where C is condition, W is weight and S is severity. There are three levels of condition based on the three levels of hierarchy, the defect categories condition, the component condition and, finally, the overall condition, describing the railway infrastructure.

When the condition is computed in percentage by the WSM model, the step of translating this percentage back to a linguistic grading scale (example: 22% to Normal (N)) is called fuzzification. The limits defining the severity levels at this step is the same as those for severity quantification in Table 5-7. Moreover, the resulting condition would be used by project managers, engineers, decision-makers and practitioners, to decide on maintenance and rehabilitation programs.

5.5 Model Implementation: Case Study and Validation

One of the main components in the model development is the implementation of the model to real case studies with real data of inspections and final decisions. This is done to check the model's applicability and credibility. This is done in two case studies from Ontario, Canada, and provided by Canarail Company.

5.5.1 Case Study 1

The first case is 40 miles of track located in Ontario, Canada. It is a class 1 track with the operation speed of 20km/h. The data format is an excel file summarizing the experts' inspection sheets (visual inspection). The tie rehabilitation programs are planned by the experts since the ties and ballasts are in bad condition. The data is put into the developed model for each milepost and the conditions of the defect category, the component and the overall condition of the railway infrastructure are found. Table 5-8 shows the obtained conditions where the overall condition is Priority 3 (P3), indicating the need for a repair program. As the model gives a detailed condition describing the state of components and their defects categories, the analysis shows that both the ballast and the sleepers are in bad condition and require maintenance, as shown in Table 5-8. Both the decision and the output of the model give the same results.

Table 5-8: Conditions of Case Study Number One

Railway Infrastructure	Rails	16%	N	P3
	Ballast	18%	P2	
	Sleepers (Ties)	27%	P1	
	Geometry	26%	N	
	Insulated Rail Joints	13%	N	

5.5.2 Case Study 2

The case is a track of 15 miles, located in Ontario, Canada, a class 5 track with an operation speed of 150km/h, considered in the 6th speed category. The data format is the same as in the 1st case. The experts' inspection sheets (visual inspection) are summarized. The decision provided by the experts state that no maintenance is needed because the track is in good condition and there are a few ineffective sleepers. The data is put into the developed model for each milepost and the conditions of the defect categories component and the overall condition are found. Table

5-9 shows that the overall condition the model provides is Normal (N), indicating that no actions need to be taken. The component conditions show all the components except sleepers in a normal condition level and Priority 3 for the sleepers. Both the decision and the condition give the same results.

Table 5-9: Condition of Case Study Number 2

Railway Infrastructure	Rails	16%	N	N
	Ballast	18%	N	
	Sleepers (Ties)	27%	P3	
	Geometry	26%	N	
	Insulated Rail Joints	13%	N	

5.6 Sensitivity Analysis

In an attempt to test the robustness of the developed model and its sensitivity to changes in the weight values, a sensitivity analysis is conducted with respect to the components of railway infrastructure. It is conducted to test the relationship between the weights of the components and the overall condition of the infrastructure. It also shows the degree to which any change in the input (i.e. the weights) could affect the potential output.

In the methodology of the sensitivity analysis, each component weight changes individually, in six ways and with 5% intervals, i.e. -15%, -10%, 5%, 0, 5%, 10% and 15%. The six intervals change each component weight and the changes in the condition are measured. This methodology is applied to rails, ballast, sleepers, geometry and insulated rail joints based on the two case studies' results.

Figure 5-3 illustrates the results of the sensitivity analysis applied to the first case study. It shows the overall condition changing corresponding to the change of the component weights. In the first case study, the rails, geometry and insulated rail joints have the same condition as these components' condition is normal and the sleepers have Priority 1 and ballasts have Priority 2 conditions. The analysis shows that the effect of the rail has a slight difference when it is compared to the equal effect that the geometry and the insulated rail joints have on the condition. The effects of the sleeper weight change shows the highest slope since it has the highest condition among the components. The ballast shows the second highest slope but the change in the condition is not severe. The overall condition is not affected by high changes. The condition does not jump to a different level for all the scenarios and the overall condition stays at Priority 3. The x axis represents the change in the weight and the y axis represents the difference in percentage of the overall condition.

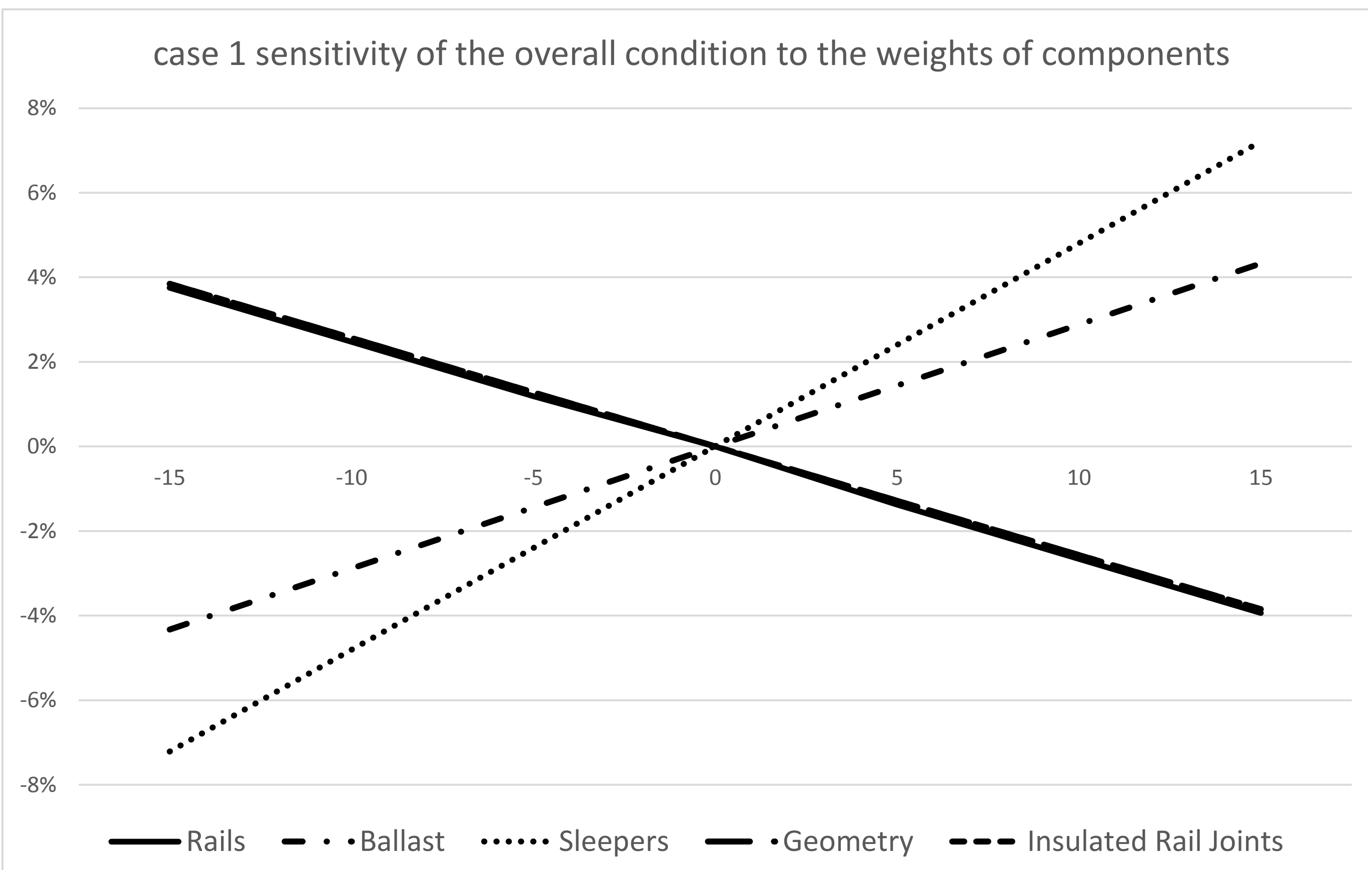


Figure 5-3 Case 1 Sensitivity Analysis

Figure 5-4 illustrates the results of the sensitivity analysis applied to the second case study. It shows the change of the overall condition, corresponding to the change of the component weights. In the first case study, the rails, geometry, ballast and insulated rail joints have the same condition while the condition of these components is Normal and the sleepers have the Priority 3 condition. The analysis shows that the effect of the rail has a slight difference compared to the equal effect that geometry, the ballast and the insulated rail joints have on the condition. The change in the sleeper weight effects show the highest slope since it has the highest condition among the components. The x axis represents the change in the weight and the y axis represents the difference in the percentage of the overall condition.

