Failure Analysis of Switch Rails and Crossings Towards Maintenance Improvement: A Case Study of Addis Ababa Light Rail Transit

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Author’s Declaration

I hereby declare that this PhD dissertation is my original and own work and does not include any known conflicts of interest. The full or part of this work was not and will not be submitted to another University for the reward of any other degree. I am just submitting for the degree of Doctor of Philosophy, to African railway center of excellence, Addis Ababa Institute of Technology, Addis Ababa University, Addis Ababa, Ethiopia.

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Abstract

Railway systems are such a complex transportation systems that consists several components like rails, switches, crossings, check rails, turnout carriers, and some other components. Maintenance of railway “switch and crossing” (S&C) systems is critical for effective and safe train operations. The material degradation and geometry optimization of switches and crossings should be considered for an efficient operation of railway system. The failures of railway tracks are an unavoidable phenomenon that affects the operation intensively. AALRTS rail material is 50 Kg/m U71Mn and the frog is Hadfield steel. Previously different failure assessment and investigation researches have been carried out, however, failure investigation techniques need to be updated frequently and assessed because the problem still exists. Markov chain model was implemented for statistical analysis of critical failures and the output results are “Mean Time To Failure” for both critical and disastrous failures. Based on the results it is possible to recommend that increasing the number o f “Ultrasonic Inspection Cars” test from 3 to 5 or increasing the test interval from 122 days to 73 days per year will minimize “Mean Time To Failure” from 3.1 years to 1.6 years. The mean time to failure results can be an input for a strategic track maintenance planning. “Failure mode, effects, and criticality analysis” (FMECA) were implemented to identify the most critical failure mode with higher risk. The welded rail specimen`s quality, hardness, and microstructural features were evaluated at different cooling rates experimentally. To identify and assess the microstructure feature and hardness of rail welding through different cooling rates three major NDT tests have been employed. Increasing the number of tests of inspection or the inspection interval will minimize the mean time to failure. Generally, all the non-destructive test results demonstrate that there is a noticeable defect on the welded rail cooled at 6°C/s. Comparatively fewer defects were observed on the welded rail cooled at 3°C/s; while acceptable defects were manifested on the one cooled at 2°C/s. The minimum cooling rate can be achieved through both preheating and post-heating process.

From the switch panel, “Failure mode, effects, and criticality analysis” (FMECA) results “gauge corner spalling” failure mode was with the highest risk priority number so that its improvement has a great influence on the maintenance efficiency.

Additionally, from the detail results of failure mode, effects, and criticality analysis (FMECA) of turnouts; failure modes under high risk category need special attention during maintenance planning and need improvement of rectification techniques. From the results of the analysis six failure modes have been laid under high risk categories whereas two failure modes have been laid under moderate risk categories and four failure modes have been laid under low risk categories. As a conclusion cooling of rail welding`s at 2°C/s cooling rate will give the material good micro-structural feature and better weld quality relatively. This minimum cooling rate 2°C/s achieved by uniform and optimum preheating and post-heating temperatures. Finally, the researcher recommend a controlled cooling rate for welding quality improvement and maintenance efficiency increment.

Keywords: Failure assessment, damages on turnouts, failure`s severity, failure modes, sensitivity analysis, Switch rail and crossings.

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LIST OF ABBREVIATIONS

AALRTS	Addis Ababa Light Rail Transit Service
FDD	Fault detection and diagnosis
AHP	analytic hierarchy process
RCM	reliability-centered maintenance
RCM	remote condition monitoring
FMA	Failure mode analysis
FMEA	failure mode and effects analysis
FMECA	failure mode effects and criticality analysis
WCZ	weld center zone
TMAZ	thermo-mechanically affected zone
HAZ	heat-affected zone
BM	the base material
LFW	linear friction welding
CGHAZ	coarse-grained heat-affected zone
NDT	non-destructive test
DB	Decibel Unit
S&C	Switch & Crossings
FEM	finite element model

1 CHAPTER ONE: INTRODUCTION

1.1 Background

AALRTS is the first Electric light rail and rapid transit in eastern and sub-Saharan Africa that is located in Addis Ababa, Ethiopia. Switches have special importance for railways, as they are the prerequisite for the development of networks, i.e. for the branching and joining of tracks. The productivity and line speed of a railway is highly influenced by the number and type of its switches. Turnouts and crossings facilitate the way for rolling stocks to run from one track in to or across another track.

The significance of crossings is to allow two tracks to intersect at the same level. Switches are structural elements requiring high investment and large-scale maintenance; they can severely hinder vehicle traffic. To purchase one effective meter of a switch (depending on the type of switch) might cost up to four times higher than for one meter of track. Switches must be arranged and designed in such a way as to achieve a favorable layout of the line- from the point of view of the dynamics of vehicle movement. The same standard of maintenance has to be achieved for switches and for track in order to prevent switches from becoming sources of disturbance [1].

The stress on the structural elements of switches is much higher than on track elements, as it is not possible to avoid places of discontinuous stress. Therefore, traditional switches can fulfill their task only up to a certain speed and stress level. Geometrical improvement can be one of the solution. Switches enable vehicles to pass from one track to another without interrupting their run. Crossings are the intersection of two tracks, diamond crossings with slips make it possible for vehicles to pass from one track to another without interrupting their run at the point of intersection.

The main types of switches:-[2]

- crossings and diamond crossings with slips
- split (single) switches
- symmetrical switches
- three-way switches

Andrew Tom Cornish in his research has categorized the type of damages which occur on switches and crossings as follows: -

1.1 Plastic deformation

Plastic deformation develops due to the dislocation movements in the grain structure of the material. As cyclic rolling loading exceeds the elastic limit of the material, contact stresses exceed the yield limit and the grains become heavily deformed and elongated, leading to local material degradation with an isotropic properties. In switch panels and at the crossing nose, repeated and high magnitude cyclic contact forces on the rail leads to accumulated plastic deformation that changes the rail profile and can stop the operation of the switch through rail material blocking the closing mechanism. The rate and magnitude of the profile change depends on both the loading and the material behavior of the rail steel.

1.2 Wear

Wear can be divided into five categories, of which three are found through wheel/rail contact;

- **Abrasion** – material or particle removal through asperities in the running surface causing high friction levels between the surfaces.

- **Impact** – high magnitude contact forces between bodies in contact lead to rapid changes in stress, causing plastic deformation, and initiation and propagation of cracks.

- **Delamination** – thin layers of material removal from the surface. These wear categories can happen independently or combined simultaneously through switches and crossings due to the high impact forces from the discontinuity of the geometry and various contact locations and magnitudes of loading.

1.3 Fracture at the web or foot of the rail

Fractures can occur either through frequent high loading beyond the “ultimate strength” of the material or through a single immediate disastrous loading.

1.4 Railhead cracks

‘Head checks’ or rail gauge corner cracks are a set of acceptable surface cracks originating on the outer rail of tracks, curved segments, and “switches and crossings”. [3]

A predictive maintenance model has been developed using “tree-based classification techniques” of machine learning for maintenance requirement prediction, action category, and trigger’s prominence of switch rails.[4]

“Risk priority number” is a key tool in order to analyze the defects of components merely by identifying the occurrence, detect-ability and severity of the failure.[5] A systematic approach of risk assessment and evaluation techniques consider preventive maintenance plans and identification of critical events whether at operational or maintenance modes.[6] Failure catalogue can be used to identify and study different failure modes on switch rails and crossings. Non-optimal wheel and rail contact geometry needs Maintenance aspects since it can be the cause for a number of defects and it is very efficient to use simulation tools. Optimization work in this area therefore has been suggested as a means of improvement for several types of defect`s modes.[7]

Taking actions when it is truly needed depending on operational hours or the volume of servicing is the goal of “Proactive maintenance”. This requires the efficient arrangement of “data collection”, “data analysis”, “data presentation” and decision making procedures.[8]

Switch rail and stock rail interaction has been expressed by a contact model prior and this model was an input for wear and RCF prediction. Predicting wear and RCF is one of the methods to address the failures on switches and crossings and a base for maintenance improvement recommendation.[9] on previous study arc welding was a repair method for worn-out rail head of light rail tracks; so that improving the method has an indirect influence on the improvement of the repair efficiency.[10] The failure on the railway track can be caused by different grounds. Degradation of the hardness of the rail material could be a preliminary cause. [11] different approaches were applied to investigate the failures on railway tracks and to predict better maintenance manners. Reliability, availability and maintainability (RAM) Discipline is one of the approach that was applicable on previous studies for the purpose of maintenance improvement.[12]

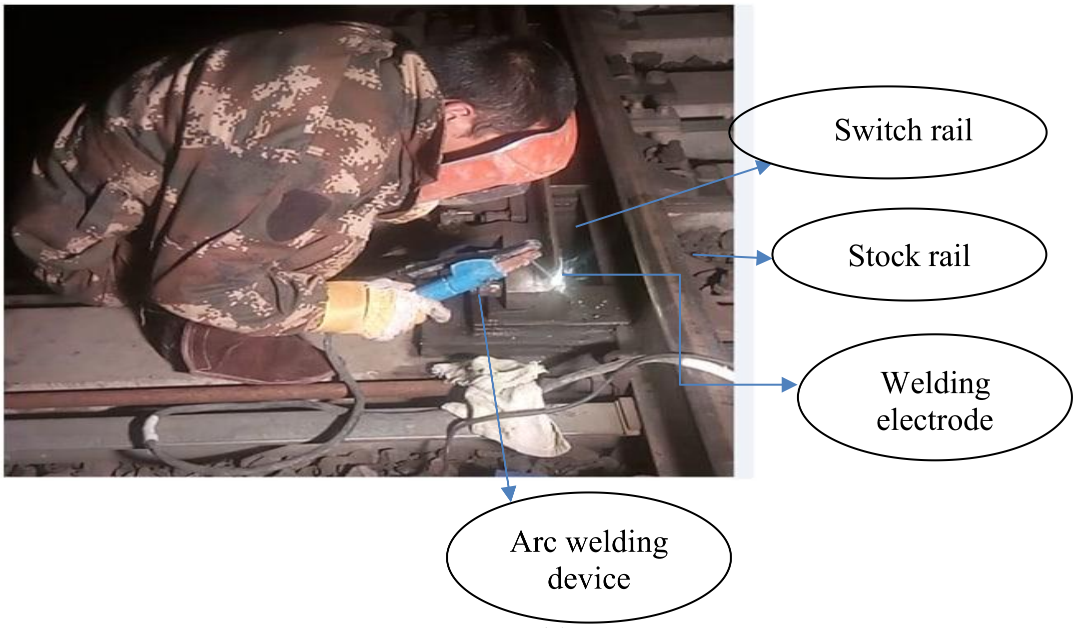
Failure modes and effects analysis is a widely used failure analysis method on railway sector including switches and crossings.[13] FEMA is also applicable for risk assessment of railway vehicles.[14] Using FEMA a schedule for preventive maintenance of railway infrastructure can be developed and risk assessment using risk priority number was also developed. [15]

There are different failure assessment and analysis techniques in railway technologies. In this paper different failure analysis techniques have been reviewed. Switches and crossings are the sources of many failures, so that it needs unceasing attention. Condition monitoring risk assessment techniques for investigating the state of the switch and crossings has been studied by different Authors using on board sensor devices.[16]

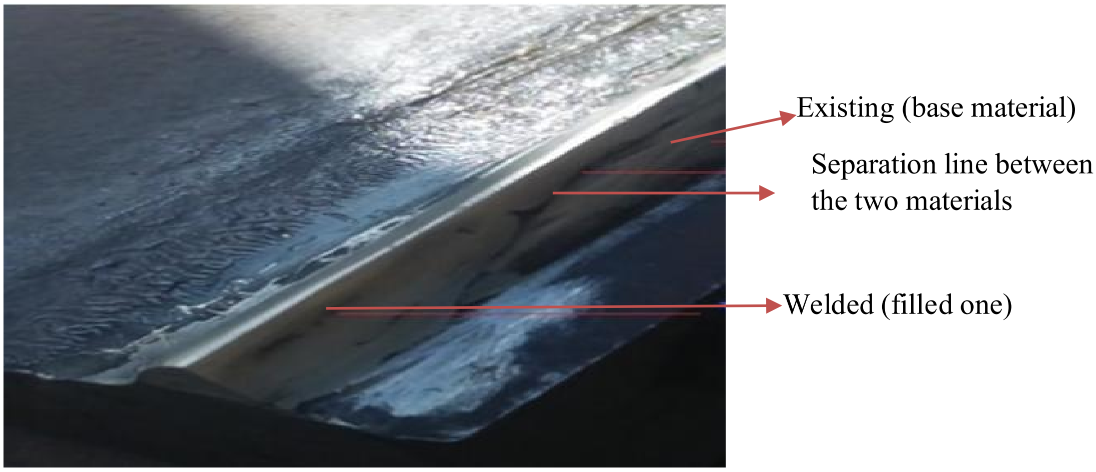
Because it is a very sensitive area, the failures on railway Switch & Crossing systems have to be studied in detail by implementing different techniques. "Fault detection and diagnosis (FDD)" method is also one of the effective fault diagnosis techniques in railway sector.[17] Failure mode and effect analysis (FMEA) is an actual method for mechanical system`s risk assessment. This method is a suitable approach to recognize the critical failure modes and offer appropriate control actions to reduce the level of risk.[18] Another research work has been accompanied about failure analysis and their influence factors on metro railway system. The results of the above research indicate that "wheel damage" is the most severe failure mode in the "bogie system" of the metro and the influence factor that has been predicted might be lack of professional abilities.[19] The Failure Mode, Effects and Criticality Analysis (FMECA) is a reliability assessment/design method that examines the possible failure modes inside a system and its apparatus; for the purpose of expressing the effects on apparatus and system performance.[20] "Continuous monitoring and proactive maintenance" methods of the railway tracks have been introduced for the purpose of railway switch maintenance improvement.[21] Comparing to ordinary line track the rail geometry dis-continuities and changeability in the system support toughness leads to high "failure rates" and to very excess maintenance and renewal budgets. Statistical failure analysis technique has been accompanied for rail turnouts of Gb network in

UK between the years 2011-2017, as a result the significant failures and potential causes have been recognized. [22]

A combination of methods such as “observation”, “interview” and an “adaptation of critical decision method”, were engaged to provoke the decision-making approaches of operators for the purpose of maintenance improvement.[23] The possible risks of unpredictable failures that are taking place in rolling stock have been recognized, inspected and assessed by using a “failure mode, effects and criticality analysis” approaches.[24] Two neural network methods called “Long Short-Term Memory (LSTM)” architecture, and the “Deep Wavelet Scattering Transform (DWST)” have been implemented on monitoring of rail switch and demonstrating their feasibility on a data-set.[25] A case study has been accompanied on airport-rail link line in Thailand by implementing “Failure Modes, Effects and Criticality Analysis (FMECA)” technique for the purpose of risk management on critical components on the crossings.[26] FMEA is a precise and systematic technique that helps to assess the potential ways through which failures can occur in an industrial or engineering process. It can also be applicable on different railway locomotive assemblies.[27] The performances of the railway wheel have been investigated by FMEA; the failure modes have been identified and also the failure analysis has been conducted.[28]



(a)



(b)

Fig 1- 1 (a) and (b) Field picture of the damaged rail filled by arc welding in Addis Ababa light rail transit switch rail

1.2 Problem Statement

The efficiency of rail transport ultimately affects the efficiency and working of the entire economic system of a country. Thus, economic impact is always the major concern for the Government and the society. Rail switches and crossings are critical rail sections that might cause continues maintenance. Hence, it is expected to have repeated maintenance requirements on rail switches which invite unprogrammed and unplaned expenditure to smooth the transportation system. Many countries are usually being threatened by such a type of problem. From previous studies we can state that "Most of railway maintenance expenditures are invested on railway turnout sections". Studying the details of failure modes and their risk factors is helpful for an effective maintenance plan.

The failures on railway switches and crossings of Addis Ababa Light Rail Transit are frequent that leads to high maintenance cost. The structures of most turnouts of AALRT are curved tracks. The gauges of the curved tracks worn-out frequently. The maintenance trend of switch rails was not efficient; that leads to redundant maintenance work. Proper maintenance lacks hence the failure rates and the mean time to failures are not clearly addressed. One of the repair approach of switch rails and crossings was repair by welding; so that improving the cooling rate has a direct influence on the improvement of the welding quality. On the bases of the above statements, giving special attention to the improvement of the maintenance trend of switch rails and crossings is an imperative fact in railway technology for efficient operation. The failure modes on turnouts of Addis Ababa Light Rail Transit (AALRT) need to be assessed and the critical failures have to be identified.

Research Questions

1. What are the failure modes on switch rails and crossings?
2. Which failure modes are critical failures with higher risk priority number?
3. What are the rectification techniques applied during maintenance of switch rails and crossings?
4. What factors can affect the maintenance efficiency of switch rails and crossings?

5. What procedures should be implemented to improve the maintenance efficiency of switch rails and crossings?

6. What factors affect the failure rates and the inspection intervals?

7. What factors affect the cooling rates of welding`s?

Fig 1- 2 Wear on main line truck gauge corner of AALRT

1.3 Objective

The main objective of this research is analysis of failures on switch rails and crossings towards maintenance improvement. In this research work a method for corrective maintenance improvement of switch rail`s and crossing`s have been introduced.

1.3.1 Specific Objectives

1. To assess the occurrence of failure modes on switch rail and turnouts of AALRT.

2. To assess the rectification of different failure modes on switch rail and crossings of AALRT.

3. To carry out the failure mode and effects and criticality analysis (FMECA) method in order to identify the critical failures.

4. To carry out experimental investigation on the rail of AALRTS in order to suggest the better welding cooling technique.

5. To facilitate the way of improving the weld quality of the rail by suggesting different techniques on the basis of the results of the study.

1.4 Scope and Limitations of the Research

1.4.1 Scope

The present work focuses on improving the corrective maintenance trend of railway switches and crossings by taking Addis Ababa Light Rail Transit (AALRT) as a case study.

1.4.2 Limitations

The limitations that the researcher has encountered are: -

1. Hence there are not specified schedule for rectification welding works for the Addis Ababa Light rail transit service it was not possible to display the schedule for welding rectification.
2. There are no well-developed welding techniques for Addis Ababa Light rail transit service; hence it was not possible to adapt different welding techniques through the study.
3. The study was mainly focused on light rail transit system because the research area was limited to light railway system.
4. This research work didn't consider the seasonal change effect`s on the failure conditions of light rail systems.

1.5 Justification of the Research

Railway transportation is a reliable and comfortable means of transportation recently. Railway turnouts are essential sections of the infrastructure of railway, utilized all the way of the network for the purpose of directing trains to the desirable way. Hence assurance of the uninterrupted running of all trains depends on the well-being of the turnouts. Hence availability and reliability of turnouts is an indispensable section for the efficiency of the whole network.

Up to now different failure assessment and maintenance improvement techniques have been suggested, whereas the aim of this research is specifically related to the welding rectification techniques of turnouts relating to the cooling mechanism.

Welding is the frequently used rectification technique of damaged rails; So that improving the welding technique can reduce the frequency of maintenance.

1.6 Structure of the research

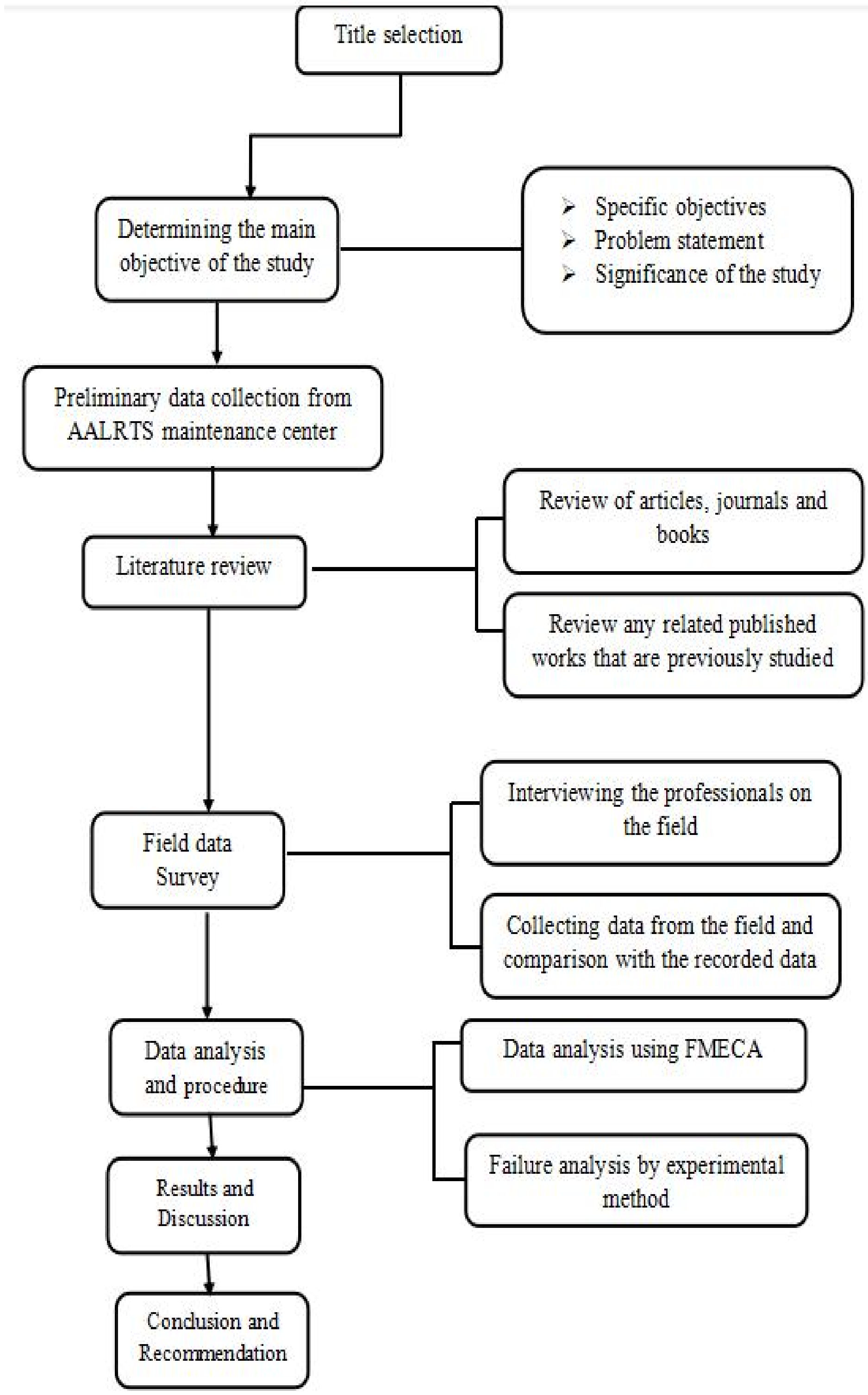


Fig 1- 3 Flow Chart of the research structure methodology

2 CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

The maintenance plan of every railway transit system has to set its own failure analysis technique. The plan may need a revision based on the outcomes of the analysis techniques. Based on the above statement this chapter of the paper will provide a review of different literature on railway transit system with their outcomes. This chapter will give an overview of failure analysis and diagnosis techniques. Published articles on different failure analysis techniques have been discussed chronologically.

