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Analysis of Track Geometry Quality Index for Addis Ababa Light Rail Transit

A Thesis Submitted to School of Graduate Studies (**African Railway Center of Excellence)** in Partial Fulfillment of the Requirements for the Degree of Master of Science in Railway Engineering (Civil Infrastructure).

By: Kalkidan Sleshi

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Addis Ababa, Ethiopia

The undersigned have examined the thesis entitled **"Analysis of Track Geometry Quality Index for Addis Ababa Light Rail Transit"** presented by Kalkidan Sleshi Mulu, a candidate for the degree of Master of Science and here by certify that it is worthy of acceptance.

Dr.-Ing.Henok Fikrie ________________ ________________
Advisor Signature Date

Mr.Ayele Tesema ________________ ________________
Co-Advisor Signature Date

Mr. Zewdie Moges ________________ ________________
Internal Examiner Signature Date

Dr.Abrham Gebre ________________ ________________
External Examiner Signature Date

Dr.Abrham Gebre ________________ ________________
Chairperson Signature Date

Dr.Ermias Tesfaye ________________ ________________
AAiT PG program Associate Director Signature Date

April, 2022
Addis Ababa, Ethiopia

DECLARATION

I declared that this thesis titled; **Analysis of Track Geometry Quality Index for Addis Ababa Light Rail Transit**, is my original work and it has not been presented before for any other institute and I will not present it to any other university for similar or any other degree award. Where material has been used from other sources it has been properly acknowledged

Kalkidan Sleshi	____________________	_____________________
Student	Signature	Date

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ABSTRACT

The use and need of railway transportation system is increasing due to different reasons; it uses less energy, environmental friendly, high speed and huge capacity. The increment of axle loads leads to the design of high quality track structure materials in order to enhance the life span of the line. Even though, the track structure is designed for a longer design period, its performance is reduced from time to time. For this reason the status of the structure should be assessed periodically. The aim of this research is to analyze the track geometry quality index of Addis Ababa Light Rail Transit (AALRT).In order to conduct this research deterministic statistical method was used. The track quality index model was developed using multiple linear regression analysis. In this method the average track irregularities of cross level, alignment, twist and gauge parameters were used as an independent variable whereas the track quality index was used as a dependent variable or response. The result showed that most of the common track irregularities in AALRT were cross level and gauge irregularities which cover 60 % and 32 % of the total irregularity percentage respectively. The research found that the maximum value of track quality index is 9.51 mm which was 63.4 % of the threshold limit (15mm). The rate of change of track quality indices were calculated for twelve segments. The maximum rate of change of track quality indices (track deterioration rates) was 7.54 mm/yr which was found in curves with embankment (ballasted track). Finally, the adequacy of the developed track quality index model was checked based on the assumptions of multiple linear regression and also it is validated using variance inflation factor (VIF).The VIF values of the four independent variables; i.e., cross level, alignment, twist and gauge irregularities are 1.12, 1.11, 1.03 and 1.08 respectively were less than 5. As a result, the model is valid and can be used in the future to show the status of the track and manage track maintenance activities.

Keywords: *Track Quality Index, Maintenance, Statistical Model, Deterministic Method.*

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ACRONYMS

AALRT	Addis Ababa Light Rail Transit
AI	Artificial Intelligence
ANN	Artificial Neural Networks
ANFIS	Adaptive Neuro-Fuzzy Inference Systems
DSS	Decision Support Systems
ERC	Ethiopian Railway Corporation
MLR	Multiple Linear Regression
TQI	Track Quality Index

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CHAPTER ONE

1 INTRODUCTION

1.1 Background

Recently, the railway transportation system has become vital in the development of the national economy. The increment of axle loads leads to the design of high quality track structure materials in order to enhance the life span of the line. Even though, the track structure is designed for longer design period its performance is reduced from time to time.

Many African countries have planned to integrate with railway transportation system in the near future. Our country, Ethiopia, has also planned to build new railway routes in different directions. In addition to the national program Ethiopia has a light rail way transit in the capital city Addis Ababa.

The track quality is not continued through the design life of the railway line. During the operation period, the railway infrastructure needs maintenance in order to give good service. For the determination of maintenance strategy, it is important to predict the track deterioration. In order to achieve the required track quality level, the track geometry and components should be monitored and afterwards the track components need maintenance and renewal when they deteriorate [1].