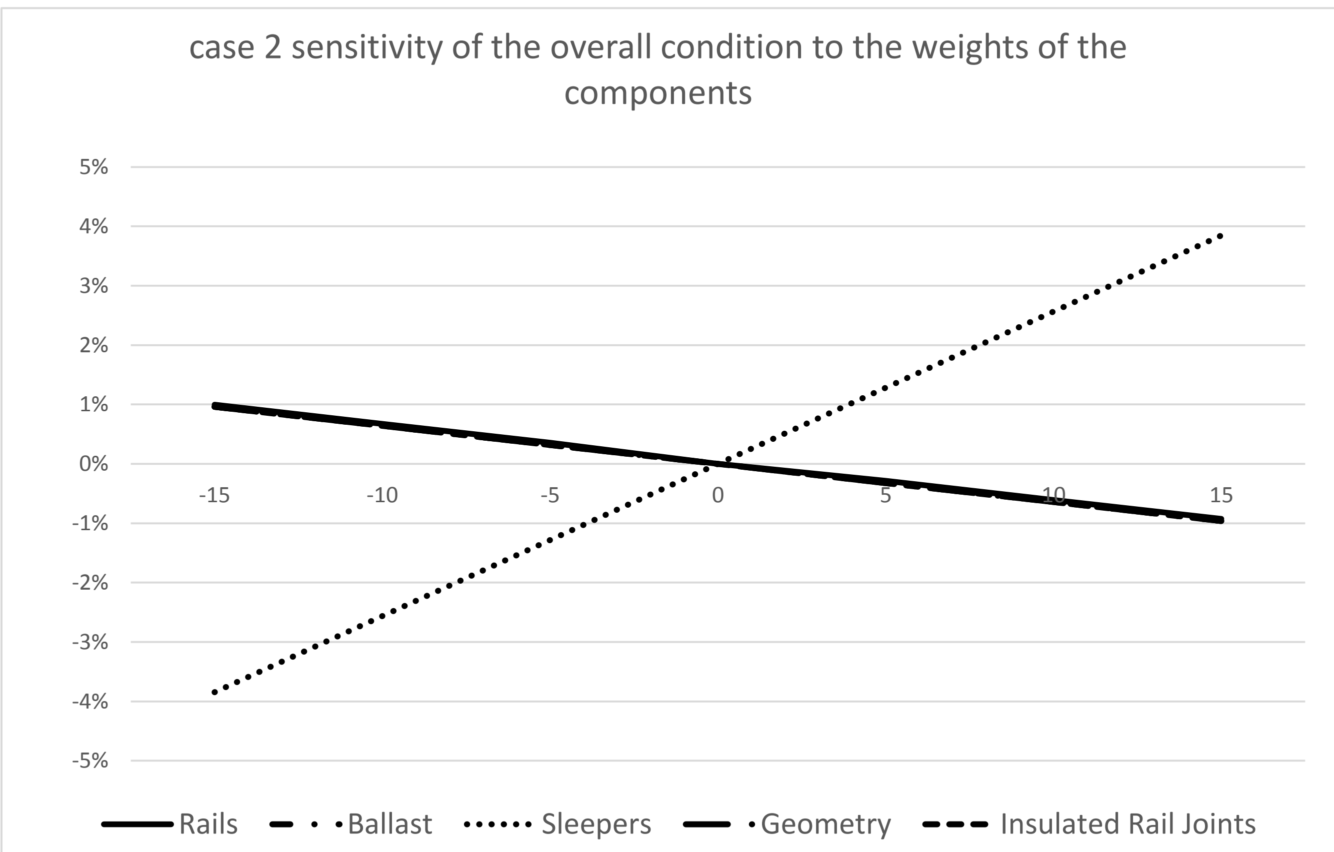


Figure 5-4 Case 1 Sensitivity Analysis

CHAPTER VI: CONDITION ASSESSMENT AUTOMATED TOOL

6.1 Introduction

After developing the defect-based railway infrastructure condition assessment model and incorporating all of its components and defects, putting this model into practice is significant. In the implementation process, one main task is to run this work in an easy and comprehensible way. Therefore, this model has been implemented in Excel, with all the input and output incorporated into it. Firstly, a comprehensive database including the two main input data sets, the weights of the components, defect categories and defects and the defect severities have been extracted from the specification for the six-speed levels. The tool includes the severity quantification limits used to translate the severities into numerical scores. Moreover, the whole aggregation process through the WSM approach is done in this framework. Six main condition assessment spreadsheets for the six-speed levels are created. The input data for the developed sheets are the inspection sheets, data gathered by the inspection technologies or both. The tool allows users, practitioners, decision-makers and managers to determine the railway infrastructure condition. It gives a detailed condition, an overall condition, component condition and defect category condition, through inputting the available defect severities as indicated in the model.

6.2 Database

To develop the automated tool based on the needs, a comprehensive database is first built to gather all the assessment criteria. The database consists of the two main input sets based on which the model is developed, the weights (W) and the severities (S) for the six speed levels of the track. Table 6-1 is an example of the database, showing the weights and the severities corresponding to rails for 20km/h tracks.

6.3 Automated Condition Assessment Model

The railway infrastructure condition assessment automated tool consists of six spreadsheets based on the six-speed levels. Each spreadsheet consists of the components, their defect categories and defects to assess the condition of railway infrastructure. To find the desired condition, the spreadsheets consist of all the calculation and aggregation procedures. If and then formats are used to determine the severity levels of each defect, based on the entered values compared to the values defined in the database. When the defect severities are defined, the aggregation procedure between the severities and the corresponding weights is also interpreted in the spreadsheets through the aggregation process mentioned in the previous chapters. The calculated condition is a three-level condition: The defect category condition, the component condition and the overall condition.

The developed spreadsheets allow users to fill the collected defect severities. Due to the different measurement criteria, two different ways to fill the collected data are developed: a drop down list for the defects with a linguistic description for the severities and a space to fill the quantitative severities. Figure 6-3 shows users trying to fill the gauge defect severity from the inspection sheets. Figure 6-4 shows the drop-down list for fish scaling spalling defect severity.

Figure 6-5 illustrates the condition assessment interface that consists of all the component, defect categories and defects concerning the railway infrastructure. This is the interface where the severities can be input and the conditions change automatically while the users fill the defect severities gathered through the inspection techniques.

The developed tool is a user-friendly interface helping users obtain the respective conditions through incorporating the defects. The defects can be taken from the experts' inspection sheets, data gathered by inspection technologies or both. The steps below describe the procedures to obtain the desired condition.

1. The first spreadsheet is the speed interface where the user can choose the speed of the track that will be assessed. Figure 6-2 represents the speed interface showing the six-speed levels from the minimum speed of the tracks, i.e. 20km/h, to 160km/h.
2. Step 1 will take the user to the condition assessment spreadsheet of the chosen speed.
3. Start filling the defect severities; some defects have a drop down list to choose from and the users can fill the severity in the rest.
4. Repeat the steps above for all of the desired components and their corresponding defect families.
5. The condition changes automatically while the users fill the collected severities.
6. When all the severities are filled, the users can save the condition under its milepost.

Figure 6-1 represents the steps and the procedures of using the automated tool. The flow chart highlights the steps mentioned earlier. It starts by choosing the speed and finishes with the choices to exit or to proceed to the next milepost.