Finally, the review section analyses the techniques and methods used in failure analysis and discuss in detail the gaps found in the section of literature review.

2.2 Failure analysis and assessment methods on switch rails and crossings

Wear is a phenomenon that causes a gross damage on frequently contacted materials; hence the reviewer is concerned to assess the wear phenomena on wheel/rail materials with their different features. The most important mechanisms that cause the profile of wheels and rails to change with time are wear and plastic deformations, further aggregated wear and rolling contact fatigue. Under the study of the turnout dynamic response, the track stiffness defined by FEM analyses has been used for the calculation of dynamic vertical and lateral wheel load. A different model of a railway vehicles were made by different researchers with the intention of manipulating the forces at points where unexpected stiffness changes happen. [29]

From previous researches an experimental research conducted aiming that increasing the hardness of railway turnout by suggesting high strength steel called Hadfield steel through the process of explosively hardening. In accordance Explosive hardening of the Hadfield steel examined and tested for sample turnout crossing. By applying “impact wave with high pressure (6 - 25 GPa)” the explosive layer type “Semtex 10SE” with 2 mm thickness was also employed on crossing made of Hadfield steel. The experimental result indicates that hardening is the best way to stabilize the turnout dimensions. [30]

In addition to experimental investigations a case study has been also adapted for railway material improvement and reducing railway accidents.[31] High-manganese steels can be applicable for the application of heavy duty cast shaped steels like railway turnout`s frogs. Adding high percentage of manganese is one way for material hardness improvement of railway crossings; but heat treatment of such steels might cause excessive surface decarburization. [32] Damages on wheel-rail contact is different in its type among them two forms of damages were in detail studied on previous studies that are: - “white etching layers (WEL) and rolling contact fatigue (RCF) cracks”. Degradation of rails of railways can`t be identified and studied only by choosing better materials; so that this reviewed paper has a gap identified as the topic did not considering other factors for degradation of rails. [33]

In the wheel–rail contact, a number of wear mechanisms may be present; abrasive wear, adhesive wear, corrosive wear and surface fatigue or delamination wear. Mild wear (wheel–rail contact`s low wear rate) identified to be caused by abrasion and oxidation, whereas catastrophic and severe wear (high or very high wear rate) are occurred because of surface fatigue and delamination.

An experimental investigation on test rigs of wheel-rail contact was conducted in the previous study in laboratory for the purpose of wear prediction. The survey of this reviewed paper presents a procedure for determining the Archard`s wear coefficient from data collected in a full-scale wheel–rail test rig, i.e. under realistic loading conditions. rail profiles simulated for the purpose of wear profiles identification. The gap suggested in this experimental and numerical study was there was dependency between the selected “wear step length” and the obtained simulation outputs of rail profiles. so that developing an accurate and efficient contact model is needed. [34]

“Investigation of wear on wheel-rail contact has been also studied by different researchers experimentally and numerically. The well-known damages on rolling contacts are: - wear, RCF and friction. Their study states that: - the rolling contact tests has been conducted by “optical microscopy” and “scanning electronic microscopy” to predict wear and RCF; but only two rail materials were compared.[35]

A Standard Approach has been considered to test wears on both materials of wheels and rails by different researchers. From the review of test approaches the researchers proposed that the best approach to study the wear of wheel and rail materials is the twin-disc approach as this provides the most cost and time effective methodology and it provides close control of test parameters which leads to more reliable and usable data. [36]

From the survey of different studies of wheel rail contact models; three “non-elliptic contact models”, namely “Kik–Piotrowski” method, “STRIPES” and “ANALYN”, were compared to the “Hertz theory” and the “CONTACT” wheel-rail contact models. Further, for the other wheel-rail contact models excluding for “CONTACT”, the contact solutions of tangential contacts were calculated by an improved and simplified theory of “Kalker (FASTSIM)”. The influence of those five contact models stated above for wheel wear prediction was investigated. The outcomes show that implementing Hertz theory and FASTSIM to resolve the tangential and normal contact problem; the “wheel wear simulation” is an excellent method in order to consider a cooperation between the scheming accuracy and efficiency.[37]

A research on “Wheel - Rail Contact`s Friction” was added by “Radu Popovici”. The Wheel - rail contact model, which is the “Hertzian elliptical contact” state, has been considered as a perfect contact model and a “mixed lubrication friction” model has been developed for in which the “interfacial layer” is acting as a lubricant governed by the “Eyring model”. however the spin effect was not considered in the wheel-rail contact model and “Hertzian elliptical contact” was not enough to define the wear on the wheel-rail contact .[38]

In this reviewed paper the authors described a model intended to obtain a better accuracy in reproducing “degraded adhesion” circumstances in railway systems and vehicle dynamics. The innovative model focuses on the main phenomena characterizing the “degraded adhesion”, and the resulting recovery of adhesion as a result of the removal of the external unknown contaminants. While a deeper investigation is needed for the effect of adhesion recovery on railway vehicle dynamics; further investigation of wheel-rail contacts and effect of wear on the surface of the wheels and rails was essential. Additionally accurate measurements of the weight and contact of the wheel is needed. [39]

Wheel and rail profile “wear prediction model” was introduced on previous studies in the applications of railway system particularly considered for railway networks that are complex; due to the extraordinary computational load required; the complete simulation of the vehicle running on the whole line was not feasible. The results coming from the innovative model have been compared both with the outputs from the complete railway network simulations and with the experimental data.[40]

A modeling strategy for simulating wear accumulation damage associated with railway switches and crossings has been presented by “Ian Coleman`s” in his PhD dissertation. Basic theories of contact stress have been combined within a novel Switch & Crossings wheel-rail “multi-point contact detection” tool to provide surface contact results, such as tangential and normal tractions and slip displacements. Ian Coleman`s has also established a three-dimensional “elasto-plastic” FE model of rolling contact along the head of a UIC60 rail type.[41]

An explanation of switches and crossings (S&C): - why they are needed, the objectives and the limitations of the study introduced by Willem-Jan Zwanenburg on the Swiss Railway Network. The lower rolling resistance caused by the “steel-on-steel” contact and thus the capability of transporting have been fully assessed. The new maintenance plan was suggested for switch and crossings but the study is limited to small improvements of existing designs. [42]

A methodology on the track geometry optimization and backing stiffness on the switch panel and of the crossing panel superstructure has been presented by previous studies to predict deterioration of Switch & Crossings components as a result of wear and plastic deformation. These reviewed researchers have shown up vividly the governing factors on components of a turnout, and damage due to plastic deformation and wear on crossing noses, switch and wing rail through observable figures. [43]

A method for the optimization of geometries of crossing`s were introduced for the purpose of contact profile improvement and minimization of the pressure on wheel rail contacts. Additionally, longitudinal profiles of the crossing nose and wing rails are optimized to minimize an estimation of the gathered damage in the transition zone. “FASTSIM algorithm” and MATLAB precise computing software’s were introduced for tangential contact problem analysis and pre- and post-processing resolutions respectively. [44]

Worn rail profiles needs to be measured in order to handle the corrective measures; in the same situation the side wear have to be measured at gauge profile and the vertical wear needs to be measured at the rail profile center. It has been studied previously that "profile wear disturbs the spreading of wheel–rail contact paired points". It has been also suggested that: - A position changes of wheel and rail contact points laterally the longitudinal progression; can lead to an effect on the dynamic interaction of turnouts and vehicles. In this reviewed paper wheel/rail contact dynamic interaction has been analyzed by multi-body system SIMPACK. Profile wear has been also identified as one of the shortcomings affecting the wheel rail/switch contact. But a further investigation is needed on profile evolution along the long the longitudinal direction. [45]

It is the true fact whenever the high contact pressure is imposed it can cause severe cyclic plastic deformation. The driving forces for rolling contact fatigue (RCF) and wear described for the wheel/rail contact, which restricts the service duration and lifetime of crossings, are contact pressure and slide.[46]

In Emmanouil Doulgerakis`s master`s thesis it has been suggested that: -the geometries of the turnout`s with discontinuity in rail profiles and lack of "transition curve" causes additional wear both on track and on vehicle. The main goal of this MSc thesis was to investigate the influence of turnouts on wheel wear of a freight vehicle. The wheel-rail contact is modelled according to Hertz`s theory and Kalker`s simplified theory, with the FASTSIM algorithm, and the wear calculations are performed according to Archard's law. [47]

A.A. Mashal`s thesis has a contribution on wheel-rail contact analysis for the purpose of wear minimization. An accurate crossing panel 3D finite element (FE) model was created in this study in order to analyses the stress state resulting from the impact event and to provide recommendations for how to successfully reduce the impact loads.

A numerical procedure was implemented to provide much accurate results by examining wheel-rail operational contact constraints Using "Explicit Finite Element Methods". Even though the FE model need further improvement for better accurate simulation of the certainty.[48]

Archard`s wear law was also implemented to numerically simulating wear in rolling and sliding contacts of wheel-rails. A simulation scheme was developed that calculates the wear at a detailed level. Based on the finding , it was stated that the reduction of volume is linearly proportional to the sliding distance, the normal load and the wear coefficient.[49]

High manganese materials have Mn content higher than 12 wt. %, which is significantly the level of Mn in the Hadfield steel, from which other types of high-manganese materials have been developed. The intention of the current method is to show physical and engineering properties of TWIP and TRIPLEX steel in the context of Hadfield steel. [50]

High manganese materials can be categorized as:

1. Hadfield steel
2. TWIP alloy (twinning induced plasticity) – i.e. the type of the realized deformation process.
3. TRIPLEX alloy (besides the fundamental Fe bases there are at least three elements).

A high-speed railway's wheel-rail dynamic interaction will be enhanced by the excitation of the observed rail corrugation, and a high-frequency dynamic force among the wheel and rail will be produced. The vibrations of the rail and wheelset are obviously affected. When both the corrugation depth and wavelength develop, the vertical force on the wheel-rail will grow as well.[51]

The development of the high-speed turnouts is a continuous activity which has been carried out for many years. During this activity the innovative elements are developed and usually verified at first within the framework of the standard geometry turnouts. In the process of verification many parameters are usually checked, measured and consecutively assessed.[52] Measuring and Inspecting Switches & Crossings with the "SICS Approach" (Synchronization/Integration of measured data, Correlation for measures and defects, Statistics on ―Big Data)" was also another way to inspect S&C. "S&C Data Management and Decision Support Systems" have believed today that has prepared to support the measurements.[53]

A review of S&C renewal methods across Europe is undertaken in this reviewed study. The study analyses and compares the S&C replacement methods used in eight countries (Spain, Sweden, Germany, Turkey, Hungary, United Kingdom, Czech

Republic and Norway) in terms of outputs, resources (labor and machinery) and quality of installation. "Track stiffness variation along the switch has a direct effect on the magnitude of impact loads that cause track deterioration." This is one of the study outcomes.[54] A model for the life expectancy of railway switches and crossings for maintenance and renewal planning has been developed based on different parameters which influence the speed of geometrical degradation or wear of the material, e.g. total train loads (expressed in cumulative tonnages), axle loads, train type, the quality of the foundation.[55]

The design and operation of the switching concept has been introduced by previous studies from requirements capture and solution generation through to the construction of the laboratory demonstrator. The original concept is compared with the design and operation of the traditional switch design. [56] A transient analysis model is presented to investigate the stiffness characteristics of high-speed railway turnouts based on the finite element method and is applied to optimize the stiffness of railway turnouts. Furthermore, the effect of the stiffness variations on the dynamic train-turnout interaction has been analyzed. The results indicate that the track stiffness characteristics are similar in the main and diverging line of railway turnout, except for the check rail sections.[57] Seid Abdul-hakim on his master`s thesis assessed the effects of radius of curved rail on rail wear using Multi-Body simulation software SIMPACK. Through this paper track radius, wheel rail contact patch area, contact pressure, vehicle speed, wheelset yaw angle parameters has been investigated to identify their effects on rail wear. [58]

Based on AREMA`s standards: "In the railway engineering austenitic manganese steel (AMS) has been used effectively in exceptional track work, namely "frogs, guard-rail wear bars, diamond crossings, and replaceable switch point tips"; in which austenitic manganese steel has a yield strength between "(345 MPa) to (414 MPa)" and modulus of elasticity is (186 x 103 MPa). "The ultimate tensile strength of AMS varies but is generally taken as (965 MPa)". "At this tensile strength, AMS demonstrates elongation with the range of "35 to 40%". Manganese steel`s fatigue limit is about "(269 MPa)". [59] Hertzian contact model was the first contact model which was the bases for other contact models. The development and improvements of researches had also outcome the improvement of contact models. Archard's wear model has been also used to predict the amount of wear. [60] A method for the switch rail profile and crossing geometry needs optimization for minimization of wear and fatigue. This technique has been introduced by BJÖRN A. PÅLSSON for the purpose of least wheel–rail contact pressure achieving. [61]For the assessment of failure on rail curves and turnouts different methodologies have been implemented. Fault detection and diagnosis (FDD), analytic hierarchy process (AHP), reliability centered maintenance (RCM), remote condition monitoring (RCM) Failure mode analysis [FMA] and failure mode and effects analysis (FMEA) are the main methods that have been discussed in detail in the review section. Nonetheless these methods have some limitations since their decision-making procedure is not sufficient. The main objective of this review section is to assess studies on the failure assessment and enhancement methods on the turnout rail sections aiming that reviewing and identifying the gaps of the main methods from the previous research works for the purpose of corrective maintenance. A systematic literature review approach has been used to assess those failure assessment and enhancement techniques, so that different fault detection, decision making, failure prediction and monitoring techniques have been addressed.

A method used for the review work is a systematic review of literature's that have been conducted regarding turnouts failure assessment and enhancement approaches based on their methodologies. For the systematic review work accessible databases Emerald Database, Taylor and Francis, ProQuest, Scopus and Google Scholar sites have been used to search and gather research articles using key words. The strategy that has been used for the search considers the specified key words: - “Failure assessment”, “Failure enhancement”, “Failure on turnouts”, and “Failure on rail curves”.

This review work has excluded other articles which have been published in different languages other than English and the reviewed researches have treated published articles on sector of railway by focusing on wear assessment and enhancement methods on rail turnouts and rail curves. Numbers of publications in each journal sites have been quantified. Most researches have been conducted in Europe while some of the researches have been conducted in Asia. It is possible to observe that there is a very limited published research works in the other continents. This systematic review includes published articles from the year January 2000 up to August 2021. Failure assessment methods that have been assessed in the review work have been quantified.

After refining journals systematically, journals obtained from Emerald Database, Taylor and Francis, ProQuest, Scopus and Google Scholar has been inserted into Mendeley database.

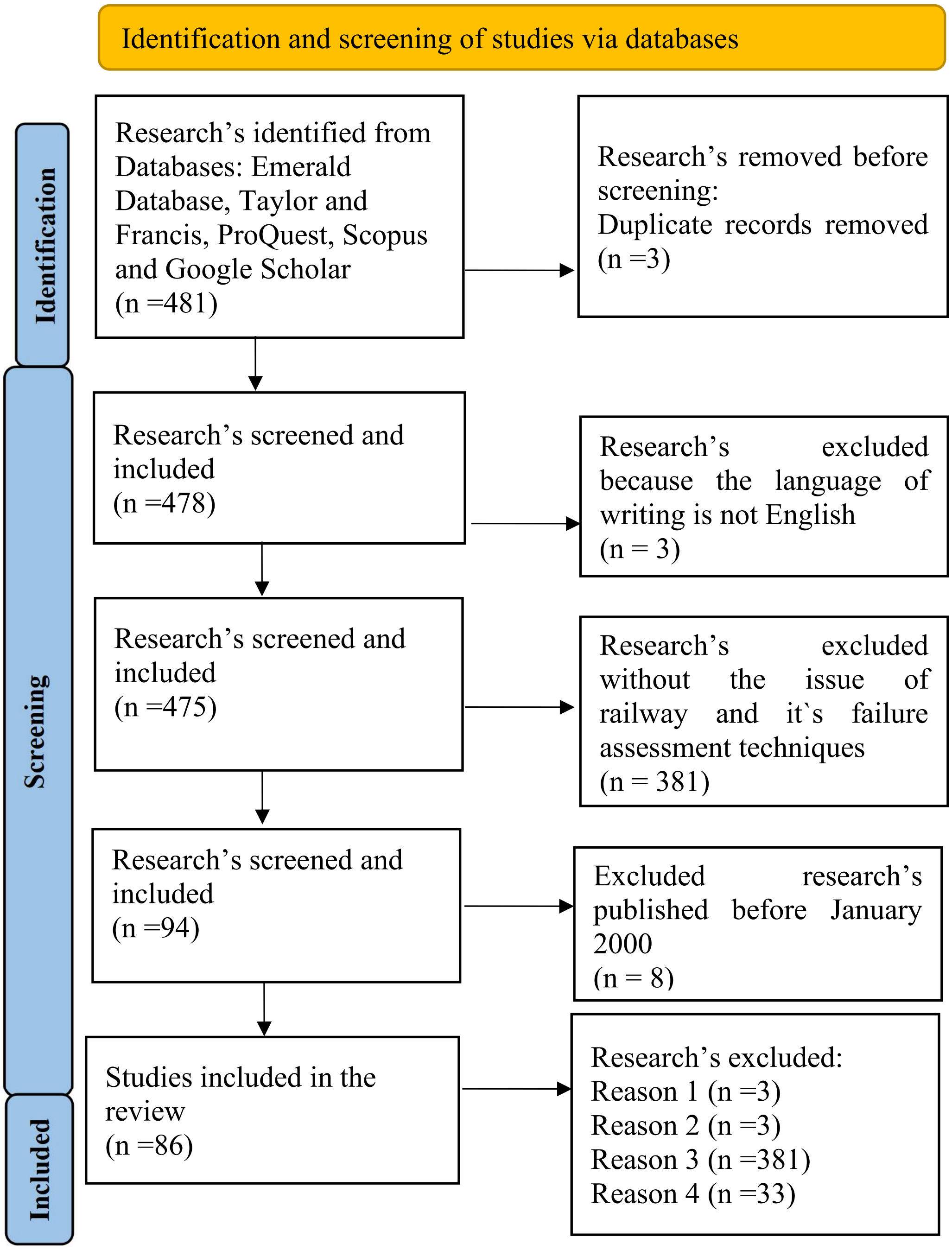


Figure 2 - 1 Identification and screening of studies from databases

Reason 1: Duplicated research`s

Reason 2: the language of writing of the research`s is not English

Reason 3: researches which are without the issue of railway

Reason 4: researches published before January 2000

The input articles for systematic literature review have been extracted by using keywords as the searching keys. Primarily 481 articles have been found by searching via keywords from Emerald, Taylor and Francis, ProQuest, Scopus and Google Scholar Databases, whereas by refining using the years of publications since January 2000, excluding if the language of writing is not English and narrowing the scope to railway sector and failure assessment methods 86 articles have been identified. At the end 86 articles have been selected for the review work.

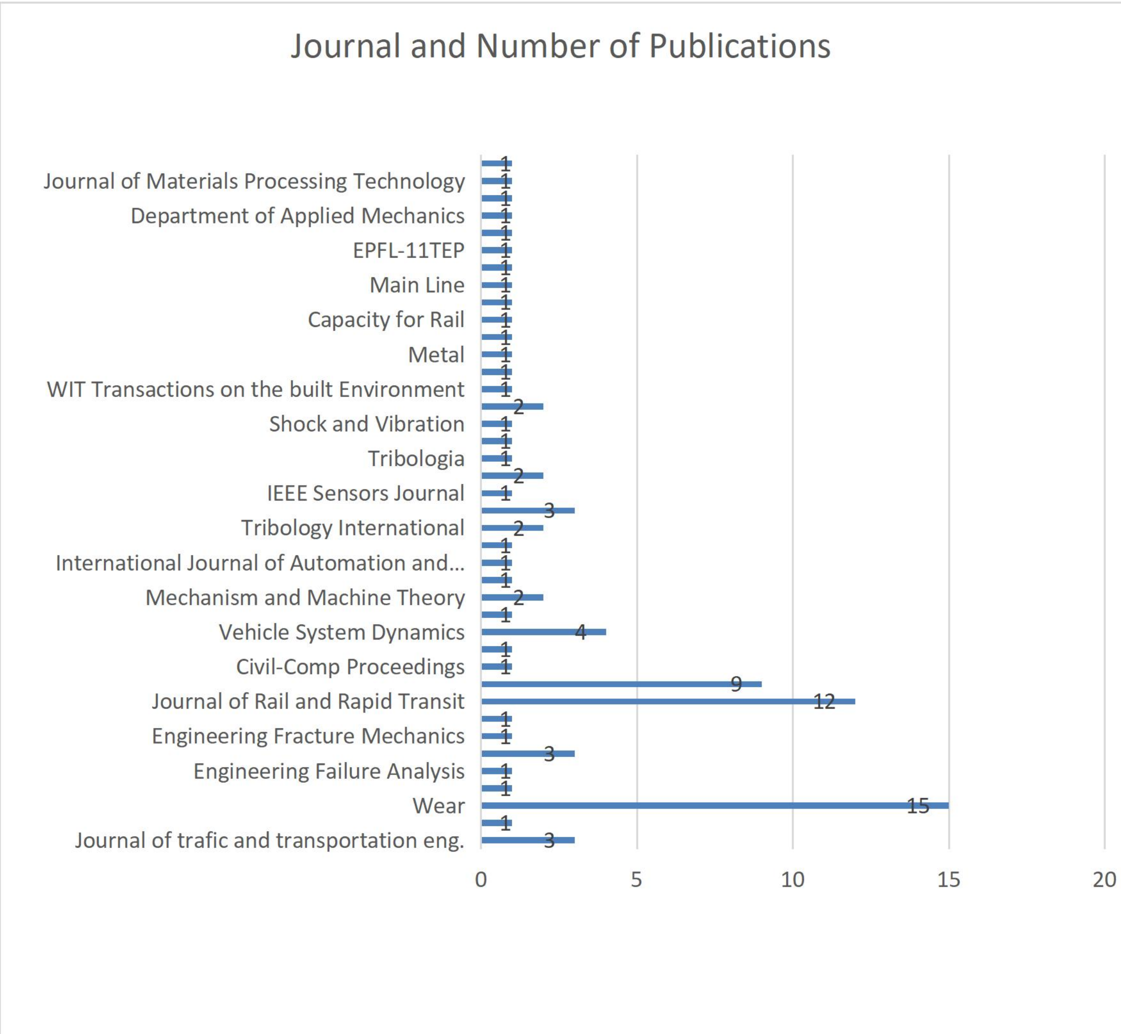


Figure 2- 2 Journals and number of publications

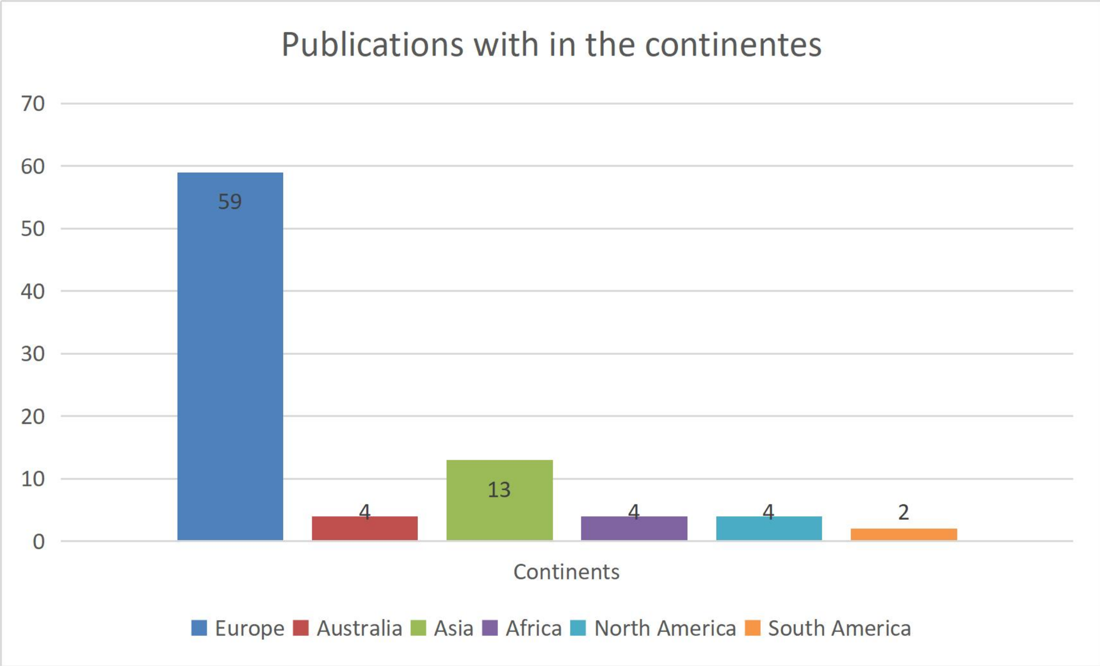


Figure 2- 3 Number of published papers with in the continents

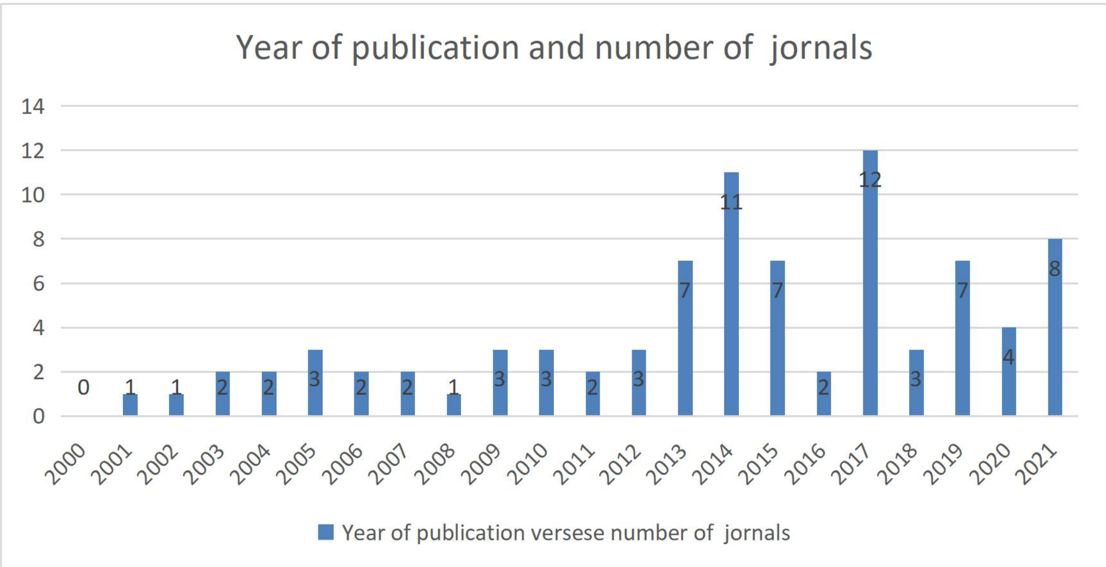


Figure 2- 4 Number of published papers since January, 2000 up to August 2021

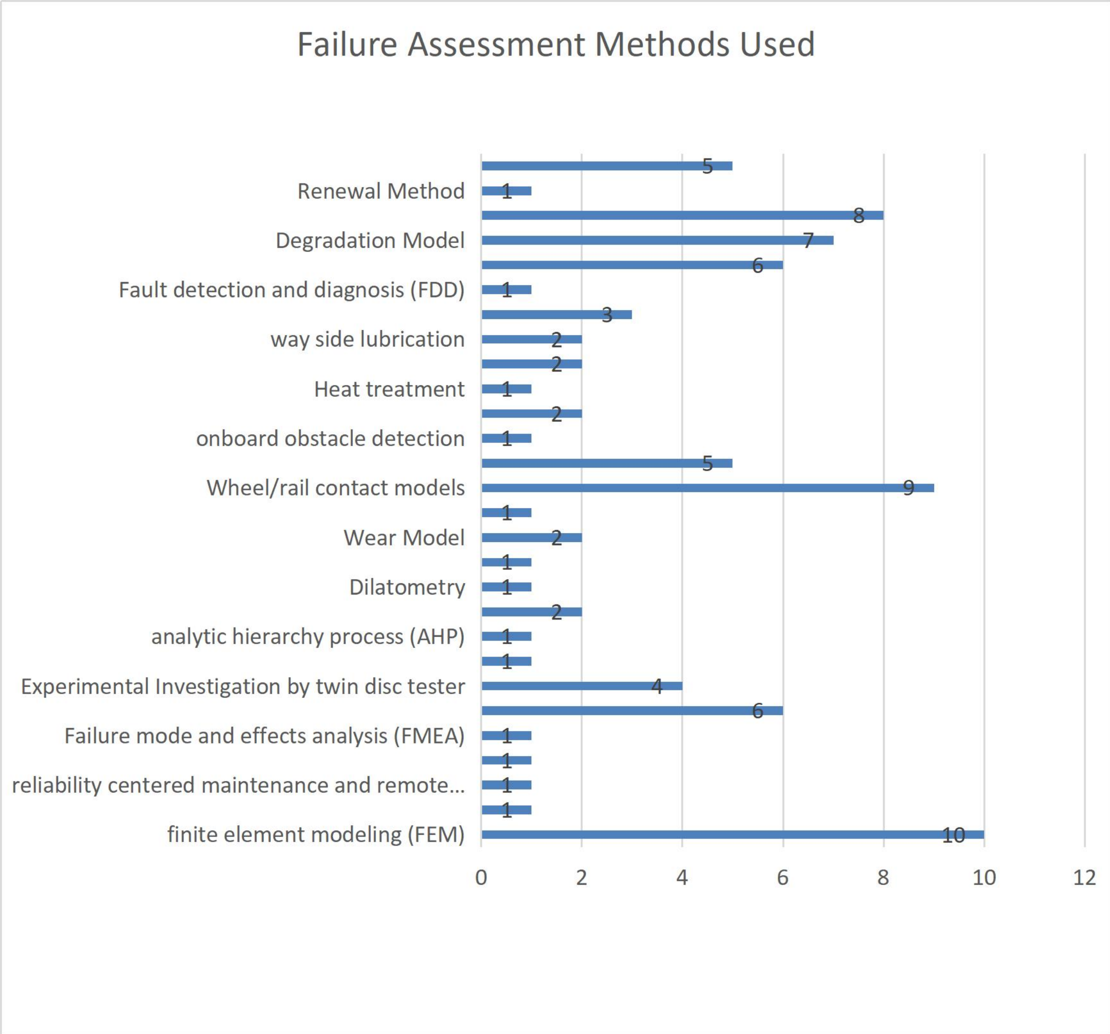


Figure 2- 5 Failure Assessment Methods Used

2.2.1 Numerical analysis and contact model approach

Qian, Y, and some researches have studied wear on turnouts and rail curves by employing Kalker method to assess wear on wheel-rail contact and identified factors for the change of wheel-rail creep curve and normal and tangential contacts. Li. H, Carkagis, have employed failure mode analysis method for railway turnouts and as a result two altered failure modes have been observed, the first one is; when the top surface of the rail head has been work hardened results in spallation of the surface of the rail head and the second one is high stress concentration commencing loading in the divergence of the turnout results increase to fatigue. E. Butini, L. Marini, have also introduced a new wear models approaches for wear assessment. [62]–[66] wheel and rail tangential and normal contact models have been used for wear assessment method both on turnouts and rail curves. S. M. Salehi, G. H. have studied the wear on rail sharp curves by focusing on the wheel-rail contact geometry.[67]–[72] life cycle cost assessment for wear prediction is also a common method of wear assessment on railway turnouts and the truck.[73], [74]

Numerical studies have been conducted by different researchers including assessment procedures, simulation works and models for the analysis of wear on turnouts, rail curves and normal trucks. Regression analysis has been utilized by Karttunen, K., Kabo, E. and Ekberg, A. by implementing a regression model. Models of contact called Non-Hertzian on wheel-rail interaction and numerical and semi-analytical models has been applied by X. Ma, P. Wang, to investigate the damages on switch section of railway turnout respectively. [75]–[81]

2.2.2 Condition based and failure mode analysis approach

"Failure mode analysis" (FMA) and "failure mode and effects analysis" (FMEA) for reliability analysis have been adapted as conventional failure analysis method by different authors for an efficient maintenance. These methods are failure analyzing techniques conducted based on types of failures including wear, RCF and any defects by studding the core effects. Likewise this methods have been applicable for railway turnouts by Li, H., in Australia and reliability assessment of the railway infrastructure has been investigated by Jidayi, Yakubu Mara in South Africa using (FMA) and (FMEA) methods respectively.[82], [83] In Spain a case study has been conducted by F. P. Garcia Márquez, aiming at wear assessment analysis by monitoring equipment's and data transmission devices of turnouts remotely.[84]

Fault detection and condition monitoring techniques have been adapted by using "reliability centered maintenance" (RCM) and "remote condition monitoring" (RCM) and both RCM2 methods by different authors including F. P. Garc and D. J. Pedregal. "Fault detection and diagnosis" (FDD) existing techniques for railway switch and crossings systems have been assessed by M. Hamadache, S. Dutta ; by affirming this methods as a base line for condition based maintenances. [17], [85]–[88] S. L. Grassie has conducted failure treatment on the field by re-profiling and removing of corrugation.[89] The "analytic hierarchy process" (AHP) method has been applied as a reliable maintenance method by A. Muluken and T. Daniel for the purpose of improvement of maintenance strategy[90]

2.2.3 Preventive maintenance approach

Visual inspection is the preeminent technique for preventive maintenance. Risk assessment has been conducted on types of lubrication application based on operation condition of rail trucks by different authors. [91] Performance of effective way side lubrication on rail curves of heavy haul truck has been analyzed by M. G. Uddin, G. [92] Efficiency of lubrication on rail curves has been assessed to evaluate its influence on the wear of the truck by H. Chen, S. Fukagai. Whereas S. R. Lewis, R. Lewis, G. Evans, have studied the performance of lubricants on rail curves by means of a twin-disc testing machine. Likewise Patric Waara has studied lubricants effect on sharp rail curves wear by implementing field and laboratory tests.[93]–[95] Wear prediction has been studied for the deterioration mechanism on wheel rail contact points by R. Enblom.[96] Failure prevention method has been applied by A. Ekberg, E. Kabo, by predicting wear, RCF and hazards on railroads beforehand happening .[97], [98]

2.2.4 Field measurements and experimental analysis approach

An experimental valuation has been conducted to assess wear and RCF on wheel tread by S. Cantini and S. Cervello.[99] experimental investigation has been also conducted on some turnout`s components for the assessment of wear and degradation by X. Liu. [100]Similarly L. Biazon has implemented twin-disc testing devise to study the wear, friction and addition on wheel-rail contact by considering the property of lubrication used, friction modifiers and conditions by detecting from the test. [94], [101], [102] field measurements have been practiced and it`s outputs have been assessed to investigate rail wear on the railway infrastructure, wayside lubrication efficiency, new material coating work on the truck, resistance of welding of the rail, and assessment of occurrence of squat and RCF on curved truck by S. M. Famurewa. [92], [103]–[106]

An extra better material has been laid on rail head surface for the purpose of increasing material hardness and wear resistance, hence an experimental test has been treated to test its strength by Ajay Kapoor. [107] Likewise an experimental work called dilatometry has been done on rail by R. R. Porcaro. [108] M. Steenbergen have investigated the rail defect called Squat experimentally. whereas the effect of cladding of the rail top surface has been studied by A. Narayanan et al using distractive and none-distractive test to determine the residual stress state.[109], [110] Dynamic modeling and full scale on hollow worn wheel have been practiced by K. Sawley and H. Wu.[111] vehicle acceptance test on the field has been accompanied on rail truck for assurance of safety against derailment by N. Wilson et al.[112] D. Ristić-Durrant, and K. Michels, have accompanied a review and field assessment on board visual obstacle detection technique by using sensors of artificial intelligence .[113] A. Dagne has conducted a heat treatment and wear test on wheel and rail material test rigs for the purpose of minimization of wear in Ethiopia.[114]

2.2.5 Finite element modeling approach

Outer rail of curved trucks is exposed to rail gauge corner fatigue crack because high stress has been generated. Finite element modeling approach has been applied to investigate this fatigue by S. A. Ranjha. [115] Similarly S. Mojumder, has investigated the impact of reverse longitudinal bending stress on the establishment of reverse transversal defects using FEM with the help of ABACUS.[116] Because of lateral forces under rail head radius there is stress that causes wear and crack, this stress has been assessed by “stress intensity factors” (SIFs) of laterally transverse crack using a method called “extended finite element method” (X-FEM).[117] Likewise, Dynamic modeling software SYMPACK has been adapted by Seid A, to investigate effects of curved rail radius on the formation of wear.[58] In the same manner M. Hiensch and P. Wiersma have implemented a finite element modeling software VAMPIRE that has been applied to study truck friendliness of trains in order to reduce degradation of switch rails.[118] Y. Li, and L. Chen, have correspondingly studied fatigue crack initiation on rails using FEM considering residual stresses effect as a cause on rail crack in China.[119]

2.2.6 Review summary of failure analysis and assessment methods

Table 2- 1 Review summary of failure analysis on switch rails and crossings.

Authors (Ref.)	Assessment system	Objective of the research	Measurement in use	Employed methods	Research gap
[29]	Case study	Track stress stiffness analysis	Dynamic vertical and lateral load	FEM	Imperfection of railway turnouts
[30]	Real time	Explosive hardening of railway crossings	3D Scanner	Experimental investigation	Not yet working under conditions having higher running loads and higher traffic
[31]	Case study	Material improvement	-	Case study of railway accidents	Maintenance frequency
[32]	Real time	Material improvement	Sample preparation	Experimental investigation	Heat treatment of rails might cause excessive surface decarburization
[33]	Real time	Comparing different rail steels from mechanical durability perspective	Field samples & test rig samples	Experimental investigation	Degradation of railway rails can`t be minimized only by choosing better materials
[34]	Real time	Prediction of wear from test rig & FEM results	Laboratory measurements from test rigs	Experimental investigation & FEM	Dependence between the selected wear step length & the obtained profiles

					simulation results of rail
[35]	Real time	Investigation of wear & fatigue of railway rails	Optical & scanning electronic microscopy	Experimental investigation	Only two rail materials are compared
[36]	Real time	Improving wear testing methods of wheel & rail materials	Laboratory tests	Experimental investigation on twin-disc machine	No full-scale specimen tests have been conducted in the laboratory
[38]	Real time	Predicting friction in wheel-rail contacts	Field measurements & fixed sliding sensors	Laboratory experiment & friction model	The spin effect in wheel-rail contact was not considered
[39]	Real time	Development of wheel-rail contact model for degraded adhesion analysis	__	Experimental investigation & adhesion model	Deeper investigation needed for the effect of adhesion recovery on railway vehicle dynamics & effect of wear on the surface of wheel & rail.
[40]	Real	Predicting profile wear	Wear model	FEM	Further validation of the wear model

	time	of wheel & rail			and experimental investigation is needed
[41]	Real time	To investigate modeling tools for switch & crossing`s wheel-rail interaction & degradation	wheel-rail contact point detection	Experimental investigation & FEM	The wheel-rail interaction models need further investigations
[42]	Case study	Improvement of the maintenance & renewal plans of the Swiss railway network	Data base	Statistical Analysis	Studies are limited to small improvements of existing designs
[43]	Real time	Simulation of dynamic system	Crossing`s geometries	FEM, simulation of dynamic Wheel–Rail interaction	__
[45]	Real time	To minimize the Sevier damages on wheel-rail contact	Devices called "MiniProf"	FEM	Rail profile evolution at different position along the longitudinal direction for different total

					tonnages needs simulation
[47]	Real time	Investigating the influence of turnouts on wheel wear of a fright vehicle	Wheel-rail contact measurement	Archard`s wear model	Two different stiffness between the rail & sleeper. Other types of vehicles & turnouts wasn`t considered
[48]	Real time	Analyzing the stress state arising from the impact load & the mitigation method	Wheel-rail contact measurement	FEM	FEM need further improvement for better accurate simulation of the certainty
[49]	Real time	standardizing a mathematical model of different phenomena of wear	Tangential traction & sliding distance	FEM	Further wear & fatigue analysis needed
[51]	Real time	Studying wheel-rail dynamic interaction comes from rail corrugation	Rail corrugation	FEM	Further work is needed on critical wavelength of corrugation

		excitation			
[52]	Real time	Optimization of the geometry of the turnout	Turnout elements	FEM	An extension work needed on turnouts branch line
[55]	Real time	Maintenance & renewal plan for railway switches & crossings	Track geometry	Statistical analysis	Melty-parametric model is model is needed for further investigation
[56]	Real time	Operation & design of switch rail track	Mechanical design of railway switches & sample preparation in laboratory	Experimental investigation	Further modeling of "Repoint-installation" for the purpose of improving traffic capacity
[57]	Real time	Investigating stiffness characteristic s of railway high speed turnouts	Stiffness measurement	FEM	Experimental stiffness investigation is needed
[58]	Real time	To study the effect of "Curved rail radius on the railway	Wheel-rail interaction curved track	Analytical multibody modeling	Aero-dynamic effect should be considered for every rolling stock running on curved

		wear”			track. Acceleration & braking effect on rail wear should be considered on dry & lubricated conditions.
[60]	Real time	Investigated the effect of track parameters on the wear of turnout rails	__	FEM, Simpack, Semi-Hertzian & FASTSIM	Further experimental investigation is needed
[61]	Real time	Optimization of railway turnouts aiming that cost minimization	Wheel-rail contact forces	optimization of railway design of turnouts based on simulation	There was a limitation on the presented crossing`s transition zone. The optimization methods are essentially focused on results and methods.

2.3 Research gaps identified on failure assessment methods

- The twin-disc testing results of rail grease lubricator indicates that there is a need for further experimental investigation using different kinds of lubrication for the prediction of wear and RCF precisely.
- There is shortage of published researches about deterioration mechanisms on wheel-rail contact to predict wear.
- The relationship between fatigue crack initiation lifespan and the residual stresses of rails has not been clearly identified in complicated working conditions, meanwhile further investigation is required.
- In the prediction of limits of safest head wear, it will be better if several sets of analysis have been considered like, loading conditions, crack size, orientations of the truck and separation of the crack, in order to realize the sensitivity of these parameters in deep.
- For experimental wear investigation using twin-disc test machine, it is better if some improvements would have been arranged on the chemical properties of test rollers, testing condition and the machine itself.
- Improved reliability can be achieved in condition monitoring systems, if the results of the technique have been transferred efficiently, if not little change can be achieved.
- Using analytic hierarchy process (AHP) method as a reliability maintenance method is better than condition monitoring systems and fault detection technics, so that combining of those methods with AHP will be more efficient.
- When the train is giving the normal operation, it will be better if the maintenance system integrates the cost of maintenance labor and spare part to the decision-making process.

2.4 Rectification of failures on welding of rails

Welding of rails can be done because of many reasons like joining one rail section to the other for continuity purpose and for inspection purpose hence, this welding work should be performed skillfully and carefully. “Cooling rate”, type of welding, “welding parameters” and material properties of the “base material” are the major aspects that can affect the quality of the weld and the microstructure and mechanical properties of the rail. [120]–[122]

Heshmat Aglan and Tanzilur Rahman have conducted a research on the assessment of mechanical properties and microstructure of pearlitic rail steels on the critical zone called “heat affected zone” (HAZ) after a process of “gas metal arc weld” (GMAW) by focusing on the “cooling rate” and the preheating temperature finally they have recommended that preheating the HAZ with 300°C and cooling at the rate 2 °C/s as an optimum cooling rate.[123] A better heat treatment techniques for high strength in the rail production system have been developed by different authors by implementing outstanding “flame-heating” techniques and incessant “slack – quenching” method.[124] D. Bajic, and I. Samardzic have introduced a new manner of arc welding for several rail profiles, defined as the “Consumable Guide Enclosed Arc Welding” (CGEAW). [125] Welding technology in rail needs a wide and deep research works.