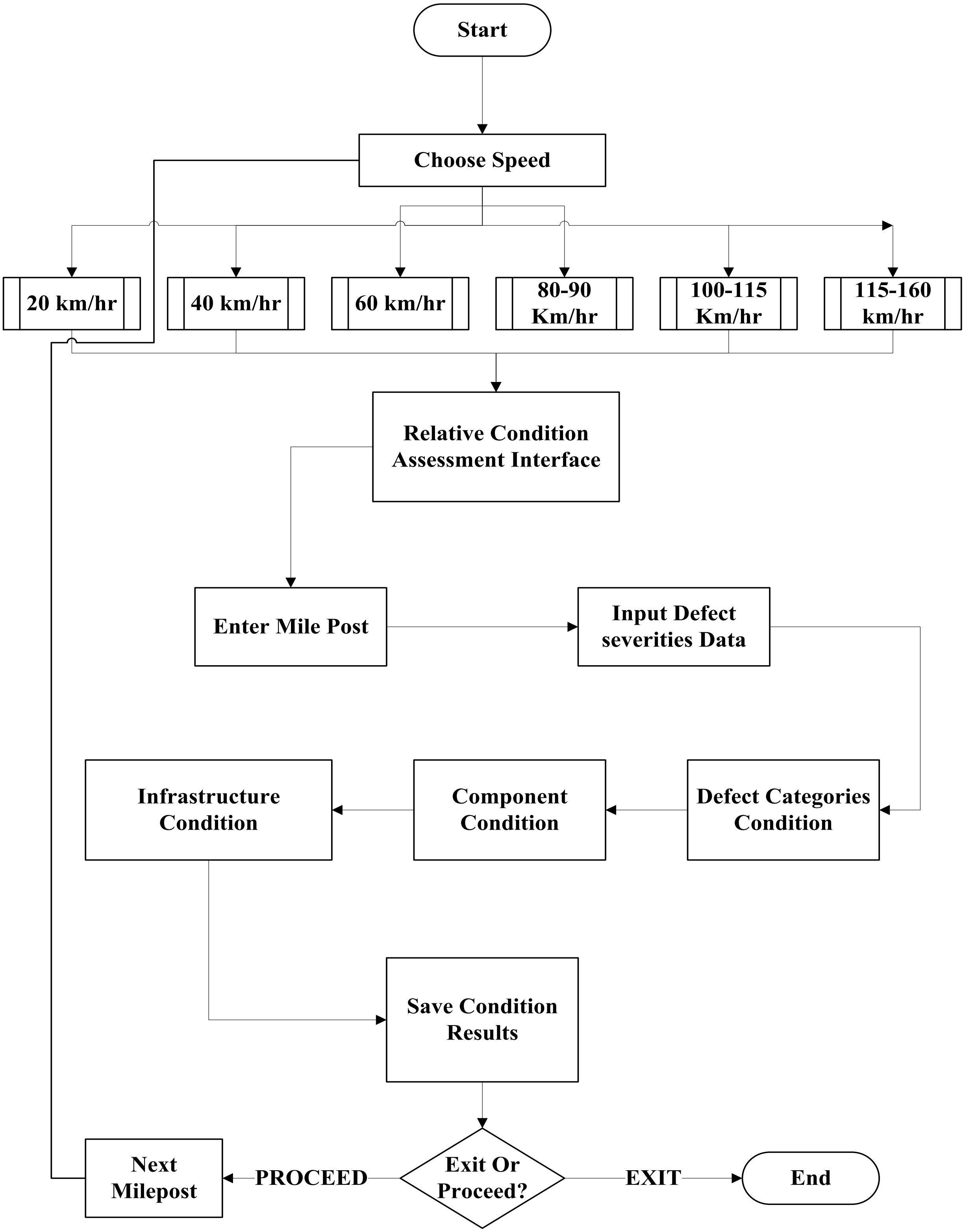


Figure 6-1 Automate Tool Flow Chart

Table 6-1 Example From the Database Showing the Main Inputs for Rail for Track Speed 20Km/Hr.

Parts	Parts Weights	Defects Categories	Defects Categories Weights	Defects	Weights	N	P3	P2	P1	E2	E1
Rails	16%	Surface defects	**35%**	Fish Scaling; Spalling	28%	No surface cracking in gauge corner or on rail head	Minor Spalling Present: Gauge Corner, and Top of rail head	Significant Spalling Present: Gauge Corner, and Top of rail head			
				Rail Contact fatigue	21%	No visible cracking on rail head	Cracks visible	Cracks 1mm deep or TDS potentially hidden during ultrasonic testing	TDM potentially hidden during ultrasonic testing	TDL potentially hidden during ultrasonic testing	
				Rail Corrosion	24%	>15	13-15		<13		
				Wheel Burns	26%	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		
				Total (∑)	**100%**						
		Rail cracks and internal defects	**41%**	Broken rail	26%				0-50	51-100	>100
				Compound Fissure	15%	4.9% or less		5% to 69.9%		70% to 99.9%	1
				Defective Welds	8%		40 to 56	57 to 90		over 90	
				Foot and Web separation	18%			20 to 40	41 to 75	76 to 150	Over 150
				Head and Web separation	18%				20 to 75	76 to 200	over 200
				Rail cracks	15%	<4	4 to 10	>10			
				Total (∑)	**100%**						
		Rail wear	**24%**	Head Loss Max %	32%				0.55		
				Curve Wear	53%		52		48		
				Tangent Wear	14%		32		26		
		Total (∑)	**100%**	**Total (∑)**	**100%**						

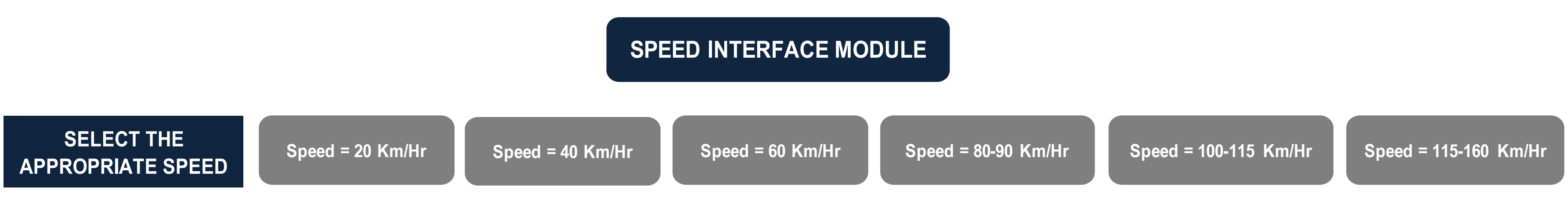


Figure 6-2 Speed Interface

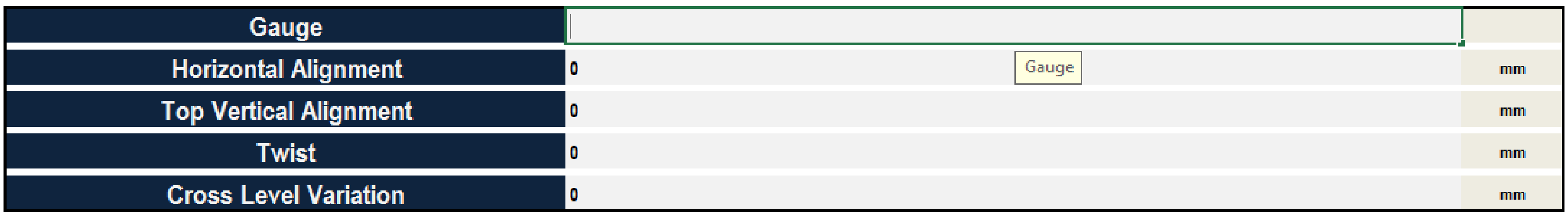


Figure 6-3 Defect Severity Inputting

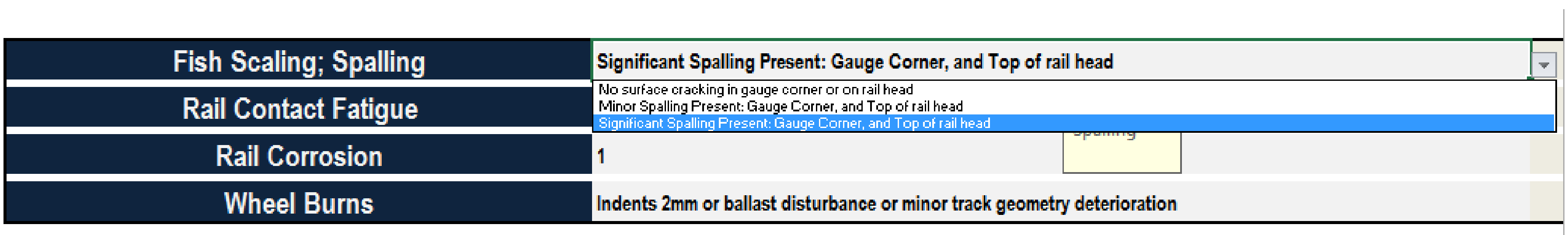


Figure 6-4 Defect Severity Drop-Down List

Parts	Defects Categories	Defect	Defect Severity	Units	Categories Score	Parts Score
Rails	Surface Defects	Fish Scaling; Spalling	No surface cracking in gauge corner or on rail head	N/A	E2	E2
		Rail Contact Fatigue	TDL potentially hidden during ultrasonic testing	N/A		
		Rail Corrosion	1	mm		
		Wheel Burns	Indents 2mm or ballast disturbance or minor track geometry deterioration	N/A		
	Rail cracks and internal defects	Broken Rail	120	mm	P1	
		Compound Fissure	100%	%		
		Defective Welds	0	mm		
		Foot and Web Separation	200	mm		
		Head and Web Separation	0	mm		
		Rail cracks	200,000	mm		
	Rail Wear	Head Loss Max. Percentage	100%	%	E1	
		Curve Wear	0	mm		
		Tangent Wear	8	mm		
Ballast	Ballast Profile	Excess Ballast	Profile as specified	N/A	N	P3
		Ballast defecincy	2	mm		
	Drainage	Fouling	Minimal fines in ballast, Fines in ballast, visible contamination on surface of ballast	N/A	P2	
		Vegitation Growth	Highly vegetated that cause water being trapped in the ballast	N/A		
Sleepers (Ties)	Sleepers Condition Defects	Clusters of Consecutive Ineffective Sleepers	0	Number	P2	P1
		Consecutive Missing Sleepers	6	Number		
		Spacing	40,000	mm		
	Sleepers Componant Defects	Loose or Ineffective Fish Bolts	No	N/A	E2	
		Severely worn sleeper pads	Yes	N/A		
		Squeezed out missing or failed insulators	Yes	N/A		
		Swage Fastenings at Fish-Plated Joint	Yes	N/A		
Geometry		Gauge	0	mm	N	
		Horizontal Alignment	0	mm		
		Top Vertical Alignment	0	mm		
		Twist	0	mm		
		Cross Level Variation	100	mm		

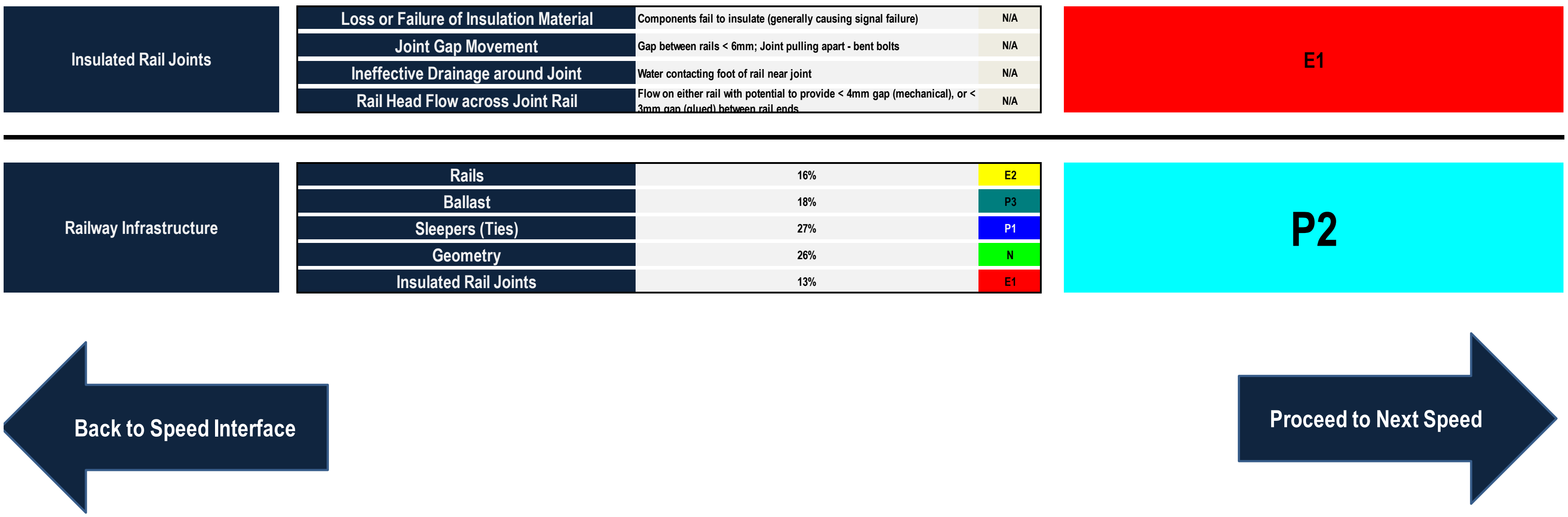


Figure 6-5 Condition Assessment Interface

6.4 Summary

This chapter presents the railway infrastructure condition assessment tool in a user-friendly and practical interface. The collected data and the adopted techniques are all incorporated in this automated tool through Excel sheets. The tool includes fuzzification and the defuzzification of the sevirities values, the obtained ANP relative importance weights and the weighted sum mean aggregation process. The input in this model is the defect severities through predefined criteria. The output is three-level conditions: The first condition is the defect category condition; then, the result of the first level condition aggregation is the component condition and the final level is the overall condition. Moreover, the adopted condition grading scale is also incorporated into this model along with color coding for each linguistic condition. To conclude, this automated tool is designed for all users from practitioners to decision-makers who perform railway condition assessment in a practical and user-friendly manner.

CHAPTER VII: CONCLUSIONS AND RECOMMENDATIONS

7.1 Research Overview

As one of the main infrastructural elements for countries, railways play a key role in the development of the civilizations in terms of passengers and goods transport. Like any other infrastructure, railway infrastructure suffers from extensive deterioration due to continuous loading, high train speeds, frequent weather changes, improper maintenance, lack of inspection and uncertain condition judgments. According to the US Federal Railroad Administration Office of Safety Analysis (Administration 2014), track defects are the second major cause of railway accidents in the US. The first major cause of railway accidents is human error, as reported. Although not reported by FRA, it is acknowledged by the National Transportation Safety Board (NTSB) that poor management of rail accidents is caused by the lack of proper rail inspections. In order to reduce the major causes of railway accidents and minimize human errors, several condition assessment models have been developed. However, most of these models have certain limitations, like the lack of structure-based condition assessment models in most cases. Therefore, this research develops a new model for railway infrastructure condition assessment, using fuzzy synthetic evaluation. This model targets practitioners, inspectors, engineers, managers and decision-makers and facilitates the prioritization of the maintenance and rehabilitation work.

To build this model, the infrastructure of the railway is divided into five main components, rails, sleepers (ties), ballast, track geometry and insulated rail joints. Then, defects concerning each of the above-mentioned components are categorized based on the nature of defects. Moreover, online and hard copy questionnaires are developed for experts' opinions to define the relative importance weight of the components, defects categories and defects. Based on the fourteen collected surveys, an ANP model has been created using SuperDecisions software to find the weights. Furthermore, defect severities have been gathered through Australian manuals. Accordingly, fuzzy membership functions are developed to uniform the different defect measuring criteria and to define the linguistic severity levels with numerical values. The output of the fuzzy membership functions are used along with the ANP weights as input in the developed WSM to aggregate the severities and the weights, to find the condition for the defect categories, the components and the overall aggregated condition. Finally, fuzzification is used to translate the outputs of the WSM back to a linguistic condition, to be used by decision-makers for rehabilitation purposes.

7.2 Research Conclusions

The following conclusions can be deduced from the development, implementation and testing of this research:

- Based on the questionnaire analysis, most of the professional participants in this study share one point of view when it comes to the comparison between two components, defect categories and defects; this shows the credibility of the weights.
- Based on the weight analysis, the sleepers have the highest weight (27%) among the components, followed by geometry weight with a slight difference (26%) and then, the ballast, rail and insulated rail joints with the weights of 18%, 16%, 13% – respectively.
- The rail internal defect category, with a weight of 41%, has the highest weight among the rail defect categories; the highest defect weight in this category is the broken rail with a

weight of 26%. This result makes sense since the broken rails are one of the main causes of railway accidents.

- The sleeper condition defects have a higher weight (63%) than the sleeper component defects (37%) and the clusters of consecutive ineffective sleeper defects have the highest weight (52%).
- The drainage defects in the ballast has a higher weight (55%) than the profile defects (45%) and the highest weight among the defects goes to the fouling (62%).
- The twist defect has the highest weight (32%) among all the geometry defects.
- The joint gap movement has the highest weight among all the defects that occur in the insulated rail joints.
- The implementation of two case studies to validate the developed model shows similar results when they are compared with the actual results. Based on the results in Case 1, the sleepers and the ballast are in a dire condition, which means maintenance is required and the decision provided on the case studies are the same. Based on the results in Case 2, the track is in good condition and the sleepers have minor defects only, which does not affect the integrity of the track. The provided decision indicates the same situation.
- The model gives Emergency 1 condition if all defects are in their worst condition, even if these conditions do not reach Emergency 1 as individuals.
- The developed model gives a detailed condition of the defect categories, the components and an overall condition to help managers and decision-makers in choosing the precise maintenance and rehabilitation actions. Otherwise, the overall condition can be misleading as it is defined by five components.

- The sensitivity analysis shows that the change of the component weights doesn't have a considerable influence on the overall condition.

7.3 Research Contributions

This study has made the following contributions through the development of the new railway condition assessment model, including but not limited to:

- Developing a railway infrastructure defect hierarchy, including components, defect categories and defects that cover the main components and defects.
- Developing a condition assessment model that covers six different speed levels of the railway system.
- Incorporating interdependency among the component, defect categories and defects.
- Developing a fuzzy synthetic evaluation model, including a customized WSM working platform to aggregate the weights and severities.
- Developing a railway infrastructure condition assessment spreadsheet, using Excel to cover the six speed levels of the tracks and to cover all different components and their defects for deducing an index that represents the whole railway infrastructure.

7.4 Research Limitations

This developed model has the following limitations:

- The model is based on a firm defect hierarchy that, if changed, would require the ANP model and WSM model change as well.