MAG welding applied on Steel joints of “S700MC” rail grade have been studied concerning fatigue life and microstructural behavior based on the cooling rate of the weld.[126] end-quench experiments have been practiced for the welded pearlite rail with a hardness 38 RC by an appropriate cooling rate.[127] Tensile residual stress is the well-known outcome on welding, if it is not treated early it can result failure. Ghazanfari, M and Hosseini Tehrani, P have investigated the effect of tensile residual stress on the UIC60 rail with flash butt welding and also put the optimization techniques in their study. [128] R. Guan, and H. Li, have investigated the formation ways of abnormal “martensite” in the welding process of “bainitic rail” by relating numerical model and an experiment. This study has assessed the cooling rate and its effect on the microstructural phase.[129] Applying heat input and pre heating the rail material at different heating temperature and variation of cooling rate of welding’s are the modern technology in railway with a detailed study for the better microstructural and mechanical properties of the “coarse grained heat affected zone” on welding’s of perlite rails.[130]–[132] A local heat treatment method of welding`s called “contact heating” has been introduce by different authors to control cooling of the welded joints.[133] the reliability and quality of a continuous rail track welding`s has been assessed by studying the modern methods suggested by different researchers by considering their relevance for the technology.[134] The effect of “cooling rate” and chemical composition on the flash but weld weldability of the 74SiMnV and U71Mn rail steels has been studied by using “Gleeble” simulation technique.[135]

Microstructural features and material hardness of U75V and UIC900A rail steels after welding has been studied by increasing the cooling rate from 0.5°C·s-1 to 1.0-2.0°C·s-1, as a result a better hardness and better microstructural features have been achieved.[136] A "pre-heating condition" has been applied on the railhead to slow the cooling rate of the weld on the head to prevent cracking, as a result an improved quality of the weld has been achieved.[137]

Phase transformation and an increase in hardness have been detected from "289 to 864 - 896 HV" while a cooling rate has been increased from 0.1 °C/s to 100°C/s and 30 °C/s respectively on the welding of R350LHT rail steel. The application of "contact heating" method in an optimum range after welding has a great benefit to minimize the length of "heat affected zones" and decreasing the occurrence of quenching structures. [138], [139] R. R. Porcaro, F and L. da Silva have studied the process and the result of flash but welding on a railway rails by numerical and experimental investigations. An assessment and evaluation on the residual stresses developed in the welding has been conducted and a comparison between the numerical analysis and the experimental investigation has been done. Formation of austenitic grain structure and variation of the hardness on the heat affected zone was also found as a result of variation on the cooling rate of the weld. [140]–[143] based on Y. Su, W. Li, and X. Dou study welding joints have been categorized in to the "weld center zone" (WCZ) (martensite), the "thermo-mechanically affected zone" (TMAZ) (pearlite with a minor volume of martensite), the "heat affected zone" (HAZ) and "the base material" (BM) (pearlite with upper bainite). In this study "linear friction welding" (LFW) have been applied on high carbon rail steel called "U71Mn" (Chinese std.) with their microstructural features. In the martensite phase of the weld zone there is an increase in micro-hardness though decrease in the toughness.[144]

K. Sugino, H. Kageyama, and C. Urashima, have assessed the metallurgical features of in-line deeper "head hardened rails" by a heat treatment.[145] Welding of a rail steel needs a detailed study in order to select and apply the best welding method from a metallurgical perspective, the selection process has been studied by by N.S. Ãˆai and T.W. Eagar.[146] Since continuous welded rails have experienced a flash butt welding for joining purposes, a detail examination and investigation is needed to get ride-off the residual stress and improve the welding quality.[147] It have been investigated that the aluminothermic welding's of rails by caring-out fatigue test at different preheating measures.[148] "Temperature distribution" and "thermal cycle effect" on the structure of the welded rail steel have been calculated by giving emphasis on the "cooling rate" of the weld.[149] Bainite steel which is intended for railway frog welding properties have been investigated experimentally and numerically on previous researches.[150] Underneath different "cooling rate" of the weld and the "heat affected zone" performance has been studied for a continuous flash but weld on rail head defects. [151]

2.4.1 Research gaps identified on rectification of failures on welding of rails

- Most of published papers regarding welding technology emphasizes on the preheating temperature and the cooling rate welding parameters regardless of focusing on the destructive and nondestructive nature of the weld.
- The effect of post-heating as the controlling mechanism of cooling rate and it`s effect on the quality improvement of the weld were not considered.
- The relation of chemical composition of the rail materials of various rail welding`s at different cooling rate was not mentioned and their contribution to material hardness was not clearly addresses.
- In addition to numerical validation of rail welding`s, field data validation also was required.

3 CHAPTER THREE: METHODOLOGY AND RESEARCH DESIGN

3.1 Introduction

The general structure of the methodology can be classified in to two as mathematical modeling and experimental investigation. The mathematical models consider a root cause analysis, sensitivity analysis and statistical analysis with the intention of failure assessment and analysis. The experimental investigation considers welding of specimens, none-destructive tests and micro-structural tests.

The first method in this research work was collecting data of Addis Ababa light rail transit (AALRTS) from the field measurements. Maintenance records were the major data source for the data analysis work next to field measurements. The maintenance center of Addis Ababa light rail transit service was the place where the relevant data for this research work was collected. The failure modes and failure effects analysis should be conducted after recording the data. In this research work a method for corrective maintenance improvement of switch rail`s has been introduced, the method to improve the welding quality and strength by controlling the cooling rate has been introduced.

3.2 Data collection procedure

Quantitative and qualitative data have been collected and analyzed as required based on their availability. The data have been collected from maintenance center of AALRTS from field measurements and recorded data. The second data source was from previously studied research works.

3.2.1 Primary data

The primary data sources were interview of engineers, experts and maintenance workers of AALRTS maintenance center and personally collected data from the field.

3.2.2 The Secondary data

The Secondary data source to this research was literature review of different journals, books and published research works.

3.3 Data analysis methods

The investigation method for failure assessment and analysis of switch rails and crossings towards maintenance improvement has considered the complexity and dynamics associated with the problem that has been dealt in this research, FMECA is considered to be an appropriate method for modeling the failures found on Addis Ababa Light Rail Transit System and an experimental investigation has been practice for the purpose of rectification improvement.

- Root cause analysis conducted by implementing fish bone and sensitivity analysis.
- Modeling: - Statistical analysis method called "Markov chain" model implemented to find out the critical failures and the measuring element for maintenance efficiency.
- the failure analysis model called the failure mode effects and criticality analysis (FMECA) has been implemented for the purpose of failure investigation and analysis in AALRT crossings.
- Experimental investigations have been implemented to justify and improve the welding quality of the switch rail.
- Parameterization: - the experimental analysis has the required parameters.

3.4 Rail Material and parameters of AALRT

Switch rails of turnouts on East-West (EW) and North-South (N-S) Line of Addis Ababa Light Rail Transit service (AALRTS) has been selected in consideration for the failure mode analysis. The wheel and rail contacting materials are R7 and R260 respectively. The traffic condition is for light rail transit in both facing and trailing move with a maximum designed speed of 70 km/h, and with nominal (non- worn) S1002 wheel profile. The rail profile is 60E1 9UIC-60) with 1:30 rail inclination and the front section of the switch rail is 76° chamfered. The curve radius is 180 m and turnout angle $8^{0}7'48''$.

- Speed limitation of 20-30 km/hr.;
- Modeling concerning AALRT Train;
- Rail of 50 Kg/m U71Mn (Tensile strength=880Mpa from Chinese standard);
- Frog is Hadfield steel integrated cast frog.

- TYPE-II pre-stressed concrete sleeper spaced at 0.6mStandard gauge, 1435mm;
- Under the assumption of equivalent traffic proportions in both routes;
- Turnout type is #7 which is used for permissible passing speeds between 30Km/h and 20 Km/h speed limits in the AALRT turnout system;
- Right branching Turnout

Table 3- 1 Mechanical properties of AALRTS rail material (50 Kg/m U71Mn)

Material Property	**Value**
Poison Ratio	0.3
Ultimate tensile strength δ_{ut} for (wheel and rail)	880Mpa
Tensile Yield strength δ_y for(wheel and rail)	640Mpa
Young modulus	207Gpa
Density	7800KG/m3
Elongation % (min)	9
Surface Hardness	260

Table 3- 2 Chemical composition of AALRTS rail material (50 Kg/m U71Mn)

Chemical element	C	Si	Cr	Mn	P	S	Mo	V	Fe	Ni	Co	Cu	Al
Composition (Wight %)	0.65	0.36	0.035	1.12	0.098	0.080	0.016	0.010	97.3	<0.008	0.016	0.053	0.008

Table 3- 3 Turnout number 7 geometric parameters from Chinese railway standard

Frog angle (deg.)	Lead curve central radius (m)	Distance between beginning and center of turnout (m)	Distance from center of turnout to heel of frog (m)	Total turnout length (m)	permissible speed (Km/h)
$8^0$7'48"	180	13	14	28	30

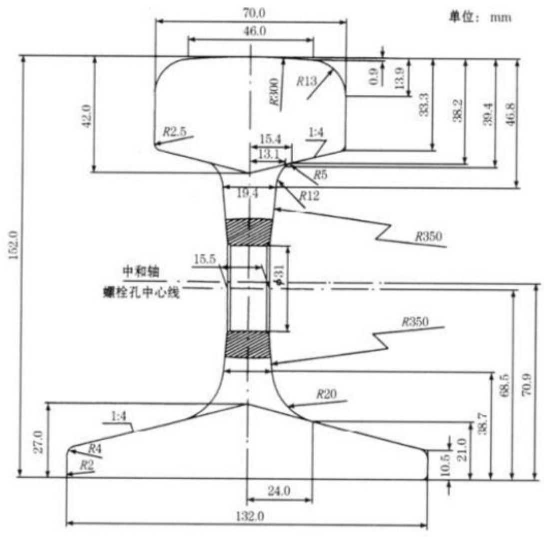


Figure 3- 1 50Kg/m rail cross-sectional geometry [mm, one digit precision]

(Source: B17)

Table 3- 4 Vehicle geometrical data of AALRT system from CREC

Length of car body:	≤30000 mm
Height of vehicle roof from top of rail (excluding pantograph):	≤3700 mm
Maximum width of car body:	2650 mm
Height of vehicle floor from top of rail (low floor area, new wheels and empty load)	≤380 mm
Height of vehicle floor from top of rail (exit and entry areas, new wheels and empty load)	≤350 mm
Height of vehicle floor from top of rail (raised floor area, new wheels and empty load)	≤900 mm
Wheelbase (powered bogie)	1900 mm
Wheelbase (unpowered bogie)	1800 mm
Clear height of passenger compartment	≥1980 mm
Wheel diameter (new wheel)	≤660 mm
Wheel diameter (Max. wear)	≤600 mm
Side doors of passenger compartment	four pairs per side
Clear opening of passenger compartment door (width x height):	≥1300×1860 mm

Table 3- 5 Vehicle weight data of AALRT from CREC

Loads	Car body weight	Passenger weight	Total weight
Empty vehicle (ton)	44	0	44
Rated passenger capacity (ton)	44	15.24	59.24
Overload (ton)	44	19.02	63.02
Axel Load	<11 (1+3%)ton		
Axel Number	6		

3.5 *Data of failed components in AALRT*

Failed components scattered through switches and crossings discussed on table 3- 6 by classifying based on the component`s type.

Table 3- 6 Statistics of failed components on crossings of AALRT in 2021

Failed components	**Total Quantity**	**Frequency (%)**
Switch rail	1198	40.1
Stock rail	906	30.3
Crossing	280	9.4
bolt	131	4.4
Rubber	126	4.2
Fastener	121	4.0
Turnout slide plate	119	4.0
Gauge block	38	1.3
ballast	24	0.8
Sleeper	21	0.7
Hydraulic buffer	15	0.5
Switch machine	10	0.3
Sum	**2989**	**100**

3.5.1 Data of Prospective Failure Modes in AALRT

Table 3- 7 Statistics of failure modes on crossings of AALRT in 2021

Failure Modes	**Total Quantity**	**Frequency (%)**
Track gauge deviation	820	27.4
Track alignment deviation	686	23.0
Needs Adjustment	472	15.8
Missed or loosed parts(bolts)	422	14.1
Broken(Cracked)	218	7.3
Track line Contaminated by waste materials	123	4.1
Miss location of components	110	3.7
Water on the top layer of the bridge (poor sewerage)	90	3.0
Soil Mixed with ballast	20	0.7
Wear	15	0.5
RCF	10	0.3
No oil in the hydraulic bumper	3	0.1
Sum	**2989**	**100**

Table 3- 8 Occurrence of damages specifically on the switch panel of AALRT from 2018 to 2022

Type of Damages	**Total Quantity**	**Frequency (%)**
Gauge corner Spalling	580	33.9
Gauge corner wear	542	17.2
Rail head wear	431	15.9
Railhead corrugation	226	15.3
Squat	178	9.4
Pit	145	5.4
Corrosion	74	2.9
Sum	**826**	**100**

3.5.2 Rectification activities regarding failures on crossings of AALRT

Table 3- 9 Rectification activities on crossings of AALRT in 2021

MAIN ACTIVITY	FREQUENCY OF THE ACTIVITY	DESCRIPTION	UNIT OF PERFORMANCE	ANNUAL ACCOMPLISHED
Lubricating	Daily maintenance activity	Radius of curve	Km	472
	Daily maintenance activity	Switch slide plate, radius of curve switch rail, guard rail, Lead curve of turnout , frog and others	pcs	8256 switches
Adjusting switches	Daily maintenance activity	rail gauge, level, profile, offset	pcs	1032 switches
Tightening loose track component	Daily maintenance activity	fasteners, joints and other	Km	67.504
Surfacing	Daily maintenance activity	level and profile	Km	250
Lining	Daily maintenance activity	gauge, horizontal alignment	Km	250
Sleepers and rail replacement	Daily maintenance activity	damage sleepers and rail	pcs	4

Clear remove weeds growing	Daily maintenance activity	main line and depots	percent	all line per day
Rail flow detection	One year 3 times in all track line		Km	67.504

Table 3- 10 Rectification actions allocated to failed components with their frequencies on crossings of AALRT in 2021

Rectification	**Total Quantity**	**Frequency (%)**	**Failed Components**
Lubricated	1032	34.5	Stock rail, Switch rail, crossing, switch components
Gauge Adjusted	567	19.0	Stock rail, Switch rail
Alignment Adjusted	390	13.0	Stock rail, Switch rail
Obstacle Removing	360	12.0	Switch rail, Crossing, stock rail, sleeper, switch components
Renewed/Replaced	300	10.0	Stretcher bar, fastener, Crossing (frog & guard rail), Turnout slide plate, Switch rail, Stock rail, Sleeper, gage block, rubber, Ballast, switch components
Tightened	185	6.2	Bolts, nuts fasteners
Cleaned	130	4.3	Stock rail, Switch rail, turnouts, switch components
Grind	15	0.5	Switch rail, Stock rail, Frog, Fish plate, guard rail
Repaired by welding	10	0.3	Switch rail, stock rail, frog, guard rail
Sum	**2989**	**100**	

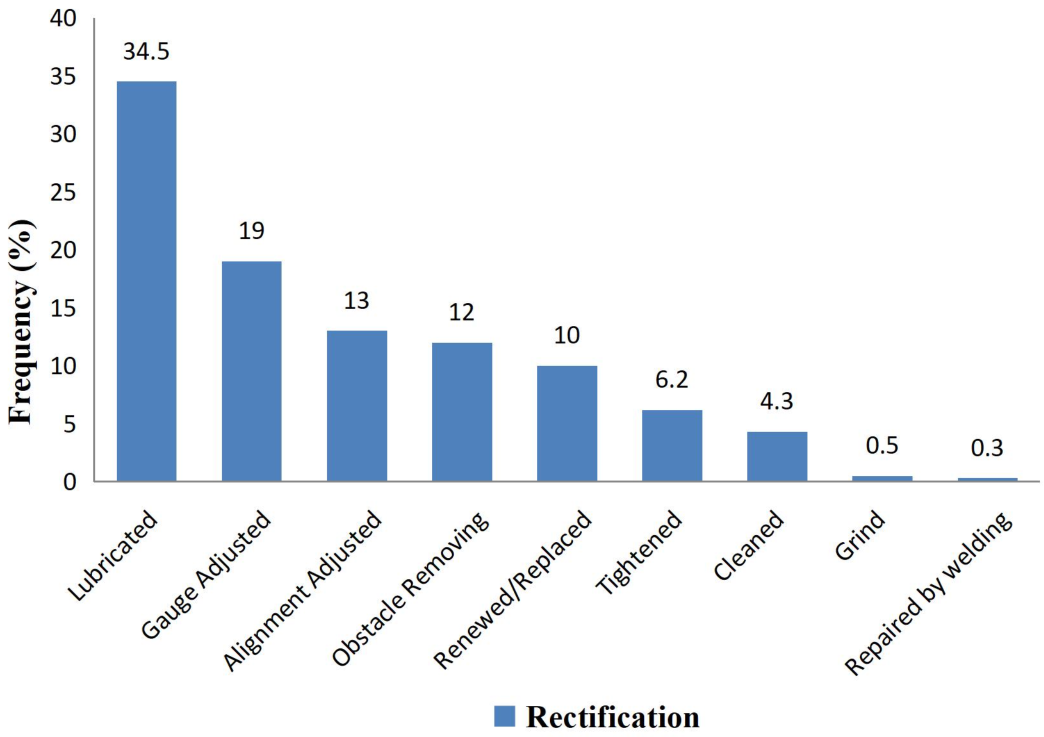


Figure 3- 2 Total rectifications that have been conducted in 2021

3.6 Root cause Analysis

Before analyzing the failures on rail turnouts root cause analysis is necessary to examine and find out the real causes; that helps in order to suggest the required maintenance work. Fish-bone diagram was implemented for the intent of identifying a cause-effect relationship between different possible parameters for the damage of the railway turnouts .

Once the possible root cause parameters are found through fish-bone diagram, the researcher will proceed through failure mode effects and criticality analysis method (FMECA) which helps to select the critical failure modes.

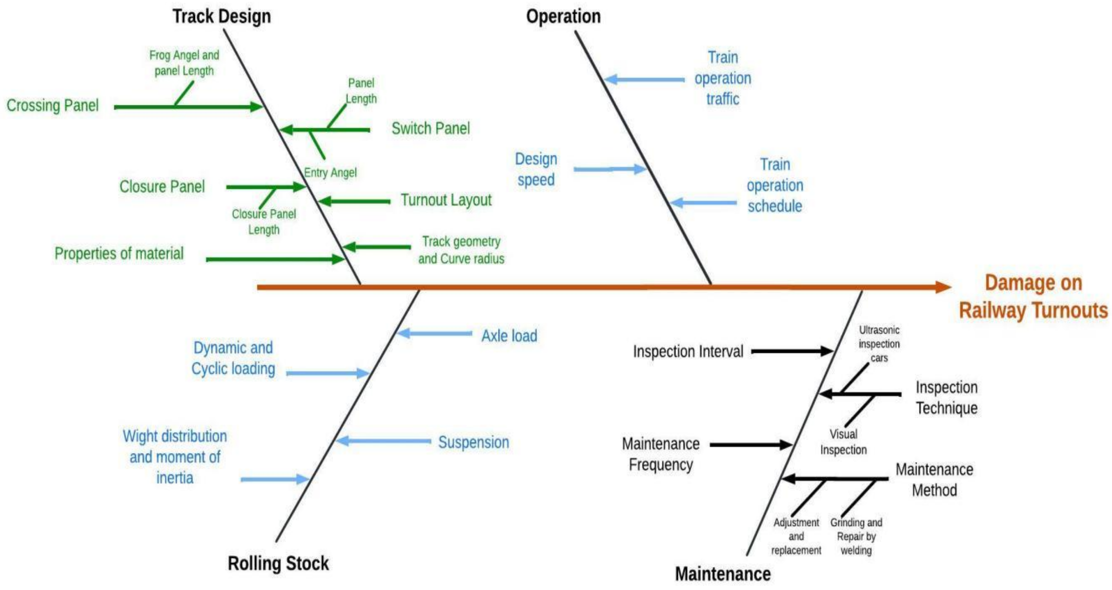


Figure 3- 3 Fish-bone diagram for damage on railway turnouts

3.7 Failure Mode, Effects and Criticality Analysis (FMECA)

3.7.1 Failures Mechanisms on turnouts

3.7.1.1 Failures caused by wheel rail interaction

It includes rolling contact fatigue (RCF), wear, plastic deformation, squat, head checks and rail corrugations.

3.7.1.2 Failures caused by external factors

This kind of failures include failures that are caused by sleeper, ballast and sub-grade materials failure and any external factors including rain, contaminating materials. It can be also caused when stretch bars, fish plats, bolts, base plats, fastening and any auxiliary accessories are cracked and broken. [86]

To investigate the failures on turnouts different failure modes and failed components data have been gathered and recorded from Addis Ababa Light Rail Transit (AALRT) on the year 2021.

Failure Modes, Effects and Criticality Analysis (FMECA) technique has been implemented in this research work for the purpose of analyzing the failure modes found in this particular railway system and the criticality of the failures will be analyzed later. Far ahead determination of different status of failure modes we can use a method of a Risk Priority Number (RPN) which makes known the overall risk of a specific failure mode happening in a particular railway system.

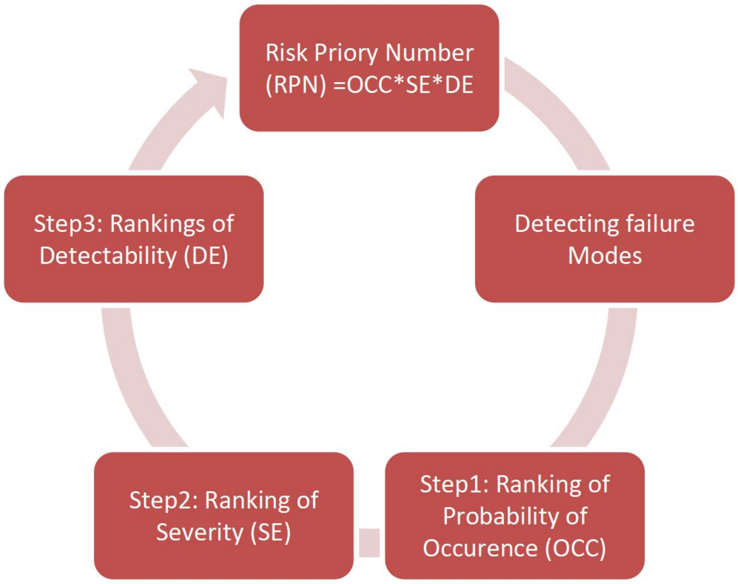


Figure 3- 4 Failure Modes, Effects and Criticality Analysis Cycle (FMECA)

The procedure of FEMCA will be discussed below.

- Occurrence of failure

Table 3- 11 Rating of the Likelihood of occurrence with its representation

Rating	**Rating No.**	**Likelihood of Occurrence**	**Range (%)**
Very high (VH)	5	Failure is almost unavoidable	FFD > 20
High (H)	4	Frequent failures	10 < FFD < 20
Moderate (M)	3	Infrequent failures	5 < FFD < 10
Low (L)	2	Comparatively few failures	0 < FFD < 5
Remote (R)	1	Failures are unlikely	FFD = 0

In this approach a failure mode occurrence ranking (O), Also “Failures Frequency Distribution” (FFD) is considered in variant of range.

- Severity of failure

Severity of a failure mode can indicate the sensitivity or the criticality of the failure. A detail of the severity of each failure and their rankings will be shown in the Table below.