- The fuzzy membership functions are calculated based on structured sets of input, e.g. defect severities. When different criteria are used, the model input has to change.
- The model does not take any deterioration factors into account.
- Only fourteen questionnaires are collected.

7.5 Future Work Recommendations

The model has been developed to accomplish the research objectives set in this study. When developed, the model has been implemented in case studies and its accuracy is proved by the results. However, the model can be expanded further. The ways to enhance the model and advance it are as follows:

7.5.1 Enhancements

- Other case studies with various component conditions to cover all possibilities can be used for the validation and a better understanding of the developed model. Other railway industries could be reached since the case studies used to validate this model are limited to a certain condition that circles around Normal and Priority 2. Besides, neither of the case studies use geometry data.
- Other railway infrastructure components and defects, such as subgrade, can be added to the model. This will give a better representation of the track condition and cover a wider range of components and defects.
- More experts can be reached to participate in the data collection stage, leading to a wider range of feedback and experience. As previously mentioned, the weight calculation has been based on fourteen sets of feedback from engineers in Canada. Besides, a larger variety of track supervisors, e.g. in maintenance and construction, can be approached.

7.5.2 Extensions

- More inspection technologies can be incorporated in the developed model to obtain accurate defect measurements. The development of new technologies and advancing the existing ones are always in progress.
- The spreadsheet can be developed to read the collected data from the track recording cars and other inspection technologies directly and automatically without the need for users to interpret them manually; this will save time and provision more accurate results.
- A condition prediction model can be designed, in which historical inspection sheets are imported and analyzed automatically using this mode. The historical data condition can be found by the existing model and the conditions will be analyzed to predict the deterioration process. As a result, time and money on data preparation could be saved rather than wasted.
- The developed model can be integrated with a rehabilitation and maintenance methodology through mapping each defect to its most suitable maintenance method. As a result, time is saved and more accurate decisions are made.
- A risk assessment model can be developed based on the developed condition assessment model. So is the prediction model to determine the risks of delaying the maintenance and to have a full life cycle of the railway infrastructure condition.

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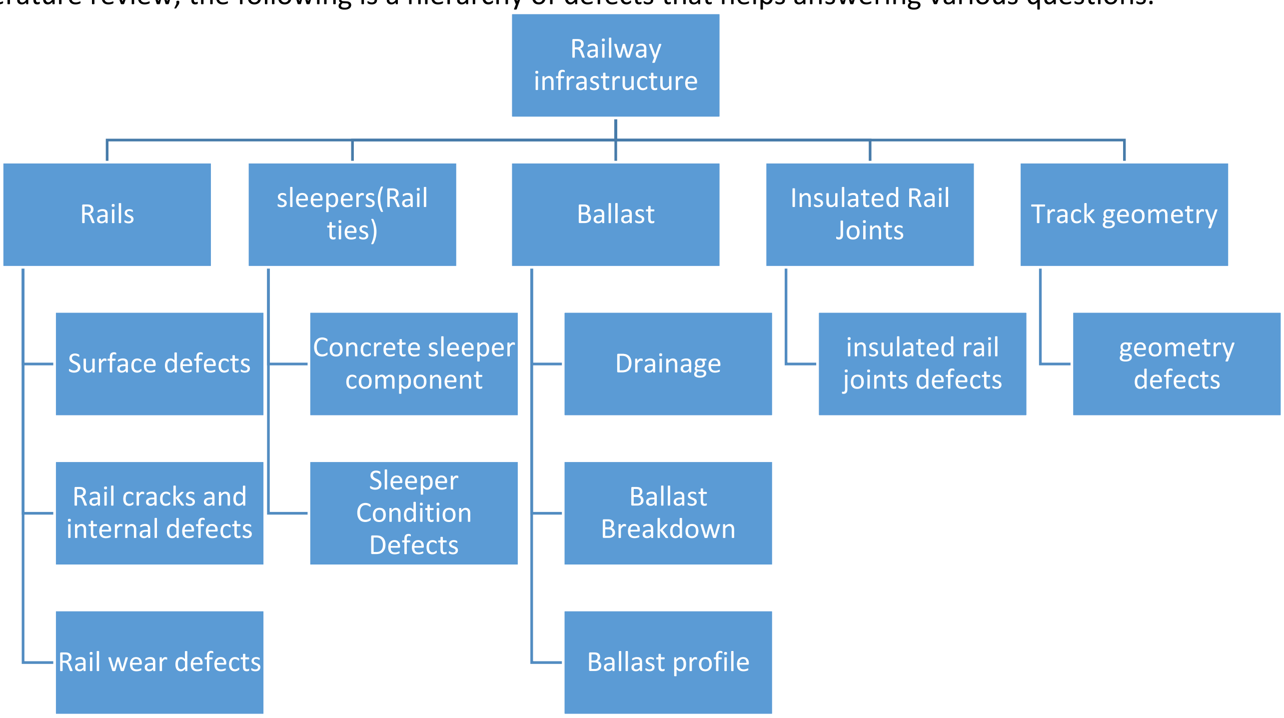
APPENDICEIES

Appendix A
Questionnaire

Defect - Based Condition Assessment Model of Railway infrastructure

Online survey:
http://www.surveyexpression.com/Survey.aspx?id=bd6d6d6f-3670-4f65-91e5-2eb9cd5c7543

Dear Sir/Madam
It is of great appreciation that you would take some time to fill the following questionnaire. The purpose is to identify the relative importance and effect of the elements, components, and defects affecting the integrity of Railway infrastructure condition. The questionnaire is used for an academic research under the supervision of Dr. Tarek Zayed at Concordia University, Montreal, Canada, to build a defect-based condition assessment model for Railway infrastructure. Based on literature review, the following is a hierarchy of defects that helps answering various questions.



PART (1) : GENERAL INFORMATION:

1. **How do you describe your occupation?**

☐ Organization Manager ☐ Construction Manager

☐ Project Manager ☐ Others __________________

2. **Which best describes your working experience?**

☐ Less than 5 years ☐ ☐ 6 -10 years
☐ 11 – 15 years ☐ ☐ 16 – 20 years
☐ More than 20 years ☐

3. **How do you describe your organization?**

☐ Public Owner
☐ Consultant
☐ NGOs
☐ International Agency
☐ Implementing Agency
☐ Others _________________

PART (2): PAIRWISE COMPARISON

In an attempt to determine the degree of importance of defects affecting the Railway infrastructure condition, kindly fill the tables in the next pages by ticking (✓) in the appropriate box from your point of view: **Example**:

Example: In the table below consider comparing "**Rails**" (Criterion X) with "**Sleepers**" (Criterion Y) with respect to the "**Railway infrastructure**"

Criterion (X)	Degree of Importance: (9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)	Remarks
Railway infrastructure											
Rails										Sleepers	
										Ballast	

If you consider that Rails is more important than Sleepers and the degree of this importance is Strong, then tick (✓) here

If you consider that both the Rails and Sleepers have Equal importance, then tick (✓) here

If you consider that Sleepers is more important than Rails and the degree of this importance is Absolute, then tick (✓) here

1) Pairwise Comparison between Elements and Components with respect to Goal: Railway

With respect to ***"Railway infrastructure"*** how important is criterion ***"X"*** or ***"Y"*** when compared to each other?

Criterion (X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)	Remarks
	← Degree of Importance →										
Railway infrastructure											
Rails										Ballast	
										Sleepers	
										Insulated rail joints	
										Track geometry	
Rails											
Surface defects										Rail cracks and internal defects	
										Rail wear defects	
Ballast											
Drainage										Ballast profile	
										Ballast Breakdown	
Sleepers											
Concrete sleeper component										Sleeper Condition Defects	
Rails											
Ballast										Sleepers	
										Insulated rail joints	
										Track geometry	
Sleepers											
Rails										Ballast	
										Insulated rail joints	
										Track geometry	
Ballast											
Sleepers										Rails	
										Insulated rail joints	
										Track geometry	
Track geometry											
Insulated rail joints										Rails	
										Sleepers	
										Ballast	
Insulated rail joints											
Track geometry										Rails	
										Sleepers	
										Ballast	