Table 3- 12 Rating of the severity of failures with its representation

Rating	**Rating No.**	**Severity of effect**
Hazardous without warning (HWOW)	10	Very high severity ranking without warning
Hazardous with warning (HWW)	9	Very high severity ranking with warning
Very high (VH)	8	System inoperable with destructive failure
High (H)	7	System inoperable with equipment damage
Moderate (M)	6	System inoperable with minor damage
Low (L)	5	System inoperable without damage
Very low (VL)	4	System operable with significant degradation of performance
Minor (MR)	3	System operable with some degradation of performance
Very minor (VMR)	2	System operable with minimal interference
None (N)	1	No effect

- Failure detection

  Failure detection is an allocated value that point out how often that specific failure mode can be observed. In this step each failure receives a detection number (D). The allocated detection number helps to measure the potential risks that the failure will escape to be detected. High detection rank refers to the most likely not to be detected.

Table 3- 13 Rating of the detection of failures with its representation

Rating	Rating No.	Likelihood of detection
Absolute uncertainty (AU)	10	No chance
Very remote (VR)	9	Very remote chance
Remote (R)	8	Remote chance
Very low (VL)	7	Very low chance
Low (L)	6	Low chance
Moderate (M)	5	Moderate chance
Moderately high (MH)	4	Moderately high chance
High (H)	3	High chance
Very high (VH)	2	Very high chance
Almost certain (AC)	1	Almost certainty

Risk Priority Number (RPN)

The RPN illustrates the occurrence of the whole risk of a specific failure mode in our railway system. After ranking the severity, occurrence, and detectability of each failure the RPN will be calculated as:-

RPN = Likelihood of Occurrence × Likelihood of Detection × Severity (1)

The failure mode results have been breakdown by categorizing based on risk. If the RPN value is the highest it indicates that, that failure mode needs attention regarding maintenance work.

3.8 Statistical analysis and modeling of failures on switch rails using Markov chain model

The growth of critical failures and degradation have been modeled by a statistical model called "Markov chain model". In the model for degraded failures four different states have been included and for critical failures two different states have been included. Additionally there is a state called "OK", altogether the Markov chain has seven states in total. After inspection the critical failures can be categorized into two;

the failures caused by degradation (F1) and sudden failures (F2). During inspection the degraded critical failures will be eliminated by repair works.

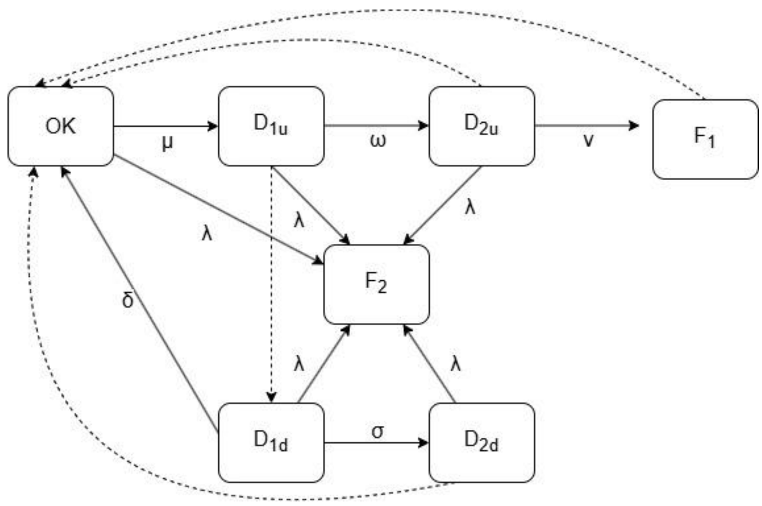


Figure 3- 5The Markov chain failure model [152]

One of the model's intriguing features is that, while there are discrete time transitions during inspections, there are continuous-time Markov transitions between the various states in the intervals between inspections.

The rail is divided into short segments such that each segment only resides in one of the following states: OK, D_1, D_2, F_1, or F_2. The rates mentioned above apply to these short segments, each measuring one metre. However, we divide the degradation states based on whether or not these are detected in order to simulate the maintenance for degradation failures as well.

When a subscript u appears on the degraded states, it means that the ultrasonic inspection car (UIC) has not recognized the deteriorated failure. Similarly, a detected degraded failure is indicated by a subscript d consequently.

D_{1u} = Undiscovered small-scale deteriorated failure .

D_{1d} = When a UIC detects a minor degradation, it intensifies (frequencies) the observations to prevent a major failure brought on by degradation.

D_{2u} = Significant deteriorated failure which is undetected; (condition considered to be OK).

D_{2d} = Unidentified significant deteriorated failure when the section of line was previously found to be in state D1, at which point it was under close observation; nevertheless, it is unknown if state D2 has been attained. The rail component is fixed right away and functions normally as soon as the state D2 is identified.

probability that inspection will identify degraded failures:-

q_1 = The probability of detecting state D_1 in a line section.

q_2 = The inspection's probability of finding a degraded failure, D_2, without being aware that the stage D_1 had been reached beforehand.

q_3 = The likelihood that the inspection will find a deteriorated failure, D_2, even though it is already known that the stage D_1 was discovered.

Let us now contemplate the possible state transitions that can arise from the examination, which could happen at instances T, 2T,... Now that the variables Xn and Yn have been introduced, we can fit the model to the inspection/failure data. For just a small portion of rail, Xn provides the true state just prior to inspection, and Yn provides the genuine state right following inspection.

$$Xn = Zn(T),\ n = 1, 2, \ldots\ldots \tag{2}$$

$$Yn = Zn+1(0),\ n = 1, 2, \ldots\ldots \tag{3}$$

The transition matrix R can be used to introduce the changes during inspections from Xn to Yn. That is Xn= R · P(T) and Yn= P(T) . R

the asymptotic statistical distribution of Xn and Yn :-

$$\Pi k = P(Xn = k);\ k = 1, \ldots, 7, \tag{4}$$

$$¥k = P(Yn = k);\ k = 1, \ldots, 7, \tag{5}$$

the related line vectors are:-

$$\Pi = (\Pi 1, \Pi 2, \ldots\ldots, \Pi 7) \tag{6}$$

$$¥ = (¥1, ¥2, \ldots\ldots, ¥7) \tag{7}$$

$$¥ = \Pi \cdot R \tag{8}$$

$$\Pi = ¥ \cdot P(T) \longrightarrow \Pi = \Pi \cdot R \cdot P(T) \tag{9}$$

$$
\begin{array}{c}
\qquad \text{OK} \quad D_{1u} \quad D_{1d} \quad D_{2u} \quad\quad D_{2d} \quad F_1 \quad \text{OK*} \\
R = \begin{bmatrix}
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 1-q_1 & q_1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 \\
q_2 & 0 & 0 & 1-q_2 & 0 & 0 & 0 \\
q_3 & 0 & 0 & 0 & 1-q_3 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\end{array}
$$

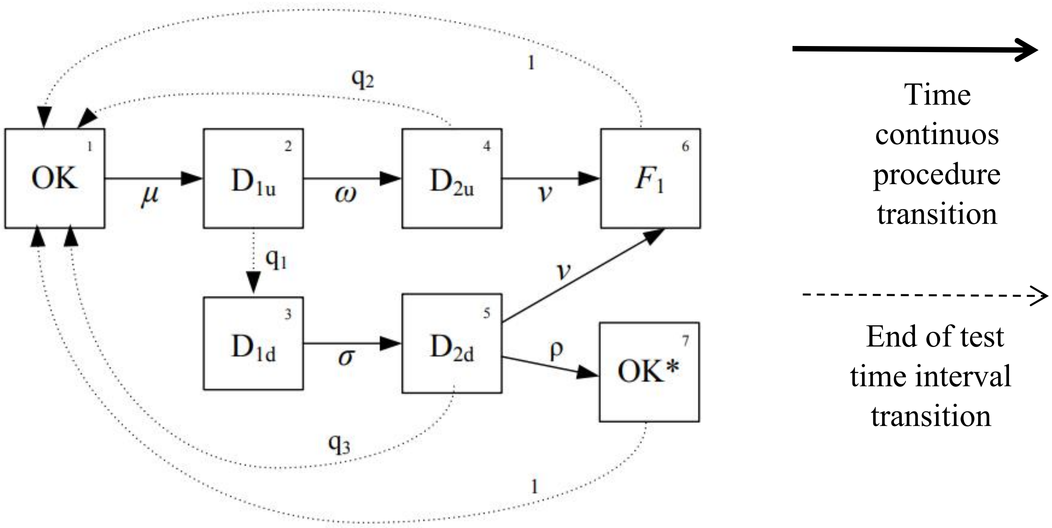


Figure 3- 6 The Markov chain model with states and rate of transitions [152]

Important assumptions for the estimation of parameters:-

- The amount of failures are evenly distributed per year and also equally distributed over the entire railway line.
- (MTTR) Mean Time To Repair = 0.
- The degradation mechanism can be handled like a static procedure.
- The changing parameters can be thought of as an exponentially distributed parameters.
- Critically failing states can be handled as absorption states that are repaired as well during inspections. This indicates that a single tiny rail segment cannot experience two major failures within a single inspection period.

Table 3- 14 Parameter estimation inputs

Definitions of Parameters	**Input Parameters**	**Qty.**
Length of rail	L	337,520m
Number of days, 2018-2022	N_1	1825
Number of days in2021	N_2	365
Length of test/inspection interval	T	122 days
Number of tests/inspections 2018-2022	N_{TF}	15
Number of tests/inspections on 2021	N_{TD}	3
Number of detection in D_1 status	N_{D1u}	370
Number of detection in D_2 status, when not yet known that state was degraded	N_{D2u}	443
Number of detection in D_2 status when it was known that status was degraded	N_{D2d}	13
Number of detection of critical failures (F_1)	N_{F1}	338
Number of detection of sudden failures (F_2)	N_{F2}	31
Detection probability of D_1 failure during test	q_1	0.4 (Decided by experts)
Detection probability of D_2 failure during test (D_1 state not yet detected)	q_2	0.7 (Decided by experts)
Detection probability of D_2 failure at test (D_1 state detected already)	q_3	0.9 (Decided by experts)
Detection rate of D_2 through additional inspections	ρ	$(2/T)\ q_3$ (Decided by experts)

Three tests were carried out in the year 2021, and degraded failures have been documented since January 1st, 2018. Since January 1st, 2018, critical failures have been documented; hence, the inspection interval will be taken to be (T=365/3=122 days).

A total of 813 degraded failures were found, of which 443 were type D_2 and 370 were type D_1 failures. Stationary probabilities for before inspection (X_n) states can be calculated as follows:-We obtain the next values for the Stationary probabilities πj (for the length of 1 m rail) using $q_1 = 0.4$, $q_2 = 0.7$ and $q_3 = 0.9$.

$\Pi_1 = 0.99832$

$$\Pi_2 = \frac{N_{D1u}}{L*N_{TD}*q_1} = 9.14*10^{-4} \quad (10)$$

$$\Pi_4 = \frac{N_{D2u}}{L*N_{TD}*q_2} = 6.25*10^{-4} \quad (11)$$

$$\Pi_5 = \frac{1}{3}\frac{N_{D2d}}{L*N_{TD}*q_3} = 4.76*10^{-6} \quad (12)$$

$$\Pi_6 = \frac{N_{F1}}{L*n_{TF}} = 6.68*10^{-5} \quad (13)$$

$$\Pi_7 = \frac{2}{3}\frac{N_{D2u}}{L*n_{TD}} = 8.56*10^{-6} \quad (14)$$

$$\Pi_1+\Pi_2+\Pi_3+\Pi_4+\Pi_5+\Pi_6 = 1 \quad (15)$$

Π_3 can be calculated based on the following function:-

$$\Pi_3 = \Pi_2 * (e^{\sigma T} - 1) * q_1 = 6.63*10^{-5} \quad (16)$$

$$\Pi = \Pi.R.P(T) \quad (17)$$

the time continuous transition rates per day (μ,ν,ω,σ) can be estimated using the relation $\Pi_{(i+1)} = \Pi_i.R.e^{TQ}$ (18)

$\mu = 8.33*10^{-6}$

$\nu = 1.45*10^{-3}$

$\omega = 2.4*10^{-3}$

$\sigma = 1.37*10^{-3}$

$\lambda = 5.03*10^{-8}$

$\rho = 1.48*10^{-2}$

Note that the figure for ρ was taken directly from expert judgment (from the above table), $\lambda = NF2/(N1 \cdot L)$ and the estimate for additional inspections is calculated as , $\rho = (2/T) \cdot q_3$.

“Mean sojourn times” designated as E[T, i] for the state i are calculated as follows. By considering a clear continuous procedure and no maintenance work, “Mean sojourn times” are evaluated as the inverse of related time continuous transition rates.

3.9 Sensitivity analysis

Reliability, availability, maintainability and safety (RAMS) of railway operation syste m are highly affected by the internal and external failures of the system and the time t aken to recover the failures.

Common consequences of failures are: - trip cancellations, Part (short) routes, Damag es, Operation Delays and so on. Sensitivity analysis has an imperative significance in an extensive range of engineering uses. The method helps to recognize the most sensi tive failures that can affect the normal operation of railway system. The sensitivity of the failure is also dependent on the time of recovery and the frequency of occurrences. The case study has been taken for the year of 2019.

3.10 Research design experimental investigation

3.10.1 Research design

The research designed as failure analysis on switches and crossings welding both analytically and experimentally. The experimental section includes welding analysis, non destructive test of the welded specimens, microstructural test and hardness test.

experimental investigation method was employed on welded rail samples by artificially grooving the rail and filling the groove by arc welding. After the welding work finished the samples have been cooled at different cooling rate. Finally, the quality of the welding was assessed by ultrasonic crack detector devise and the micro-structural features of the weld have been investigated.

3.10.2 Welding of the rail using arc welding method

In "Addis Ababa Light Rail Transit" worn-out and damaged rails have been maintained by welding. Arc welding was the one selected for welding of those damaged rails. The CONARC 49 / H4 7018 electrode has been used for welding the sample rails. 70 means 70,000 pounds worth of tensile strength, it means the welding can handle 70,000 pounds before that weld breaks. This electrode is the best one from other electrodes that are used for arc welding since it can handle a better load with better coating additionally it is a little bit bigger rod so it can handle the higher amperage with a clean looking weld. The power source applied for the welding is 400v and 75 Amp.

This research work has attempted to improve the welding trend of AALRTS by improving the cooling rate. In the experimental investigation, after the welding has been completed the specimens have been cooled in three different cooling rates. The minimum cooling rate can be achieved by both preheating and post-heating procedures and the recommended values are 250 - 450° C/s.

Figure 3- 7 Sample rails artificial damaged and filled by welding

3.10.3 Crack detection of the sample rails using non-destructive test (NDT)

A crack detection technique known as "non-destructive test" (NDT) was applied to assure the quality of the weld by applying three different approaches known as "ultrasonic" crack detection, "liquid penetration" and "magnetic crack detection". These crack-detecting devices have the capacity of detecting cracks to a depth of 6mm. The rail specimens were prepared with a dimension of 5mm depth and 18mm wide artificially grooved on the center and the groove was filled by the welding procedure. The ultrasonic machine detects any cavity by emitting sound waves throughout the specimen; if a cavity occurs in the welded section the device will reflect the sound wave within a short period. The decibel unit or (dB) Unit is 1/10 of a bel which is a unit derived from logarithms to the base 10. If two ultrasonic signals have intensities I_0 and I_1 and we can compare and see those two signals that will vibrate the transducer and produce output electrical signals whose power will be P_0 and P_1 respectively. The ratio of these signals $I0/I1$ is equal to the ratio of electrical power.[153]

$$\frac{I_0}{I_1} = \frac{p_0}{p_1} \quad (19)$$

$$P = V^2 \quad (20)$$

$$\frac{I_0}{I_1} = \frac{p_0}{p_1} = (\frac{v_0}{v_1})^2 \quad (21)$$

The logarithm to the base 10 of both factors in the equation gives.

$$\log_{10}\frac{I_0}{I_1} = \log_{10}\frac{p_0}{p_1} = \log_{10}(\frac{v_0}{v_1})^2 \quad (22)$$

Since the decibel is $\frac{1}{10}$ Bel

$$2\log_{10}\frac{v_0}{v_1} \text{ Bels} = 20\log_{10}\frac{v_0}{v_1} \text{ decibels} \quad (23)$$

Figure 3- 8 Ultrasonic crack detection device

3.10.4 Micro-structural test of the rails specimens

Primarily material specimens of rail were prepared decisively to make it suitable for the test as follows. For the micro-structural observations, the specimens were prepared within the standard metallographic preparation. After the preparation was completed; the specimen`s micro-structural features were assessed by using the Olympus C-35DA-2 metallurgical microscope. The figure below describes specimens prepared suitably to be observed in the microscope.

Primarily the sample materials have been prepared to make it suitable for the test as follows.

Figure 3- 9 Samples prepared for the microstructural test

For the microstructural test the samples have been prepared by polishing with emery paper in the size 280, 400,500 and 1000, finally polished by a very fine fabric. While polishing DP-Special Diamond Past and DP-Lubricant blue was applied for a better surface finish as a lubricant. The samples that are prepared for the microstructural test have been etched by using an etch-ant containing 2% nitric acid and 98% alcohol and soaked for a minute. Finally, the samples microstructural features have been assessed using the Olympus C-35DA-2 metallurgical microscope.

4 CHAPTER FOUR: RESULT AND DISCUSSION OF FAILURE ANALYSIS

4.1 Root cause Analysis

Root cause analysis conducted to find out the sensitive parameters of damages of Addis Ababa Light rail transit turnout sections. The factors for different failure modes can be identified earlier by implementing root cause analysis. A fish bone diagram developed demonstrating the potential causes. The potential causes sensitivity towards the damages of turnouts determined as follows. [144]

Table 4- 1 Sensitivity analysis of damages on railway turnouts

Potential failure causes			Sensitivity to Damage on railway turnouts Out of 100%
Maintenance	Inspection interval		15%
	Inspection technique	Visual inspection	8%
		Ultrasonic inspection cars	7%
	Maintenance method	Rail adjustment	1%
		Rail replacement	2%
		Greasing and grinding	2%
		Repair by welding	5%
	Maintenance Frequency		10%
Track design	Crossing panel	Frog angel	1%
		Panel length	2%
	Switch panel	Panel length	1%
		Entry angel	2%
	Closure panel	Panel length	1%
	Turnout geometry and layout		3%
	Properties of material		8%
	Curve radius		7%

Operation	Train operation traffic	4%
	Design speed	4%
	Train operation schedule	2%
Rolling sto ck	Axle load	2%
	Suspension	2%
	Dynamic and cyclic loading	7%
	Wight distribution and moment of inertia	4%

From the root cause analysis four basic parameters are set as a cause for rail turnout`s damage. Track design, rolling stock, operation and maintenance are the four basic parameters which are sensitive to the damage on turnouts. Among which maintenance is highly sensitive for the damage of turnouts with 50% of coverage; next to maintenance, “track design” takes the next portion 25% of the total potential root cause. Rolling stock and operation parameters have less effect for the damage of turnouts relatively.

From the maintenance issue “inspection interval” is highly sensitive to the damage of turnouts, whereas “maintenance frequency” is the second sensitive element for rail turnouts damage. “Visual inspection” from the maintenance issue and “properties of material” from track design takes the third position as a potential cause for damages on turnouts.

Root cause analysis can be an input for planing efficient and effective maintenance plan. An effective maintenance plan usually needs a clearly addressed failure modes, whereas that failure mode might have different root causes.

4.2 Statistical Markov chain analysis results

Table 4- 2 Computation of "sojourn mean times" and "mean time to failure" (MTTF), assumptive of there was no maintenance for a portion of 1 km rail length.

Definitions of Parameters	**Input Parameters**	**Inspection interval (T)**	
		122 days (actual observation value)	**73 days (recommended value)**
E[T, OK]	$(1/\mu)$	0.3 years	0.2 years
$E[T, D_{1u}]$	$(1/\omega)$	1.1 years	0.7 years
$E[T, D_{2u}]$	$(1/v)$	1.9 years	0.8 years
$MTTF_1$	$(1/\mu+1/\omega+1/v)$	3.3 years	1.7 years
$MTTF_2$	$(1/\lambda)$	54.5 years	54.5 years
MTTF	$(1/MTTF_1 + 1/MTTF_2)^{-1}$	3.1 years	1.6 years

Knowing the critical failure mode is a key for an effective maintenance schedule. Maintenance work includes preventive and corrective maintenance's. The maintenance work needs improvement to improve the quality of the operation. The aim of this method is to recognize the most sever and critical failure modes in turnouts of Addis Ababa Railway Transit System (AALRTS).

A well known mathematical model called " Markov chain model" exercised to investigate the failures which are detected during the track inspection works with the failure rate. A total of 813 degraded failures were found from the inspection, of which 443 were major degraded failures (D_2) and 370 were minor degraded failures (D_1).

Three ultrasonic crack tests were carried out by ultrasonic inspection cars in every year, and detected failures will be documented accordingly. Since January 1st, 2018, critical failures were documented; hence, the test interval will be taken to be 122 days per year. For the Markov chain model :- the rail length, the length of test interval, number of observations for critical and shock failures, the failure rate and probabilities are the input parameters of the model.

Table 4.2; entertains different failure analysis terms for the purpose of maintenance improvement. "Markov chain" model assists to calculate the spent times in various states and likewise the "mean time to failure" for both critical failure modes (F_1) and sudden failure modes (F_2).

"E[T, OK] " :- anticipated staying times in OK state has a value 0.3 years in the actual inspection interval and 0.2 years in the recommended inspection interval.

"E[T, D_{1u}]" :- anticipated staying times in D_{1u} state has a value 1.1 years in the actual inspection interval and 0.7 years in the recommended inspection interval.

"E[T, D_{2u}]" :- anticipated staying times in D_{2u} state has a value 1.9 years in the actual inspection interval and 0.8 years in the recommended inspection interval.

"$MTTF_1$" :- mean time to failure for critical failure modes (F_1) has a value 3.3 years in the actual inspection interval and 1.7 years in the recommended inspection interval.

"$MTTF_2$" :- mean time to failure for sudden failure modes (F_2) has a value 54.5 years in both actual inspection interval and recommended inspection interval.

"MTTF" :- the average mean time to failure for critical failure modes (F_1) and sudden failure modes (F_2) has a value 3.1 years in the actual inspection interval and 1.6 years in the recommended inspection interval.

The anticipated staying times in different detection states indicate that decreasing the the test interval has a direct influence on the detection probability within a short period of time.

The output results that are "Mean Time To Failure" for both failure modes manifests that; based on the results it is possible to recommend that increasing the number of test from 3 to 5 or decreasing the test interval from 122 days to 73 days will minimize "Mean Time To Failure" from 3.1 years to 1.6 years.

4.3 Failure Mode, Effects and Criticality Analysis (FMECA) Results

This method intends to recognize the most sever and critical failure modes in turnouts of Addis Ababa Railway Transit System (AALRTS). Knowing the critical failure mode is a key for an effective maintenance schedule. Maintenance work includes preventive and corrective maintenance's. The maintenance work needs improvement to improve the quality of the operation. The failures on the switch panel of AALRT have been analyzed by using a scientific method called "failure mode, effects, and criticality analysis" (FMECA).

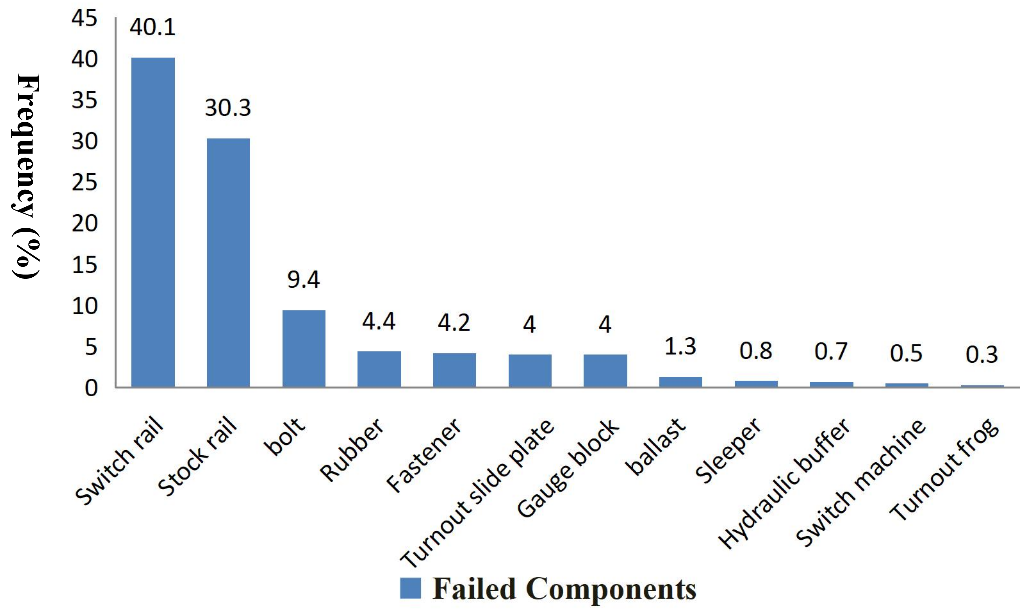


Figure 4- 1 Total quantity of components that are failed in 2021

The above chart shows that switch rail and stock rail are frequently failed components that will take the ration more than 70% of failed components on turnouts of AALRT in the year of 2021. Whereas components: - bolt, rubber, fastener, turnout slide plate and gauge block take portion about 26 % of the total failed components and the rest ballast, sleeper, hydraulic buffer, switch machine and turnout frog take a less portion 3.6% of the total failed components.

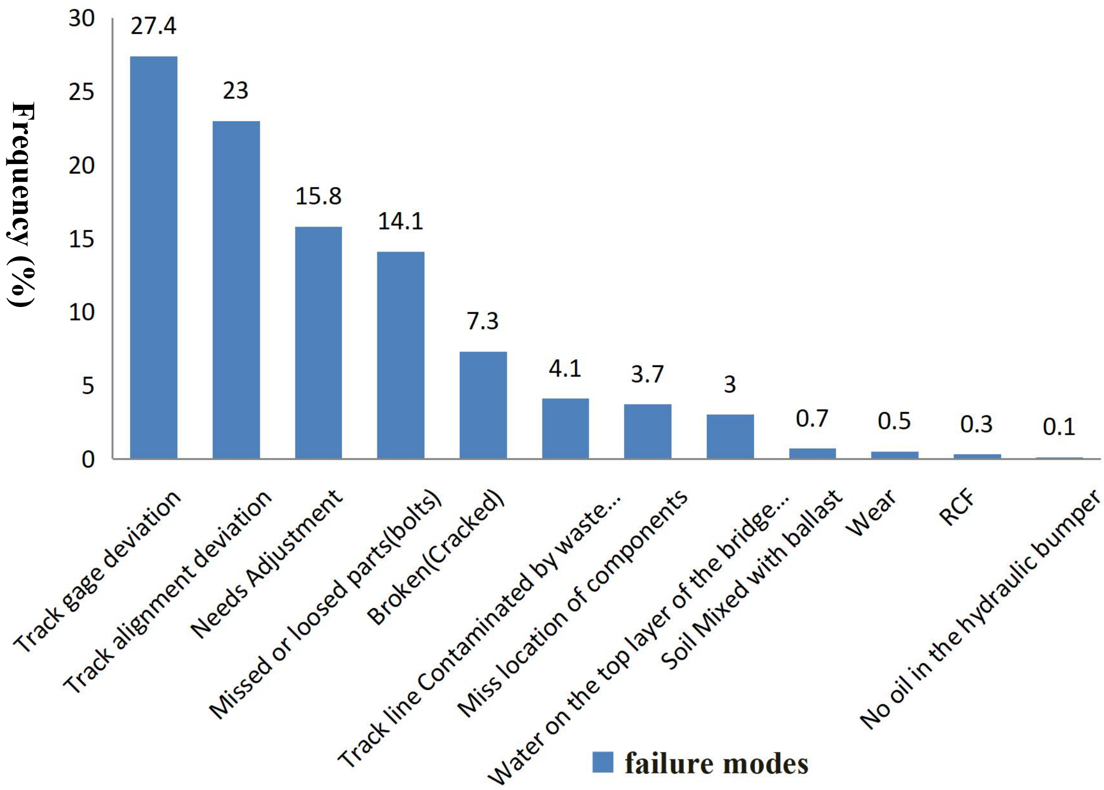


Figure 4- 2 Total failure modes that are reveals in 2021

The above chart shows that Track gauge deviation and track alignment deviation are frequently occurred failure modes that will take the portion more than 50% of the total failure modes on turnouts of AALRT in the year of 2021. Comparatively, Needs Adjustment, Missed or loosed parts (bolts), Broken (Cracked), Track line Contaminated by waste materials, Miss location of components and Water on the top layer of the bridge (poor sewerage) failure modes take portion about 48 % of the total failure modes. Whereas, Soil Mixed with ballast, Wear, RCF and No oil in the hydraulic bumper take a less portion of appearance 4.6% of the total failure modes.

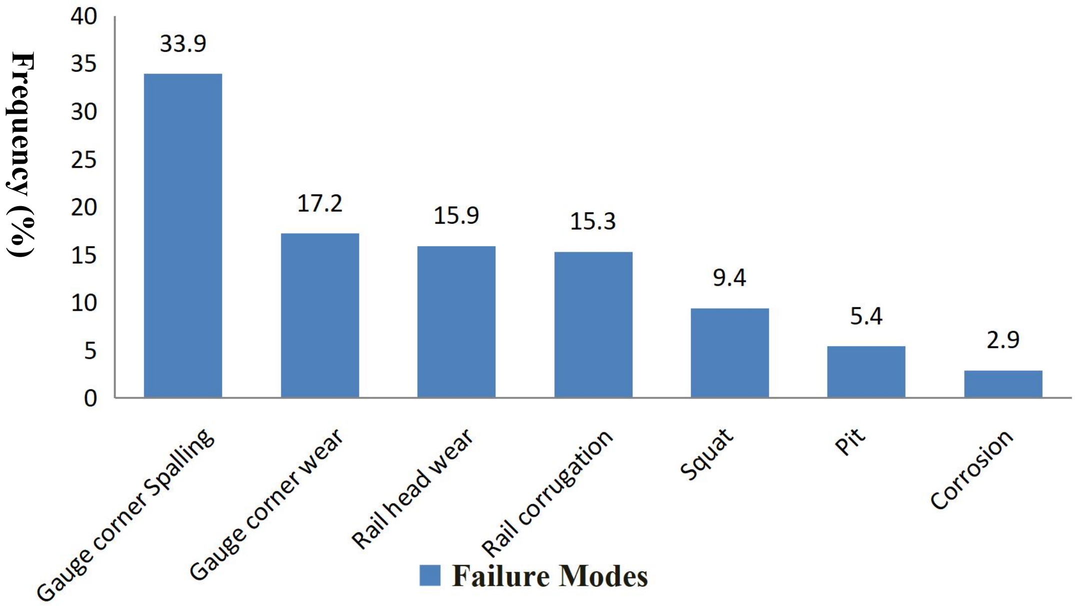


Figure 4- 3 Types of damages that are observed on the switch panel of AALRT from 2018 to 2022

The above chart demonstrates that gauge corner spalling and gauge corner wear frequently happened failure modes that will cover more than 50% of the total failure modes on the switch panel of AALRT from the year 2018 to 2022. Whereas the failure modes; Rail head wear, Railhead corrugation, and squat take the portion of 40.6% of the total failure modes. Finally, pit and Corrosion have less portion of occurrence which is 8.3% of the total failure modes.

Table 4- 3 the detail results of failure mode, effects and criticality analysis (FMECA)

Failure Modes	**Likelihood of Occurrence (1-5)**	**Likelihood of Severity (1-10)**	**Rate of Detection (1-10)**	**Risk Priority Number (RPN)**
Needs Adjustment	4	6	5	120
Broken (Cracked)	3	7	5	105
Missed or loosed parts(bolts)	4	4	5	80
Wear	2	8	5	80
Miss location of components	3	5	5	75

Track line Contaminated by waste materials	3	4	6	72
RCF	2	5	5	50
Soil Mixed with ballast	2	3	6	36
Track gage deviation	5	3	2	30
Track alignment deviation	5	3	2	30
Water on the top layer of the bridge (poor sewerage)	3	3	2	18
No oil in the hydraulic bumper	1	2	2	4
Total RPN				**700**

From failure modes of turnout`s "need adjustment" is a failure mode with a maximum risk priority number 120 and next to that "Broken (Cracked)" is the second failure mode with 105 risk priority number.

The severity of need adjustment failure mode ranked as 6. The frequently broken or cracked components of crossings are the fastenings, rubbers, gauge blocks and slide plates. Their detect-ability rank is medium that is ranked as 5 with moderate occurrence and low severity assigned by numbered as 3 and 7 respectively.

Missed or loosed parts of turnouts are also fastenings, rubbers, gauge blocks and slide plates. They need an immediate replacement after the failure occurs. The assigned values are low (4) severity and high (4) occurrence value.

Even if the occurrence is low wear is the most sever failure mode in railway system. More than 75% of turnout components specially switch rail and stock rail are highly affected by wear. Miss-location of components of turnouts like gauge block, spring rod and rubber is a failure mode which has a moderate severity and detection level ranked as 5 respectively.

Dirt leaves and other contaminating materials that can cause failure on switch machine are easily detectable failure modes but their severity is less comparatively. In AARTS Rolling Contact Fatigue (RCF) failure usually have been repaired by grinding or welding repair method, the failure by itself is not sever failure, but if it is not repaired for a long period of time rail cracking may occur. Assigned by low occurrence (2) and low (5) severity level.

Water on the top layer of the bridge (poor sewerage) can be seen by an open eye but the occurrence is less because it occurs only on the rainy seasons. When the soil mixed with ballast it will cause degradation of ballast and degradation of the ballast may cause degradation of other turnout components, so that the severity of this failure is minor in level which is 3. Track gauge deviation and track alignment deviation are failure modes occurring on Switch rails and Stock rails. The occurrence of Track gauge deviation and track alignment deviation are very highly ranked by 5, and also the detectability of these failures are high (2) but have minor severity level (3). Water on the top layer of the bridge (Poor sewerage) is a highly detectable failure mode but the severity is minor. No oil in the hydraulic bumper failure mode can be detected easily but the severity rank is very low.

Failure Mode: What could drive wrong?

Failure Causes: Why would the failure occur?

Failure Effects: What could be the effects of failure?

Likelihood of Occurrence: in the scale of 1–10 (10 = very likely to occur)

Likelihood of Detection: in the scale of 1–10 (10 = very unlikely to detect)

Severity: in the scale of 1–10 (10 = most severe effect)

Risk Priority Number (RPN): Likelihood of Occurrence × Likelihood of Detection × Severity

To recognize the failure zones with greatest risk, I have categorized the failures based on their RPN in to three altered categories.

Category1. When Risk Priority Number is high

Category2. When Risk Priority Number is Moderate

Category3. When Risk Priority Number is Low

When RPN probability of failure mode is more than 10 % will be categorized to Category1.

When RPN probability of failure mode is between 5 and 10 % will be categorized to Category2.

When RPN probability of failure mode is less than 5 % will be categorized to Category3.

According to the top categorization all failure modes credited to three categories. Category1. Needs Adjustment, Broken (Cracked), Missed or loosed parts (bolts), Wear, Miss-location of components and Track line Contaminated by waste materials

Category2. RCF and Soil Mixed with ballast

Category3. Track gauge deviation, Track alignment deviation, Water on the top layer of the bridge (poor sewerage) and No oil in the hydraulic bumper.

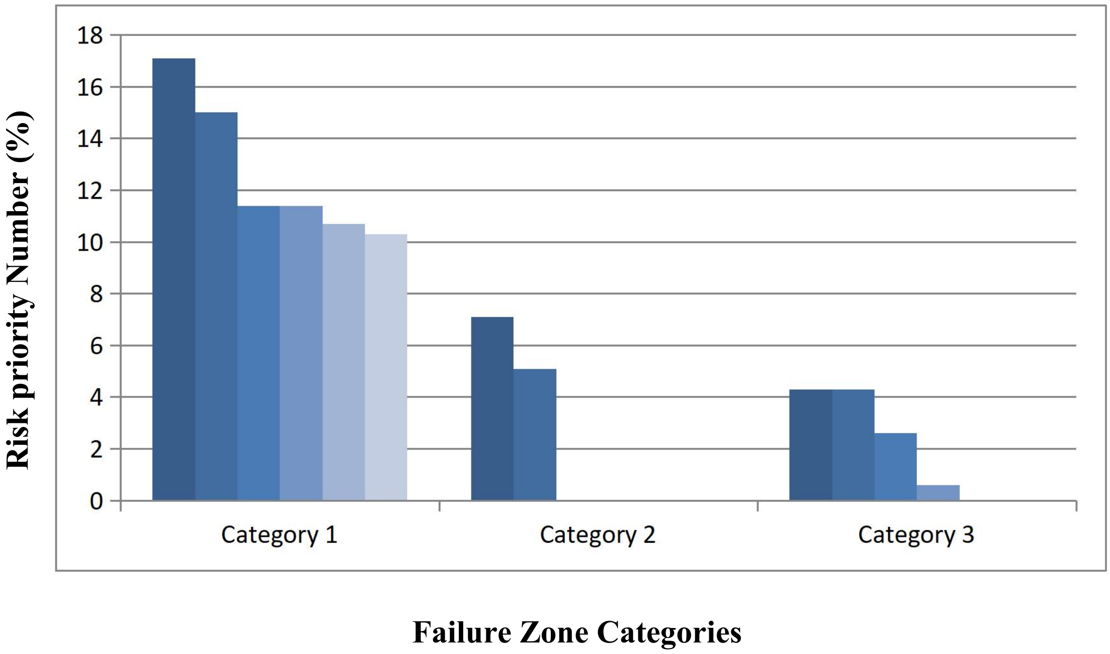


Figure 4- 4 Failure zone categories

Based on the above graph the behavior of failures on turnouts of AALRT can be summarized as three categories and the priority for maintenance work is also recommended depending on the risk priority number. Most of the failure modes are categorized under the first category which is the highest risk priority number. There are only two failure modes under the second category which needs a moderate priority next to category 1. Failures under Category 3 have low risk effect so that rectification is needed only for long term treatment.

Table 4- 4 the detailed outputs of failure mode, effects, and criticality analysis (FMECA) switch panel of AALRT

Failure Modes	**Likelihood of Occurrence (1-5)**	**Likelihood of Severity (1-10)**	**Rate of Detection (1-10)**	**Risk Priority Number (RPN)**
Gauge corner Spalling	5	7	4	140
Gauge corner wear	4	6	4	96
Rail head wear	3	5	4	60
Railhead corrugation	3	3	6	54
Squat	2	4	5	40
Pit	2	4	5	40
Corrosion	2	2	2	8
Total RPN				**438**

The failures on the switch panel of AALRT have been analyzed by using a scientific method called “failure mode, effects, and criticality analysis” (FMECA).
The failure frequency distribution (FFD) determines the occurrence of each failure mode. Some components of turnout’s needs adjustment and it should be adjusted immediately otherwise it will be the cause of other failures. From failure modes of switch panel “Gauge corner Spalling” is a failure mode with a maximum risk priority number 140 and next to that “Gauge corner wear” is the second failure mode with 96 risk priority number.

4.4 Sensitivity analysis results

Sensitivity analysis results of the three incidents. [144]