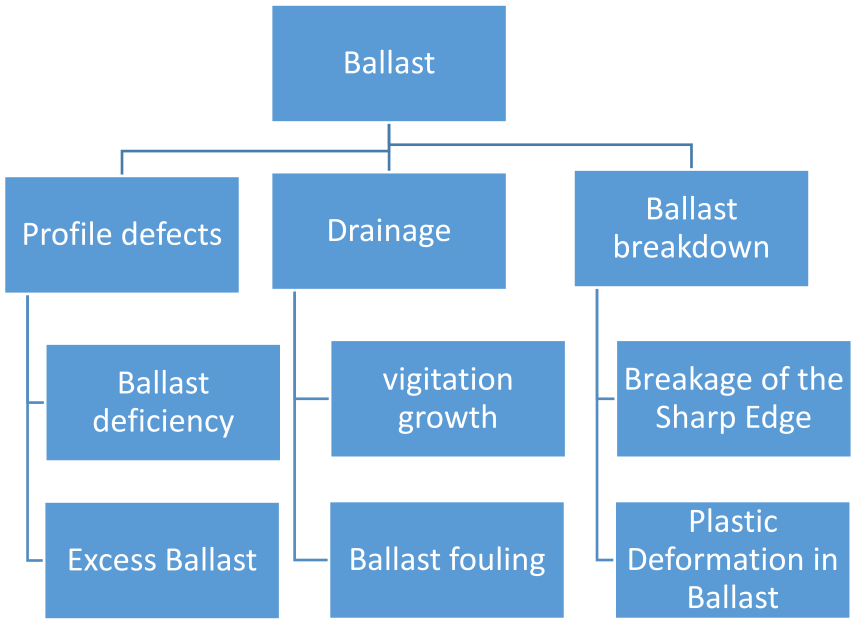
Rails

Rails	
Rail cracks and internal defects	Defective Welds
	Broken rail
	Bolt Hole Cracks
	Head and Web separation
	Foot and Web separation
	Compound Fissure
	Piped Rail
	Crushed Head
surface defects	Rail Corrosion
	Fish Scaling; Spalling
	Rail Contact fatigue
	Wheel Burns
	Notches
	Surface Squats
Rail wear defects	Curve Wear
	Tangent Wear
	Head Loss Max %

Criterion (X)	Degree of Importance									**Criterion (Y)**	**Remarks**
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Rail cracks and internal defects											
Surface defects										Rail wear defects	
Rail wear defects											
Surface defects										Rail cracks and internal defects	
Surface Defects											
Rail wear defects										Rail cracks and internal defects	
Rail cracks and internal defects											
Rail Cracks										Defective Welds	
										Broken rail	
										Bolt Hole Cracks	
										Head and Web separation	
										Foot and Web separation	
										Compound Fissure	
Surface Defects											
Rail Corrosion										Fish Scaling, Spalling	
										Rail Contact fatigue	
										Wheel Burns	

										Surface Squats	
										Notches	
					Rail wear defects						
Tangent Wear										Curve Wear	
										Head Loss Max %	

Ballast:



Criterion (X)	Degree of Importance									**Criterion (Y)**	**Remarks**
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
					Ballast profile						
Drainage										Ballast Breakdown	
					Ballast Breakdown						
Drainage										Ballast profile	
					Drainage						
Ballast Breakdown										Ballast profile	
					Ballast profile						
Ballast deficiency										Excess Ballast	
					Ballast Breakdown						
Breakage of the Sharp Edge										Plastic Deformation in Ballast	
					Drainage						
Vegetation Growth										Ballast fouling	

Sleepers:

Sleepers	
sleeper components defects	Squeezed out missing or failed insulators
	Severely worn sleeper pads
	Loose or Ineffective Fish Bolts
	Swage Fastenings at Fish-Plated Joint
Sleeper Condition Defects	Consecutive Missing Sleepers
	Spacing
	Clusters of Consecutive Ineffective Sleepers
	Rail Movement relative to sleeper, including effect of rail
Timber sleepers defects	Ineffective Timber Sleepers at Joints
	General Condition Description Timber Sleepers

Criterion (X)	Degree of Importance (9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	Criterion (Y)	Remarks
Sleepers											
sleeper component defects										Sleeper Condition Defects	
Sleeper condition defects											
Clusters of Consecutive Ineffective Sleepers										Consecutive Missing Sleepers	
										Spacing	
										Rail Movement relative to sleeper, including effect of rail roll	
Sleeper component defects											
Loose or Ineffective Fish Bolts										Squeezed out missing or failed insulators	
										Swage Fastenings at Fish-Plated Joint	
										Severely worn sleeper pads	
Timber Sleeper defects											
General Condition Description Timber Sleepers										Ineffective Timber Sleepers at Joints	

Track Geometry:

Geometry defects	Gauge
	Horizontal alignment
	Top Vertical alignment
	Twist
	Cross level variation

Criterion (X)	Degree of Importance									**Criterion (Y)**	**Remarks**
	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute		
Track geometry											
Cross level variation										Gauge	
										Horizontal alignment	
										Top Vertical alignment	
										Twist	

Insulated Rail Joints:

Insulated Rail Joints Defects	Loss or failure of insulation material
	Joint Gap Movement
	Ineffective Drainage around Joint
	Rail head flow across joint Rail
	Loss or failure of insulation material

Criterion	Degree of Importance	**Criterion**	

(X)	(9) Absolute	(7) Very Strong	(5) Strong	(3) Moderate	(1) Equal	(3) Moderate	(5) Strong	(7) Very Strong	(9) Absolute	(Y)	Remarks
Insulated Rail Joints											
Joint Gap Movement										Loss or failure of insulation material	
										Ineffective Drainage around Joint	
										Rail head flow across joint Rail	
										Loss or failure of insulation material	

Thank You for Filling this Questionnaire.

Contact Me at:

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Appendix B
Defects Severities

Defects Severities

Speed 20 km/hr

Speed 20 Km/hour								
Parts	**Defects Categories**	**Defects**	**N**	**P3**	**P2**	**P1**	**E2**	**E1**
Rails	Surface defects	Fish Scaling; Spalling	No surface cracking in gauge corner or on rail head	Minor Spalling Present: Gauge Corner, and Top of rail head	Significant Spalling Present: Gauge Corner, and Top of rail head			
		Rail Contact fatigue	No visible cracking on rail head	Cracks visible	Cracks 1mm deep or TDS potentially hidden during ultrasonic testing	TDM potentially hidden during ultrasonic testing	TDL potentially hidden during ultrasonic testing	
		Rail Corrosion	>15	13-15		<13		
		Wheel Burns	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		
	Rail cracks and internal defects	Broken rail				0-50	51-100	>100
		Compound Fissure	4.9% or less		5% to 69.9%		70% to 99.9%	1
		Defective Welds		40 to 56	57 to 90		over 90	
		Foot and Web separation			20 to 40	41 to 75	76 to 150	Over 150
		Head and Web separation				20 to 75	76 to 200	over 200
		Rail cracks	<4	4 to 10	>10			
	Rail wear	Head Loss Max%				0.55		
		Curve Wear		52		48		
		Tangent Wear		32		26		

Ballast	Ballast Profile	Excess Ballast	Profile as specified	Surplus ballast in excess of specified profile exists	Potential to interfere with correct function of track			
		Ballast defecincy	0-6	6-12	>12			
	Drainage	Fouling	Minimal fines in ballast, Fines in ballast, visible contamination on surface of ballast	Ballast fouled by fines and debris	Saturated Ballast visibly pumping and unable to maintain track within geometry maintenance limits			
		Vegitation Growth	Minimum vegetation	Some vegetation are blocking the voids	Highly vegetated that cause water being trapped in the ballast			
Sleepers (Ties)	Sleepers Condition Defects	Clusters of Consecutive Ineffective Sleepers	0-2	3	4	5	>5	
		Consecutive Missing Sleepers	0		1	2	>2	
		Spacing	<900 mm		900-1200	1200-1500	>1500	
	Sleepers Componant Defects	Loose or Ineffective Fish Bolts	No	Yes				
		Severely worn sleeper pads	No	Yes				
		Squeezed out missing or failed insulators	No	Yes				
		Swage Fastenings at Fish-Plated Joint	No	Yes				

Geometry	Geometry	Gauge	21-30		31-32	33-34	35-37	>37
		Horizontal alignment	>39		40-48	49-52	53-54	>54
		Top Vertical alignment	0-30		31-32	33-34	35-40	>40
		Twist	<52		53-59	60-64	65-70	>70
		Cross level variation	<60		61-66	67-71	72-75	>75
Insulated Rail Joints	Insulated Rail Joints	Loss or failure of insulation material	No insulation material failure		Insulation material visibly cracked or disintegrated		Components fail to insulate (generally causing signal failure)	
		Joint Gap Movement	No joint closing	Insulation key being squeezed out; Joint pulling apart - visible gap at insulation key	Gap between rails < 6mm; Joint pulling apart - bent bolts			
		Ineffective Drainage around Joint	No ineffective drainage		Water lying in joint vicinity	Water contacting foot of rail near joint		
		Rail head flow across joint Rail	No head flow	Flow on either rail with potential to provide < 6mm gap (mechanical), or < 4mm gap (glued) between rail ends	Flow on either rail with potential to provide < 4mm gap (mechanical), or < 3mm gap (glued) between rail ends			