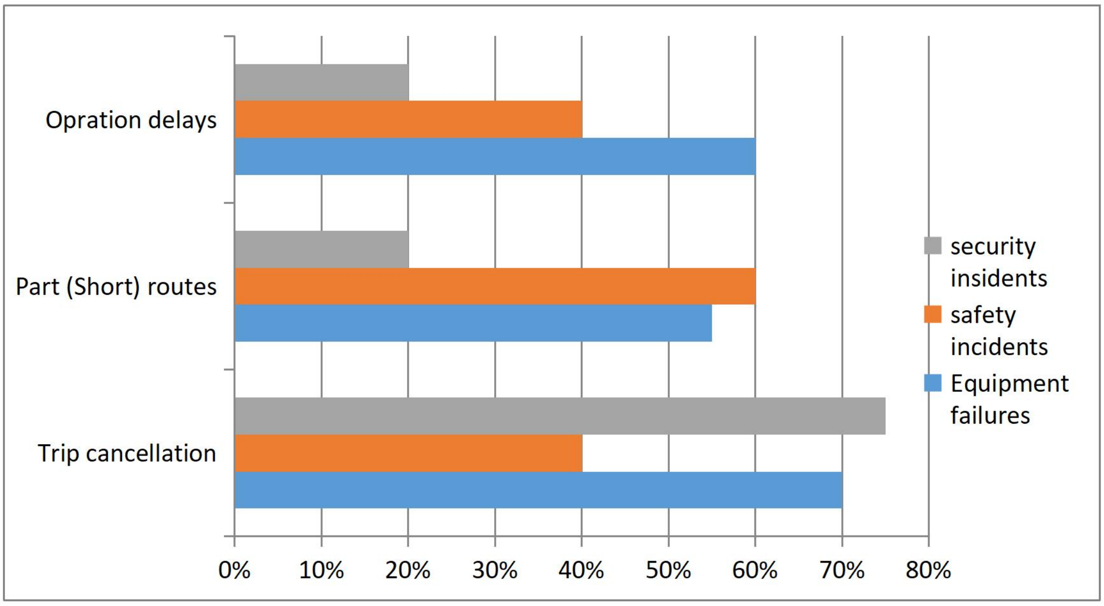


Figure 4- 5 Major Failures affecting railway operation versus their consequence

4.4.1 Frequency Analysis of failures

Figure 4- 6 Frequency Analysis of Safety incidents

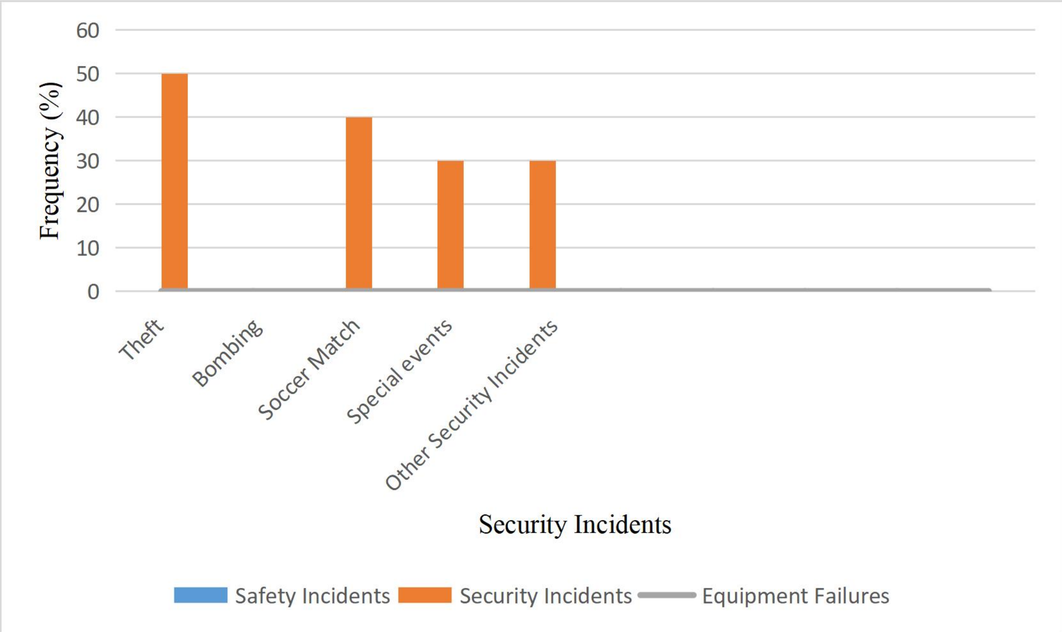


Figure 4- 7 Frequency Analysis of Security incidents

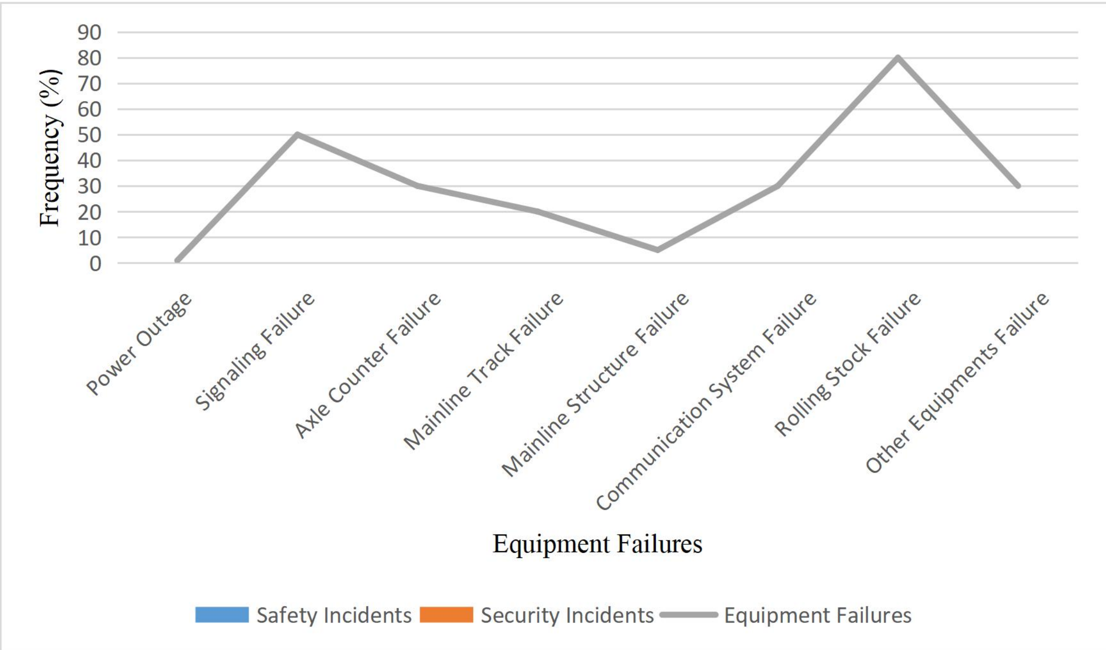


Figure 4- 8 Frequency Analysis of Equipment Failures

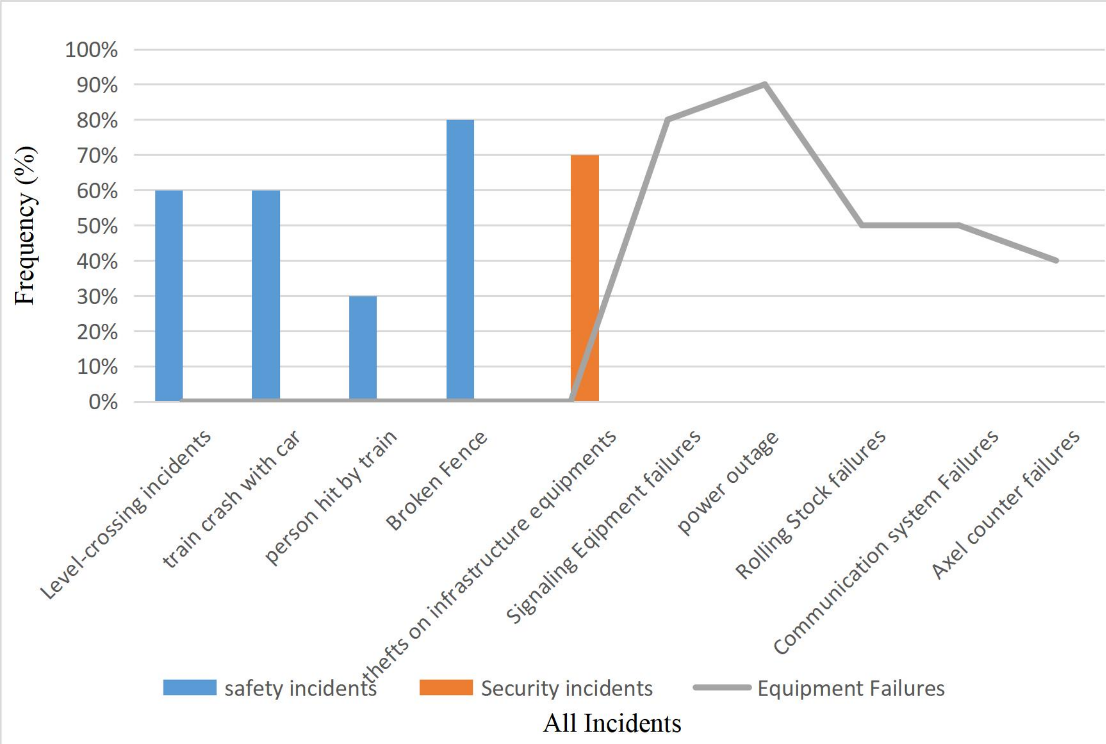


Figure 4- 9 Frequency Analysis of All Failures

4.4.2 sensitivity Analysis of failures

Table 4- 5 Sensitivity analysis of Safety incidents on railway operation

Sensitivity Out of 100%	**Train crash with cars**	**Person hit by train**	**Broken Fence**	**Suicides and attempted suicides**	**Derailment**	**Fire**	**Other Safety issues**
train delay hours	30%	1 0%	30%	1 0%	8%	2%	1 0%
number of trip cancellations	10%	10%	40%	10%	0%	5%	25%
number of part routs	15%	5%	60%	3%	0%	2%	15%
Time taken for recovery	35%	35%	10%	8%	0%	2%	10%

Table 4- 6 Sensitivity analysis of security incidents on railway operation

Percent of Sensitivity Out of 100%	Thefts (thefts of power cables and other equipment's from the infrastructure)	bombing	Football Match	Other Security incidents
train delay hours	35%	0%	35%	30%
number of trip cancellations	25%	0%	50%	25%
number of part routs	25%	0%	50%	25%
Time taken for recovery	25%	0%	50%	25%

Table 4- 7 Sensitivity analysis of Equipment Failures on railway operation

Sensitivity Out of 100%	Power Outage	Signaling Failure	Axel Counter Failure	mainline Track failure	mainline Structure failure	Communication system Failure	Rolling Stock Failure	Other Equipment failures
train delay hours	35%	6%	6%	2%	0%	6%	30%	1 5%
number of trip cancellations	60%	8%	0%	4%	0%	0%	20%	8%
number of part routs	60%	10%	0%	0%	0%	0%	25%	5%
Time taken for recover	40%	10%	5%	5%	0%	10%	20%	10%

The results that have been discovered from the analysis of the data indicate the percentage of sensitivity of failures on the normal operation of AALRTS. The researcher tried to analyze the issue by grouping in three major categories: -safety incidents, security incidents and equipment failures. Concerning the frequency of failures, safety incidents particularly level-crossing incident is the major failure happening frequently, while within Security incidents theft is the major failure happening frequently relative to other incidents. Finally, power outage among the group of equipment failures is the major failure happening frequently. But it is not wise enough to conclude that "a failure happening frequently is a failure highly affecting the operation"; because in-order to affect the operation the failure should have a direct effect in the operation. Concerning the sensitivity analysis, power outage is the first failure that can be able to stop the operation automatically; secondly signaling failures take the second portion; then it is possible to observe Communication system Failures and rolling stock failures will take the next portion of affecting the operation. The other failures will exhibit less effect in the operation one after the other. Safety incidents depending on their severity will affect the operation accordingly. Among the Safety incidents level-crossing incidents take a wider coverage of sensitivity. The sensitivity of Security incidents is very low comparing to other groups; because they don`t have a direct relation to the normal operation.

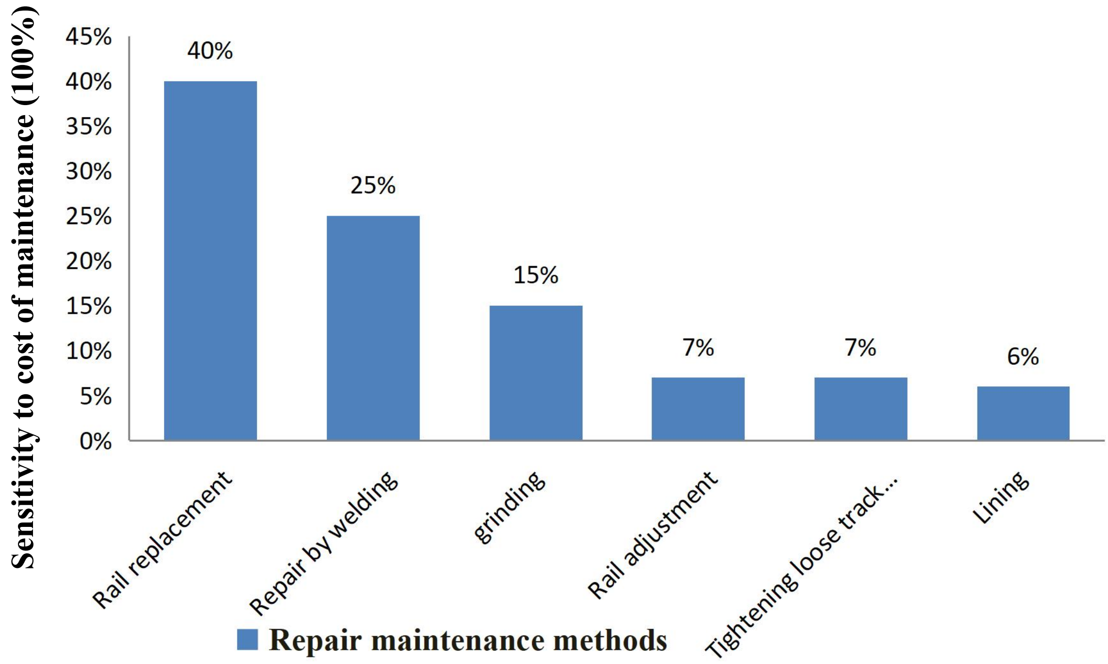


Figure 4- 10 Sensitivity analysis of maintenance methods to the cost of maintenance

The sensitivity of different repair methods towards the cost of maintenance analyzed on figure 4 -10. Rail replacement is highly cost dependant maintenance factor hence it's the last option than the other methods. Welding is the second maintenance method which is highly sensitive to cost of maintenance so that this research intended to improve this repair method accordingly.

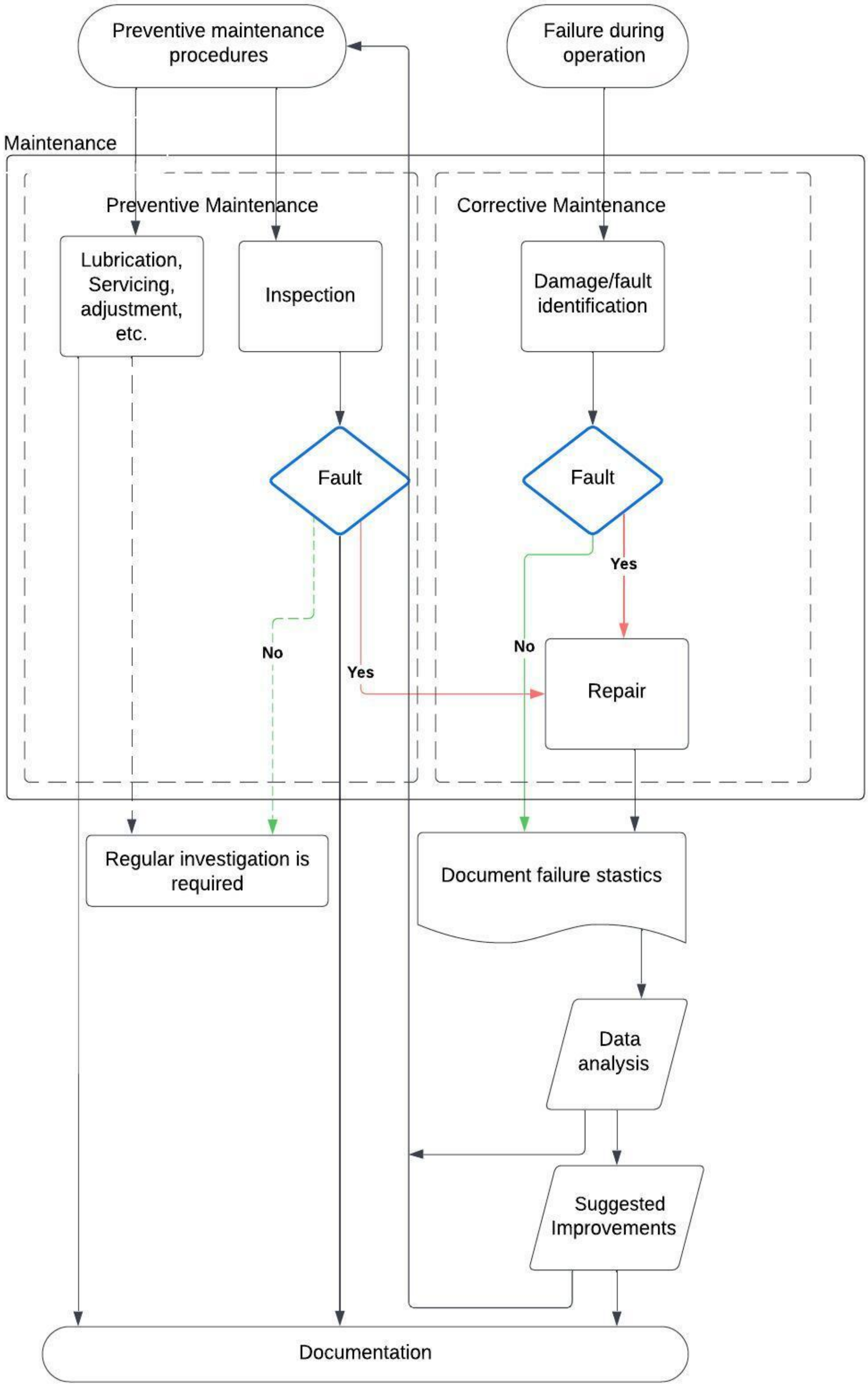


Figure 4- 11 Flow chart of track maintenance suggested for Addis Ababa light rail transit

5 CHAPTER FIVE: RESULT AND DISCUSSION OF EXPERIMENTAL INVESTIGATIONS

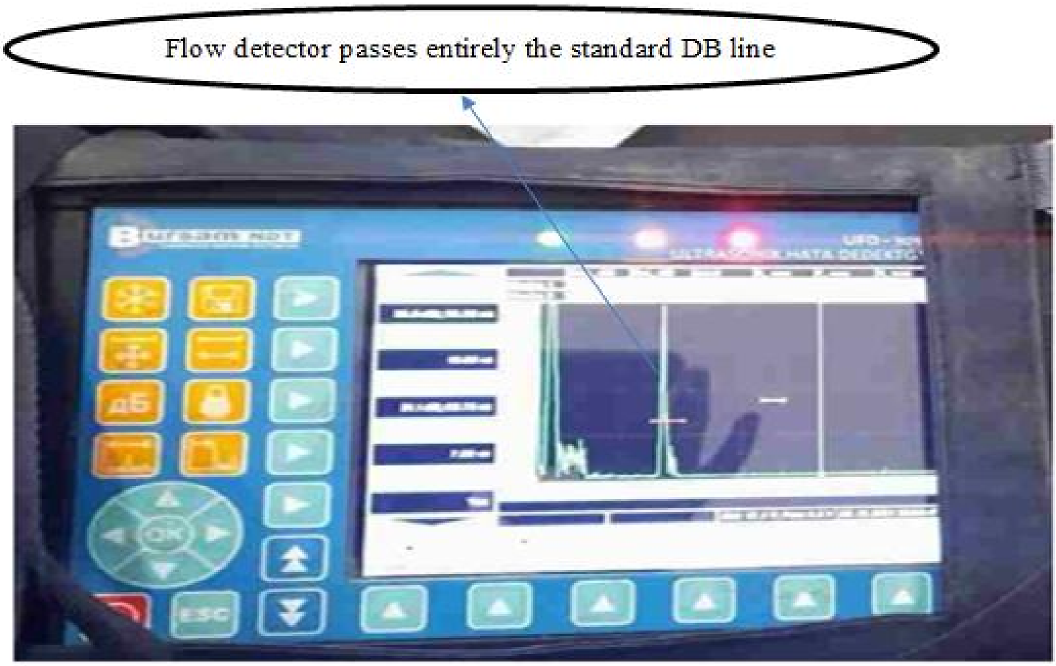
5.1 Experimental results

The experimental investigation work only address one of the repair methods of switches and crossings which is called “repair by welding”. the researcher has assessed different repair methods of switches and crossings like :- “rail adjustment”, “tightening”, “lining”, “grinding” and “repair by welding”. Considering the sensitivity analysis of maintenance methods to the cost of maintenance, “repair by welding” is the second sensitive repair method next to “rail replacement”. Based on the above statement the researcher come across to improve the welding technique by considering controlled cooling rate as a major factor for efficient rail repair and improved maintenance.

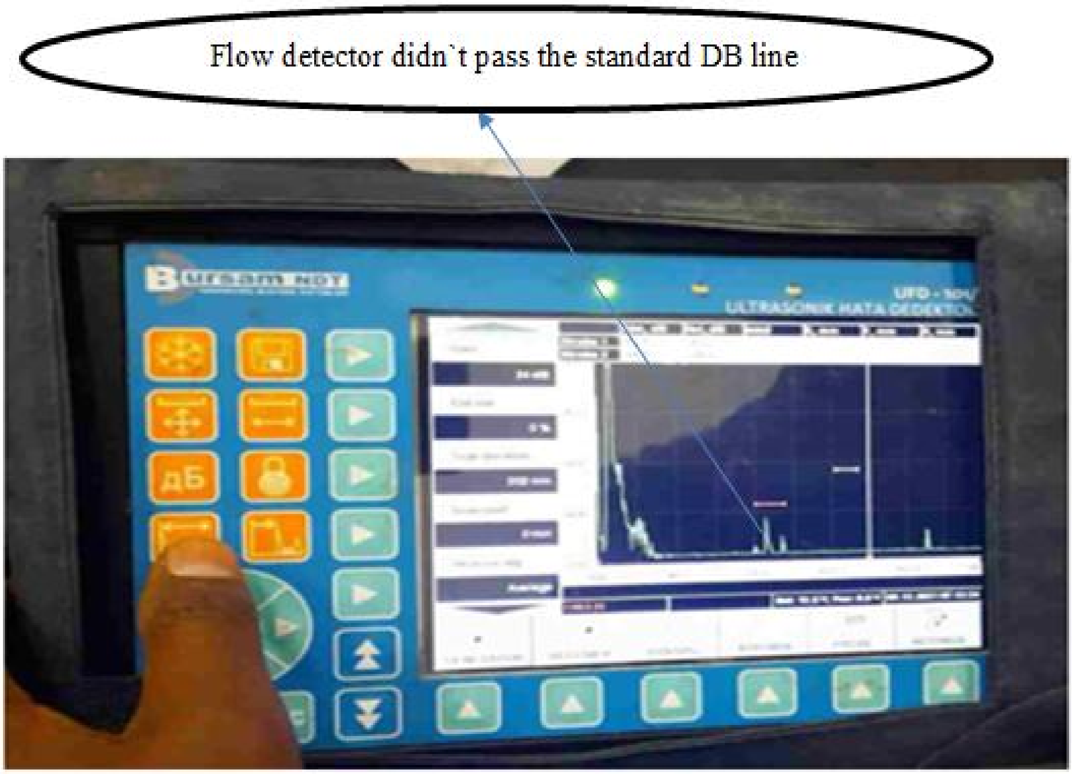
5.1.1 Crack detection of specimens through non-destructive test (NDT)

The industry uses non-destructive testing (NDT) as a validation and evaluation approach to assess a material's, component's, structure's, or system's features for distinctive variations, welding imperfections, and disturbance without resulting damages to the original component.

(a)



(b)



(c)

Figure 5- 1 Ultrasonic crack detection results for welded rail specimens cooled at (a) 3°C/s, (b) 6°C/s, and (c) 2°C/s respectively at 24 DB gain standard

The ultrasonic crack detection devise indicates the depth of the crack in the test-peace by emitting sound waves.

There is flow detector line which varies depending on the crack depth in the weld area. Whereas there is a standard gauge line called "decibel unit" line which is red in color; and the standard measure is 24DB value which means if the flow detector passes this standard DB line the crack depth is significant. The ultrasonic ''NDT'' results point out; there is a crack formed on the welded section of the rail specimen that was cooled at 6° C/s, whereas the crack on the welded section of the rail specimen that was cooled at 3° C/s cooling rate is within the optimum level. There was no crack detected on the welded section of the rail specimen that was cooled at 2° C/s; only porosity were observed.

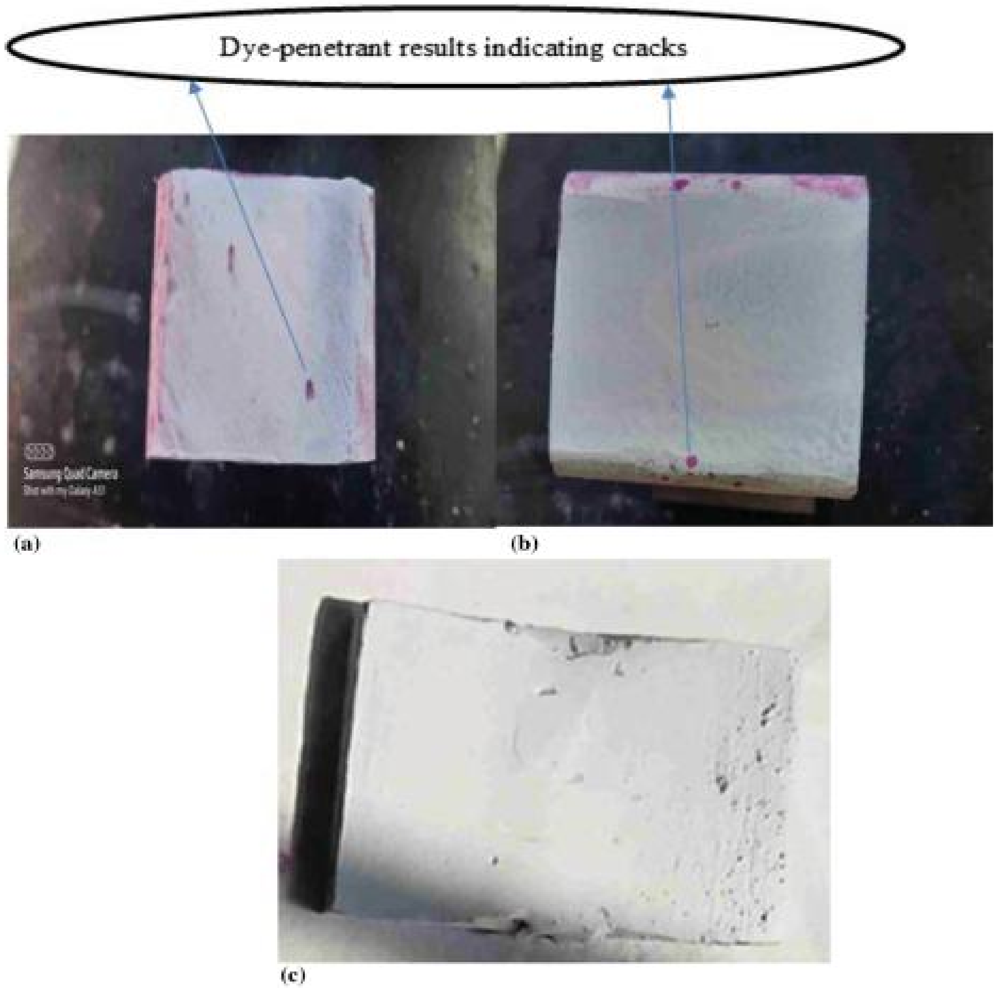


Figure 5- 2 Results from dye-penetrate inspection for welded rail specimens cooled at (a) 3°C/s, (b) 6°C/s, and (c) 2°C/s respectively

The liquid penetrant NDT test applies spray penetrable chemicals directly to the welded component and after waiting some minutes the crack will be observed clearly on the surface through penetration. The flaw detection results of welded rail specimens indicate that there are some cracks detected on welded rails cooled at 3℃/s and 6℃/s, while there was no crack detected on the welded rail cooled at 2℃/s.

Figure 5- 3 Non-destructive crack detection test results using the magnetic field for rail specimens cooled at (a) 2°C/s and (b) 6°C/s respectively

Magnetic crack detection devise uses metal particles that will be attracted towards the magnetic detecting devise.The results mark that there was more concentration of magnetic fluids on the center of the welded zone of the rail cooled at 6 ℃/s than that of cooled at 2 ℃/s rail which indicates the presence of a crack.

The failures on railway infrastructure of Addis Ababa Light rail transit especially on turnouts have been occurred frequently. To minimize the occurrences of failures, maintenance improvement has a great significance. The ultrasonic "NDT" results point out; there is a crack formed on the welded section of the rail specimen that was cooled at 6°C/s, whereas the crack on the welded section of the rail specimen that was cooled at 3°C/s cooling rate is within the optimum level. There was no crack detected on the welded section of the rail specimen that was cooled at 2°C/s; only porosity were observed. Post-heating avoids a martensitic microstructure from developing and the weld from cooling down too rapidly.

The liquid penetrant NDT results of welded rail specimens indicate that; there are some cracks detected on welded rails cooled at 3°C/s and 6°C/s; while there was no crack detected on the welded rail cooled at 2°C/s. Magnetic crack detection devise detect cracks by implementing magnetic particles as a crack indicators and magnetic crack detection devise as a crack detector devise. The results of magnetic detector devise mark that there was more concentration of magnetic particles on the center of the welded zone of the rail that was cooled at 6°C/s than that of cooled at 2°C/s rail which indicates the presence of a crack.

Table 5- 1 Chemical composition of "Addis Ababa Light Rail Transit Service" (AALRTS) rail material (50 kg/m U71Mn) from Spectro-meter test

Chemical element	C	Si	Cr	Mn	P	S	Mo	V	Fe	Ni	Co	Cu	Al
Composition (Wight %)	0.65	0.36	0.035	1.12	0.098	0.080	0.016	0.010	97.3	<0.008	0.016	0.053	0.008

Table 5- 2 Chemical composition of the welded rail specimen cooled at 6 °C/s cooling rate from the Spectro-meter test

Chemical element	C	Si	Cr	Mn	P	S	Mo	V	Fe	Ni	Co	Cu	Al
Composition (Wight %)	0.187	0.491	0.048	1.11	0.114	0.097	0.019	0.013	97.6	<0.008	<0.009	0.041	0.071

Table 5- 3 The chemical composition of the welded rail specimen cooled at a 3 °C/s cooling rate from the Spectro-meter test.

Chemical element	C	Si	Cr	Mn	P	S	Mo	V	Fe	Ni	Co	Cu	Al
Composition (Wight %)	0.172	0.451	0.050	1.19	0.107	0.082	0.019	0.015	97.6	<0.008	0.009	0.045	0.004

Table 5- 4 Chemical composition of the welded rail specimen cooled at 2 °C/s cooling rate from the Spectro-meter test

Chemical element	C	Si	Cr	Mn	P	S	Mo	V	Fe	Ni	Co	Cu	Al
Composition (Wight %)	0.170	0.450	0.057	1.17	0.107	0.082	0.019	0.016	97.6	<0.008	0.009	0.041	0.004

Additionally, the Spector-meter test manifests bainite in 0.170%C, 1.17%Mn steel continuously cooled from 630°C. The welded rail cooled at 6°C/s has reflected the microstructural feature of bainite with few martensite formations on the weld center and the heat-affected zones. Additionally, the Spector-meter test manifests bainite in 0.187% C, 1.11% Mn steel continuously cooled from 630°C. While the welded rails cooled at 3°C/s have the microstructural feature bainite with some ferrite formation on the weld center and the heat-affected zones. Additionally, the Spector-meter test manifests bainite in 0.172% C, 1.19% Mn steel continuously cooled from 630°C.

Table 5- 5 Surface hardness of the welded rail`s at different welding zones and cooled at different cooling rates

Measured distance from the center of the weld (mm)	**Hardness (M Pa)**		
	Welding cooled at a cooling rate of 2 °C/s	**Welding cooled at a cooling rate of 3 °C/s**	**Welding cooled at a cooling rate of 6 °C/s**
-60	910	950	1025
-50	860	950	1000
-40	825	860	930
-30	980	1055	1080
-20	1000	1025	1115
-15	1080	1295	1480
-10	1000	1080	1180
0	980	1025	1115
10	1000	1055	1180
15	1080	1340	1530
20	980	1000	1080
30	950	1025	1115
40	805	910	950
50	860	950	1000
60	880	980	1025

Table 5.5 states that the hardness values of welded rail specimens cooled at a cooling rate of 2 °C/s, 3 °C/s and 6 °C/s measured at a distance from -60 mm up to 60 mm form the center of the material.

Table 5- 6 Mechanical properties of welded rail materials

Measured distance from the center of the weld (mm)	Tensile strength of material (M Pa)			Elongation(%)		
	Welding cooled at 2 °C/s	Welding cooled at 3 °C/s	Welding cooled at 6 °C/s	Welding cooled at 2 °C/s	Welding cooled at 3 °C/s	Welding cooled at 6 °C/s
-60	910	950	1025	12	12.5	13.5
-50	860	950	1000	11.3	12.5	13.2
-40	825	860	930	10.9	11.4	12.3
-30	980	1055	1080	12.9	13.9	14.2
-20	1000	1025	1115	13.2	13.5	14.7
-15	1080	1295	1480	14.2	17	19.5
-10	1000	1080	1180	13.2	14.2	15.6
0	980	1025	1115	12.9	13.5	14.7
10	1000	1055	1180	13.2	13.9	15.6
15	1080	1340	1530	14.2	17.7	20.2
20	980	1000	1080	12.9	13.2	14.2
30	950	1025	1115	12.5	13.5	14.7
40	805	910	950	10.6	12	12.5
50	860	950	1000	11.3	12.5	13.2
60	880	980	1025	11.6	12.9	13.5

Table 5.6 states that Tensile strength and elongation of welded rail specimens cooled at a cooling rate of 2 °C/s, 3 °C/s and 6 °C/s that was measured at a distance from -60 mm up to 60 mm from the center of the material.

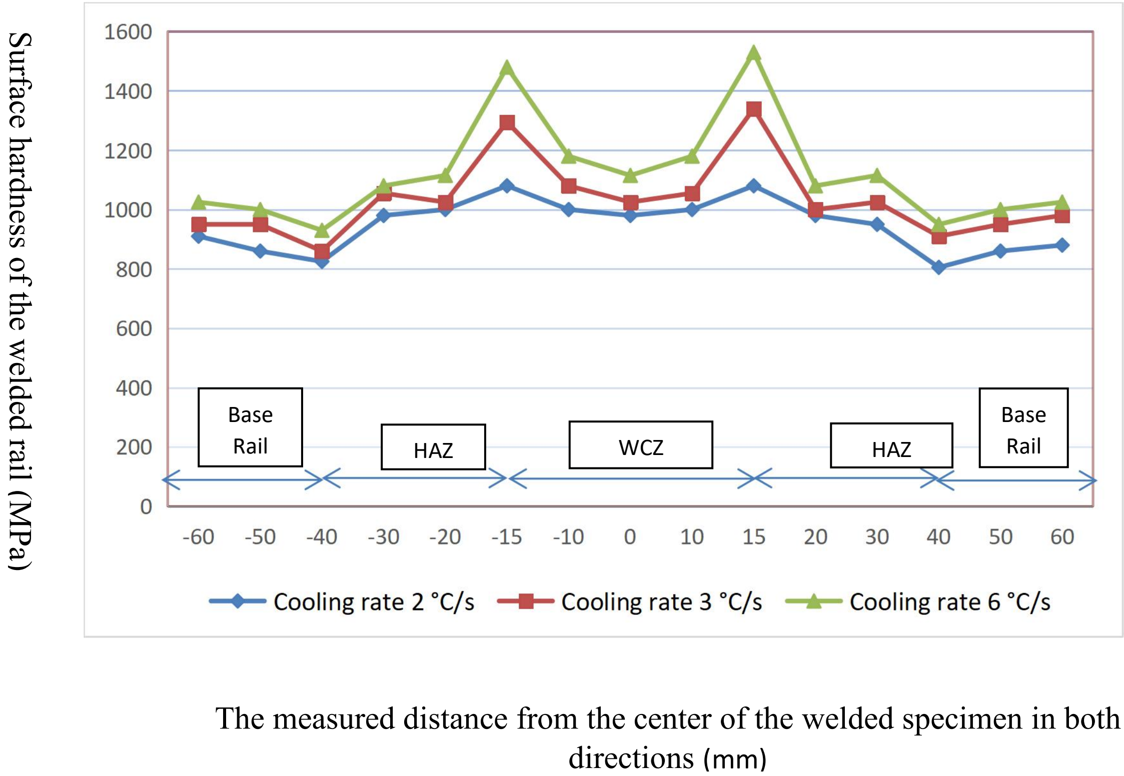


Figure 5- 4 Hardness of the welded specimen at different welding zones and cooled by different cooling rates.

The welded rail material is categorized in to three major sections that are:- the weld center zone, the heat affected zone and the base material.

A hardness test was manipulated on the welded rail specimens at different welding zones. The test results of hardness indicate that the welded sections had the greatest hardness value on the transition zone from the weld center zone to the heat-affected zone in all of the cooling mediums. The minimum hardness values were registered on the transition zone from the heat-affected zone to the base material because of the heat effect. Welded rail cooled at 6°C/s has better hardness than cooled at 3°C/s and cooled at 2°C/s welded rails. These results specify that; the heat from the weld center to the base material affects the hardness of the material dramatically.

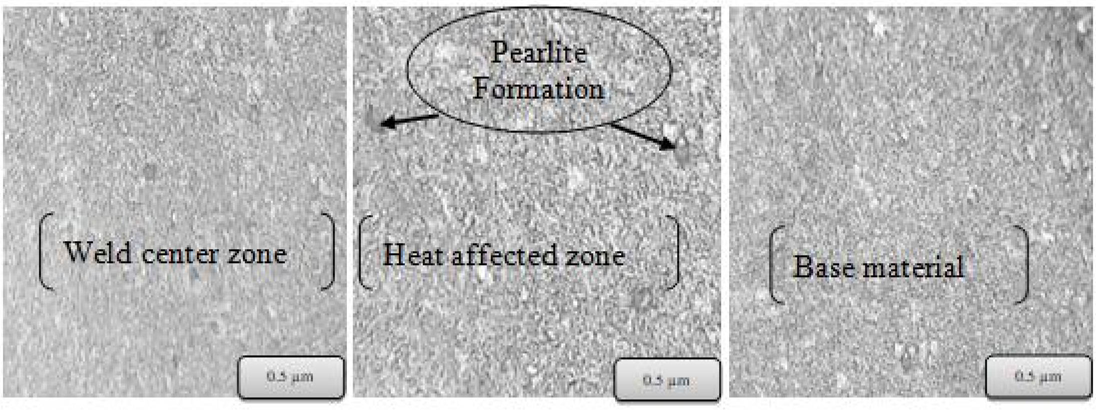


Figure 5- 5 Micro-structural features of welded rail specimen that were cooled at 2°C/s cooling rate

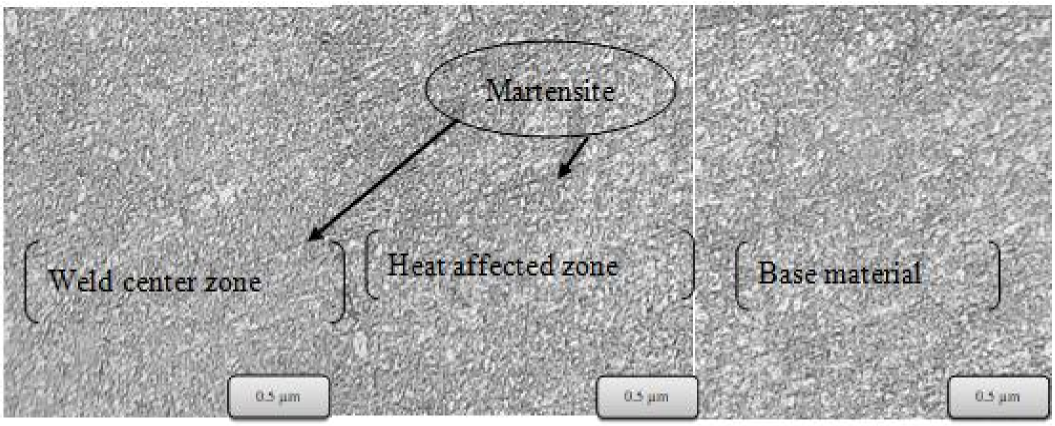


Figure 5- 6 Micro-structural features of welded rail specimen that were cooled at 6°C/s cooling rate

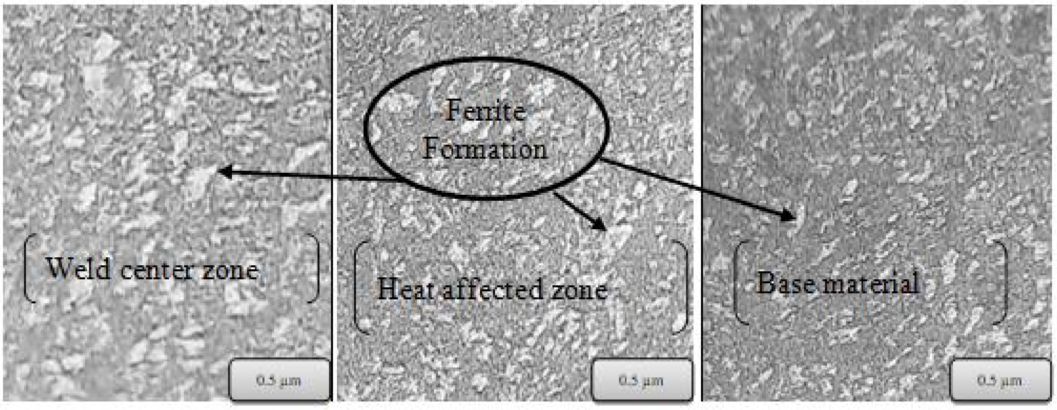


Figure 5- 7 Micro-structural features of welded rail specimen that were cooled at 3°C/s cooling rate

The second test that was conducted for the assessment of the cooling methods of the welded rails was micro-structural.The micro-structural test was conducted by The micro-structure of flash but welds commonly depends on the cooling rate of the rail wedding's. Numerous factors, including temperature, the cooling medium, welding gaps, welding length and preheating time, might influence the cooling rate. When the weld is cooled slowly the microstructural lamellar will pattern pearlite than ferrite and the grain structure lamellar size decreases when we go away from the weld center gradually. The microstructural test results have indicated that welded rails cooled at 2°C/s exhibits bainite microstructural features on all welding zones uniformly.

6 CHAPTER SIX: CONCLUSION AND RECOMMENDATION

6.1 Conclusion

Finally, the researcher concluded based on the results of the analysis. From the sensitivity analysis power failure is the major failure that can reduce the reliability of the operation; whereas safety incidents particularly level crossing accidents take the next coverage. Within the equipment failures signaling equipment's failures take the next level in the contribution of interruption of the operation. Rolling stock failures and other equipment failures will exhibit less effect in the operation one after the other.

Turnouts are critical section of railway system and leads to high maintenance costs when failure occurs. Failure risk assessment has been conducted in this research work for every potential failure mode. Detail investigation of different failures on turnouts has been conducted that allows identifying the most critical failures. A root cause analysis exercised by implementing a fish-bone diagram to identify the potential causes for turnout damages. Increasing the number of tests of inspection or the inspection interval will minimize the mean time to failure. An approach called FMECA has been introduced in this study that helps to classify critical failures. Once the critical failures have been identified it will ease the maintenance schedule of the system and the risk of the failures can be controlled.

Different cooling rates on welding of rail specimens are evaluated experimentally aiming for maintenance improvement of the switch rails. To identify and assess the microstructure feature and hardness of rail welding through different cooling mediums three major tests have been employed. Generally, all the nondestructive test results demonstrate that there is a noticeable defect on the welded rail cooled at 6°C/s. Comparatively fewer defects were observed on the welded rail cooled at 3 °C/s, while acceptable defects were manifested on the one cooled at 2°C/s, whereas the one cooled at 2°C/s manifests a large coverage of perlite relatively indicating that the welded specimen cooled more slowly than the other ones.

The results of the hardness test indicated that the one cooled at 6°C/s had more hardness than the other specimen. Even if cooling at 6°C/s gives the material a better hardness, there is a gross welding defect in it. Better welding quality can be achieved with fewer defects by cooling the welding of the rail at 3°C/s, whereas at 2°C/s cooled rails have a better welding quality compared to that of a cooled at 3°C/s specimen. As a conclusion, cooling of rail welding's at 2°C/s cooling rate will give the material good microstructural feature and better weld quality relatively. Preheating and post-heating are basic elements of welding process since they can determine the cooling rate consecutively.The minimum cooling rate can be achieved through both preheating and post-heating process and the suggested values are 250 - 450° C/s. The quality of the maintenance of switches and crossings is dependable on the inspection interval and the quality of the maintenance methods. Mean time to failure results can be an input for strategic track maintenance planing.

The quality of the welding on switch rails and crossings can be assured by:-

- Manipulating effective analysis of the weld.
- Conducting visual surface crack identification and ultrasonic crack detection at an optimum inspection interval.
- Conducting both destructive and None-destructive fracture tests.
- Controlling the cooling rate.

Based on the results achieved, the researcher recommend a controlled cooling rate for welding quality improvement and maintenance efficiency increment.

The maintenance efficiency of switches and crossings can be controlled by an effective maintenance procedures like welding, grinding, and lining procedures. The proper welding procedure can sustain the quality of repair maintenance.

6.2 Recommendation for further study

Based on the output results of this research work the following recommendation for further study are suggested:-

- Adapting different failure analysis techniques and considering different scenarios will be better for a better output.
- Considering seasonal changes for degradation of railway track helps also to find out a refined results.
- An experimental investigation on the wear rate of the damaged welded rails will magnify the output results of the quality of the rail.
- It will be better if the maintenance system integrates the cost of maintenance labor and spare part to the decision-making process.

Finally, the researcher would like to recommend that the maintenance center should give a high attention to the identified equipment failures which are categorized according to their level of sensitivity. They can improve their trend of maintenance by increasing the level of preventive maintenance and minimize the level of corrective maintenance by planning according to the criticality of the failure modes. Some spares which are not compatible to the system might fail frequently so that preparing genuine and compatible spare parts and improving the rectification techniques of crossings will dramatically improve the maintenance efficiency. This research work can be an input for Addis Ababa Light Rail Transit and any concerned body for the purpose of increasing their maintenance efficiency.

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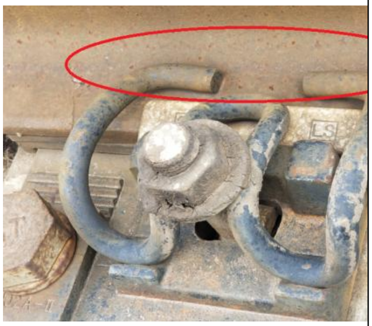
Appendix

Table A-1:- Failures found on crossings of EW and NS lines of AALRT

S/No	EW/NS Left Track/Right Track	Detection area/DK/ Mileage/ Turnout serial number	Track component /device/Track Item	Type of Fault/Failure Modes	Description about maintenance procedure
1	EW 14-EW21	In indicated bridge section	Top Surface layer of bridge	Silt, mud, and waste closed the down pipe top surface of opening  	Clean the track and avoid unwanted obstacles from the top layer of the bridge

2	EW14-EW15(In both left and right track)	11+350-11+450	Rubber	Some of under rail rubbers are leave their right place and some are also in the wrong position 	Maintain the track and Place the rubber in the proper place and change the damaged one by a new one
3	EW14-EW15(In right track (ON right rail)	10+223	Outer curve rail	In the near future it is expected this rail to be damaged (wear). 	Need continuous treatment (improve track gauge, level and versine in this section)
4	EW15-EW16(In left track)	10+073	Fastener	Wrong placement of spring rod	Shift the spring rod to the right place and change the gauge block

					by new one
5	EW15-EW16(In left track)	9+730 and around this dk	Gauge block	The gauge block already breaks and in next photo the gauge block not existed  	So you have to be change this damaged gauge block by new one and insert gauge block in the empty place one
6	EW15-EW16(In left and right track)	Between the two station	track	Alignment and high low problem is available on the track. 	Check and maintain the high low problem and the track alignment
7				spring rod is stretched or	Change the

	EW15-EW16(In left track)	9+650	Fastener	its performance is decreased or it is existed place is wrong 	spring rod or correct the arrangement of gauge block and spring rod
8	EW16 turnout	NO-11608,11604	Turnout	Turnout curve switch rail and its side stock rail have been wear    	If it is possible it should be welded immediately otherwise change the switch rail And crosscheck the spacer condition

					
10	EW16 turnout	All the four turnouts	turnout	Unwanted waste(dirt) under the switch rail and old grease are not cleaned  	Clean the old grease from turnout slide plate and avoid unwanted stock wastes under the switch rail
11	In left track in left rail	8+023	Fastener	Broken spring rod 	Change the broken spring rod by new one
12	In right track in left rail inside the gauge	7+829	Gauge block	Damaged gauge block	Change the damaged gauge block by new one

					
13	In right track in right rail	7+813	bolt	Rail pad bolt not tighten 	Tight the rail pad bolt
14	In right track in right rail	7+640	Short sleeper	The filled glue is not adequate enough 	Need additional glue on this short sleeper
15	EW20	ldeta station	Station	Cleaned waste stocked on the side of station 	Clean and avoid safely the waste from the station
16	Up direction (EW21-	5+862	Fence	Fence accessory damage	One base and one top connector

	EW22)				only required for this fence maintenance (close the fence timely)
17	Up direction (EW21-EW22)	5+590	Fence	Fence accessory damage (absence of normal connector) 	One normal connector only required for this fence maintenance (close the fence timely)
18	EW22	Torhailoch station	Station	Dust and cleaned waste is damped on the track due to this the ballast on most station not well so need treatment 	Create awareness for the person who clean the station
19	EW22	Torhailoch station (at the end of the track)	Hydraulic buffer	The oil tank not have adequate oil in the tank 	Fill the tank with its own oil