Defects Severities
Speed 40 km/hr

Speed 40 Km/hour								
Parts	Defects Categories	Defects	N	P3	P2	P1	E2	E1
Rails	Surface defects	Fish Scaling; Spalling	No surface cracking in gauge corner or on rail head	Minor Spalling Present: Gauge Corner, and Top of rail head	Significant Spalling Present: Gauge Corner, and Top of rail head			
		Rail Contact fatigue	No visible cracking on rail head	Cracks visible	Cracks 1mm deep or TDS potentially hidden during ultrasonic testing	TDM potentially hidden during ultrasonic testing		TDL potentially hidden during ultrasonic testing
		Rail Corrosion	>15	13-15		<13		
		Wheel Burns	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		
	Rail cracks and internal defects	Broken rail				0-50	51-100	>100
		Compound Fissure	4.9% or less		5% to 69.9%		70% to 99.9%	1
		Defective Welds		40 to56	57 to 90		over 90	
		Foot and Web separation				20 to 40	41 to 75	76 to 150
		Head and Web separation				20 to 75	76 to 200	over 200
		Rail cracks	<4	4 to 10	>10			
	Rail wear	Head Loss Max %				0.55		
		Curve Wear		52		48		
		Tangent Wear		26		32		

Ballast	Ballast Profile	Excess Ballast	Profile as specified	Surplus ballast in excess of specified profile exists	Potential to interfere with correct function of track or			
		Ballast defecincy	0-6	6-13	13-16	>16		
	Drainage	Fouling	Minimal fines in ballast, Fines in ballast, visible contaminatio n on surface of ballast	Ballast fouled by fines and debris	Ballast visibly pumping and unable to maintain track within geometry maintenance limits			
		Vegitation Growth	minimum vegetation	some vegetation are blocking the voids	highly vegetated that cause water being trapped in the ballast			
Sleepers (Ties)	Sleepers Condition Defects	Clusters of Consecutive Ineffective Sleepers	0-2	3	4	5	>5	
		Consecutive Missing Sleepers	Nil		1	2	>2	
		Spacing	<900 mm		900-1200	1200-1500	>1500	
	Sleepers Componant Defects	Loose or Ineffective Fish Bolts	N	Y				
		Severely worn sleeper pads	N	Y				
		Squeezed out missing or failed insulators	N	Y				
		Swage Fastenings at Fish-Plated Joint	N	Y				

Geometry	Geometry	Gauge	21-28	29-30	31-32	33-34	35-37	>37
		Horizontal alignment	>29	30-39	40-48	49-52	53-54	>54
		Top Vertical alignment	0-27	28-30	31-32	33-34	35-40	>40
		Twist	<46	47-52	53-59	60-64	65-70	>70
		Cross level variation	<55	56-60	61-66	67-71	72-75	>75
Insulated Rail Joints	Insulated Rail Joints	Loss or failure of insulation material	No insulation material failure			Insulation material visibly cracked or disintegrated		Components fail to insulate (generally causing signal failure)
		Joint Gap Movement	No joint closing	Insulation key being squeezed out; Joint pulling apart - visible gap at insulation key	Gap between rails < 6mm; Joint pulling apart - bent bolts			
		Ineffective Drainage around Joint	No ineffective drainage		Water lying in joint vicinity	Water contacting foot of rail near joint		
		Rail head flow across joint Rail	No head flow	Flow on either rail with potential to provide < 6mm gap (mechanical), or < 4mm gap (glued) between rail ends	Flow on either rail with potential to provide < 4mm gap (mechanical), or < 3mm gap (glued) between rail ends			

Defects Severities
Speed 60km/hr

Speed 60 Km/hour								
Parts	**Defects Categories**	**Defects**	**N**	**P3**	**P2**	**P1**	**E2**	**E1**
Rails	Surface defects	Fish Scaling; Spalling	No surface cracking in gauge corner or on rail head	Minor Spalling Present: Gauge Corner, and Top of rail head	Significant Spalling Present: Gauge Corner, and Top of rail head			
		Rail Contact fatigue	No visible cracking on rail head	Cracks visible	Cracks 1mm deep or TDS potentially hidden during ultrasonic testing		TDM potentially hidden during ultrasonic testing	TDL potentially hidden during ultrasonic testing
		Rail Corrosion	>15	13-15		<13		
		Wheel Burns	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	
	Rail cracks and internal defects	Broken rail				0-50	51-100	>100
		Compound Fissure	4.9% or less		5% to 69.9%		70% to 99.9%	1
		Defective Welds		40 to 56	57 to 90		over 90	
		Foot and Web separation			20 to 40	41 to 75	76 to 150	Over 150
		Head and Web separation				20 to 75	76 to 200	over 200
		Rail cracks	<4	4 to 10	>10			
	Rail wear	Head Loss Max %				0.55		
		Curve Wear		52		48		
		Tangent Wear		32		26		

Ballast	Ballast Profile	Excess Ballast	Profile as specified	Surplus ballast in excess of specified profile exists	Potential to interfere with correct function of track			
		Ballast defecincy	0-6	6-10	10-14	>14		
	Drainage	Fouling	Minimal fines in ballast, Fines in ballast, visible contaminatio n on surface of ballast	Ballast fouled by fines and debris	Ballast visibly pumping and unable to maintain track within geometry maintenance limits			
		Vegitation Growth	Minimum vegetation	Some vegetation are blocking the voids	Highly vegetated that cause water being trapped in the ballast			
Sleepers (Ties)	Sleepers Condition Defects	Clusters of Consecutive Ineffective Sleepers	0-2	3	4		5	>5
		Consecutive Missing Sleepers	Nil			1	2	>2
		Spacing	<900 mm			900-1200	1200-1500	>1500
	Sleepers Componant Defects	Loose or Ineffective Fish Bolts	No	Yes				
		Severely worn sleeper pads	No	Yes				
		Squeezed out missing or failed insulators	No	Yes				
		Swage Fastenings at Fish-Plated Joint	No	Yes				

Geometry	Geometry	Gauge	21-26	27-28	29-30	31-32	33-37	>37
		Horizontal alignment	>20	21-29	30-39	40-48	49-54	>54
		Top Vertical alignment	0-24	25-27	28-30	31-32	33-40	>40
		Twist	<40	41-46	47-52	53-59	60-70	>70
		Cross level variation	<50	51-55	56-60	61-66	67-75	>75
Insulated Rail Joints	Insulated Rail Joints	Loss or failure of insulation material	No insulation material failure			Insulation material visibly cracked or disintegrated		Components fail to insulate (generally causing signal failure)
		Joint Gap Movement	No joint closing		Insulation key being squeezed out; Joint pulling apart - visible gap at insulation key	Gap between rails < 6mm; Joint pulling apart - bent bolts		
		Ineffective Drainage around Joint	No ineffective drainage			Water lying in joint vicinity	Water contacting foot of rail near joint	
		Rail head flow across joint Rail	No head flow	Flow on either rail with potential to provide < 6mm gap (mechanical), or < 4mm gap (glued) between rail ends	Flow on either rail with potential to provide < 4mm gap (mechanical), or < 3mm gap (glued) between rail ends			

Defects Severities
Speed 80 km/hr

Speed 80-90 Km/hour

Parts	Defects Categories	Defects	N	P3	P2	P1	E2	E1
Rails	Surface defects	Fish Scaling; Spalling	No surface cracking in gauge corner or on rail head	Fish Scaling 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		
		Rail Contact fatigue	No visible cracking on rail head		Cracks visible	Cracks 1mm deep or TDS potentially hidden during ultrasonic testing	TDM potentially hidden during ultrasonic testing	TDL potentially hidden during ultrasonic testing
		Rail Corrosion	>15	13-15		<13		
		Wheel Burns	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	
	Rail cracks and internal defects	Broken rail				0-50	51-100	>100
		Compound Fissure	4.9% or less		5% to 69.9%		70% to 99.9%	1
		Defective Welds		40 to 56	57 to 90		over 90	
		Foot and Web separation			20 to 40	41 to 75	76 to 150	Over 150
		Head and Web separation				20 to 75	76 to 200	over 200
		Rail cracks	<4	4 to 10	>10			
	Rail wear	Head Loss Max %				0.55		
		Curve Wear		52		48		
		Tangent Wear		32		26		

Ballast	Ballast Profile	Excess Ballast	Profile as specified	Surplus ballast in excess of specified profile exists	Potential to interfere with correct function of track			
		Ballast defecincy	0-4	4-8	8-12	12-16	>16	
	Drainage	Fouling	Minimal fines in ballast, Fines in ballast,	visible contamination on surface of ballast	Ballast fouled by fines and debris	Ballast visibly pumping and unable to maintain track within geometry maintenance limits		
		Vegitation Growth	Minimum vegetation		Some vegetation are blocking the voids	Highly vegetated that cause water being trapped in the ballast		
Sleepers (Ties)	Sleepers Condition Defects	Clusters of Consecutive Ineffective Sleepers	0-2	3	4		5	>5
		Consecutive Missing Sleepers	Nil			1	2	>2
		Spacing	<900 mm			900-1200	1200-1500	>1500
	Sleepers Componant Defects	Loose or Ineffective Fish Bolts	No	Yes				
		Severely worn sleeper pads	No	Yes				
		Squeezed out missing or failed insulators	No	Yes				
		Swage Fastenings at Fish-Plated Joint	No	Yes				

Geometry	Geometry	Gauge	21-22	23-26	27-28	29-30	31-37	>37
		Horizontal alignment	>15	16-20	21-29	30-39	40-54	>54
		Top Vertical alignment	0-20	21-24	25-27	28-30	31-40	>40
		Twist	<35	36-40	41-46	47-52	53-70	>70
		Cross level variation	<40	41-50	51-55	56-60	60-75	>75
Insulated Rail Joints	Insulated Rail Joints	Loss or failure of insulation material	No insulation material failure			Insulation material visibly cracked or disintegrated		Components fail to insulate (generally causing signal failure)
		Joint Gap Movement	No joint closing		Insulation key being squeezed out; Joint pulling apart - visible gap at insulation key	Gap between rails < 6mm; Joint pulling apart - bent bolts		
		Ineffective Drainage around Joint	No ineffective drainage			Water lying in joint vicinity	Water contacting foot of rail near joint	
		Rail head flow across joint Rail	No head flow		Flow on either rail with potential to provide < 6mm gap (mechanical), or < 4mm gap (glued) between rail ends	Flow on either rail with potential to provide < 4mm gap (mechanical), or < 3mm gap (glued) between rail ends		

Defects Severities
Speed 100-115 km/hr

Speed 100-115 Km/hour								
Parts	**Defects Categories**	**Defects**	**N**	**P3**	**P2**	**P1**	**E2**	**E1**
Rails	Surface defects	Fish Scaling; Spalling	No surface cracking in gauge corner or on rail head	Fish Scaling 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		
		Rail Contact fatigue	No visible cracking on rail head		Cracks visible	Cracks 1mm deep or TDS potentially hidden during ultrasonic testing	TDM potentially hidden during ultrasonic testing	TDL potentially hidden during ultrasonic testing
		Rail Corrosion	>15	13-15		<13		
		Wheel Burns	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	
	Rail cracks and internal defects	Broken rail				0-50	51-100	>100
		Compound Fissure	4.9% or less		5% to 69.9%		70% to 99.9%	1
		Defective Welds		40 to 56	57 to 90		over 90	
		Foot and Web separation			20 to 40	41 to 75	76 to 150	Over 150
		Head and Web separation				20 to 75	76 to 200	over 200
		Rail cracks	<4	4 to 10	>10			
	Rail wear	Head Loss Max %				0.55		
		Curve Wear		52		48		
		Tangent Wear		32		26		

Ballast	Ballast Profile	Excess Ballast	Profile as specified	Surplus ballast in excess of specified profile exists	Potential to interfere with correct function of track			
		Ballast defecincy	0-4	4-8	8-10	10-16	16	
	Drainage	Fouling	Minimal fines in ballast, Fines in ballast,	visible contaminatio n on surface of ballast	Ballast fouled by fines and debris	Ballast visibly pumping and unable to maintain track within geometry maintenance limits		
		Vegitation Growth	Minimum vegetation		Some vegetation are blocking the voids	Highly vegetated that cause water being trapped in the ballast		
Sleepers (Ties)	Sleepers Condition Defects	Clusters of Consecutive Ineffective Sleepers	0-2	3	4		5	>5
		Consecutive Missing Sleepers	Nil			1	2	>2
		Spacing	<900 mm			900-1200	1200-1500	>1500
	Sleepers Componant Defects	Loose or Ineffective Fish Bolts	No	Yes				
		Severely worn sleeper pads	No	Yes				
		Squeezed out missing or failed insulators	No	Yes				
		Swage Fastenings at Fish-Plated Joint	No	Yes				

Geometry	Geometry	Gauge	<21	21-22	23-26	27-28	29-34	>35
		Horizontal alignment	>13	13-15	16-20	21-29	30-52	>52
		Top Vertical alignment	0-16	17-20	21-24	25-27	28-34	>34
		Twist	<32	32-36	36-40	41-46	47-64	>65
		Cross level variation	<36	36-40	41-50	51-55	56-71	>71
Insulated Rail Joints	Insulated Rail Joints	Loss or failure of insulation material	No insulation material failure			Insulation material visibly cracked or disintegrated		Components fail to insulate (generally causing signal failure)
		Joint Gap Movement	No joint closing		Insulation key being squeezed out; Joint pulling apart - visible gap at insulation key	Gap between rails < 6mm; Joint pulling apart - bent bolts		
		Ineffective Drainage around Joint	No ineffective drainage			Water lying in joint vicinity	Water contacting foot of rail near joint	
		Rail head flow across joint Rail	No head flow		Flow on either rail with potential to provide < 6mm gap (mechanical), or < 4mm gap (glued) between rail ends	Flow on either rail with potential to provide < 4mm gap (mechanical), or < 3mm gap (glued) between rail ends		

Defects Severities
Speed 115-160 km/hr

Speed 115-160 Km/hour								
Parts	**Defects Categories**	**Defects**	**N**	**P3**	**P2**	**P1**	**E2**	**E1**
Rails	Surface defects	Fish Scaling; Spalling	No surface cracking in gauge corner or on rail head	Fish Scaling 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		
		Rail Contact fatigue	No visible cracking on rail head		Cracks visible	Cracks 1mm deep or TDS potentially hidden during ultrasonic testing	TDM potentially hidden during ultrasonic testing	TDL potentially hidden during ultrasonic testing
		Rail Corrosion	>15	13-15		<13		
		Wheel Burns	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	
	Rail cracks and internal defects	Broken rail				0-50	51-100	>100
		Compound Fissure	4.9% or less		5% to 69.9%		70% to 99.9%	1
		Defective Welds		40 to 56	57 to 90		over 90	
		Foot and Web separation			20 to 40	41 to 75	76 to 150	Over 150
		Head and Web separation				20 to 75	76 to 200	over 200
		Rail cracks	<4	4 to 10	>10			
	Rail wear	Head Loss Max %				0.55		
		Curve Wear		52		48		
		Tangent Wear		32		26		

Ballast	Ballast Profile	Excess Ballast	Profile as specified	Surplus ballast in excess of specified profile exists	Potential to interfere with correct function of track			
		Ballast defecincy	0-4	4-8	8-10	10-16	16	
	Drainage	Fouling	Minimal fines in ballast, Fines in ballast,	visible contaminatio n on surface of ballast	Ballast fouled by fines and debris	Ballast visibly pumping and unable to maintain track within geometry maintenance limits		
		Vegitation Growth	Minimum vegetation		Some vegetation are blocking the voids	Highly vegetated that cause water being trapped in the ballast		
Sleepers (Ties)	Sleepers Condition Defects	Clusters of Consecutive Ineffective Sleepers	0-2	3	4		5	>5
		Consecutive Missing Sleepers	Nil			1	2	>2
		Spacing	<900 mm			900-1200	1200-1500	>1500
	Sleepers Componant Defects	Loose or Ineffective Fish Bolts	No	Yes				
		Severely worn sleeper pads	No	Yes				
		Squeezed out missing or failed insulators	No	Yes				
		Swage Fastenings at Fish-Plated Joint	No	Yes				

Geometry	Geometry	Gauge	<21		21-22	23-26	27-32	>33
		Horizontal alignment	>13		13-15	16-20	21-48	>48
		Top Vertical alignment	0-16		17-20	21-24	25-32	>32
		Twist	<32		32-36	36-40	41-59	>59
		Cross level variation	<36		36-40	41-50	51-66	>66
Insulated Rail Joints	Insulated Rail Joints	Loss or failure of insulation material	No insulation material failure			Insulation material visibly cracked or disintegrated		Components fail to insulate (generally causing signal failure)
		Joint Gap Movement	No joint closing		Insulation key being squeezed out; Joint pulling apart - visible gap at insulation key	Gap between rails < 6mm; Joint pulling apart - bent bolts		
		Ineffective Drainage around Joint	No ineffective drainage			Water lying in joint vicinity	Water contacting foot of rail near joint	
		Rail head flow across joint Rail	No head flow		Flow on either rail with potential to provide < 6mm gap (mechanical), or < 4mm gap (glued) between rail ends	Flow on either rail with potential to provide < 4mm gap (mechanical), or < 3mm gap (glued) between rail ends		