Track geometry degradation is usually expressed by five track geometry irregularities: the longitudinal levelling irregularities, the horizontal alignment irregularities, the cant irregularities, the gauge deviations and the track twist. Many railway professionals tend to sum up all these irregularities into a track geometry quality index which is typically function of the standard deviations of each irregularity Previously many experimental studies have validated a linear relationship between the standard deviation of longitudinal leveling defects and accumulated tonnage [2 & 3].

Track quality index is one of the most important parameters used to know the status of the track and as a result to select the cost effective and efficient maintenance strategy based on the given information. AALRT has been in service since 2015 and it needs determination of the track quality index to know the status of the track as well as to identify the maintenance technique and schedule. Therefore, this research was conducted to analyze the track geometry quality index for Addis Ababa Light Rail Transit.

1.2 Statement of the Problem

Once the railway infrastructure is built, it uses for several design period by the help of maintenance. Since the maintenance operation is difficult as well as costly, it should be cost effective and efficient. The average annual maintenance and renewal expenditures per 1 km of tracks revolve around €50,000 for West-European networks [1]. Even though the maintenance cost data of Addis Ababa Light Rail Transit was not prepared properly due to lack of information, the global experience shows that the maintenance cost covers significant portion of railway industry budget. Therefore, in order to have cost effective and efficient maintenance strategy the condition of the track should be known. For this purpose track quality index plays a great role and this study mainly focused on the analysis of track geometry quality index of AALRT.

1.3 Objective of the Study

1.3.1 General Objective

The general objective of the study is to analyze the track geometry quality index of Addis Ababa Light Rail Transit (AALRT).

1.3.2 Specific Objectives

- ✓ To identify the common track irregularities of AALRT.
- ✓ To determine the track quality index.
- ✓ To determine track deterioration rate of AALRT.
- ✓ To develop the track quality index model for AALRT.

1.4 Scope and Limitation of the Study

The study analyzes the track geometry quality index based on the four track geometry; cross level, alignment, gauge and twist irregularities data collected for two consecutive months. Since track irregularity has two major components; track structure and track geometry irregularities, the scope of this study was limited to track geometry irregularities. In addition, the study was conducted in the line from kality to St.George (Menelik II square).Due to unavailability of longitudinal level defect data the study did not considered longitudinal level irregularity.

CHAPTER TWO

2 REVIEW OF RELATED LITERATURE

2.1 Introduction

Track geometry degradation is quantified by five track defects: the longitudinal levelling defects, the horizontal alignment defects, the cant defects, the gauge deviations and the track twist [2]. Andrade and Teixeira [3] have presented rail-track geometry degradation and uncertainty related to the phenomenon at the design phase and properly quantify the uncertainty related to the rail-track geometry degradation on recently upgraded lines. Statistical model of railway track geometry degradation using hierarchical Bayesian models was developed by Andrade and Teixeira [4].The study consider standard deviations of longitudinal level irregularities and of horizontal alignment irregularities rather than track quality indexes in the modeling process.

Globally, rail transport authorities have been facing a significant challenge when predicting rail infrastructure maintenance work [5]. Soleimanmeigouni *et al*. reviewed and classified the available models for track geometry degradation models [6]. Similarly, a comprehensive discussion of existing research and a comparison of different models of degradation of rail tracks is also presented by Elkhoury *et al*. [7].

Sadeghi and Askarinejad [8] used Statistical and Engineering methods to improve current track deterioration modeling techniques. The engineering approach uses theory and testing of track structures whereas the statistical approach uses Correlation analysis, analysis of variance and regression analysis. Finally the study uses the combined effect of the two approaches.

Vale and Lurdes presented a stochastic model for characterizing the geometrical track degradation process over time [9]. Falamarzi *et al*. reviewed different models for rail track degradation prediction including mechanistic, statistical and Artificial Intelligence (AI) models [10].

Guler *et al.* modelled the railway deterioration state using multivariate regression by considering multiple parameters which are traffic loads, velocity, curvature (1/R), gradient, cant, sleeper-type, rail-type, rail length, falling rock, land-slide, snow and flood [11].

Liu *et al.* developed short-range prediction model which applies the calculus thinking and method to estimate track defects over small track lengths on a single-day basis using track waveform data generated by track geometry car for the section of Beijing-Shanghai Railway Line (Jing-Hu Line) [12]. The study has presented the measured and estimated track surface difference as well as the developed linear regression function as shown in the following Figure 2.1.

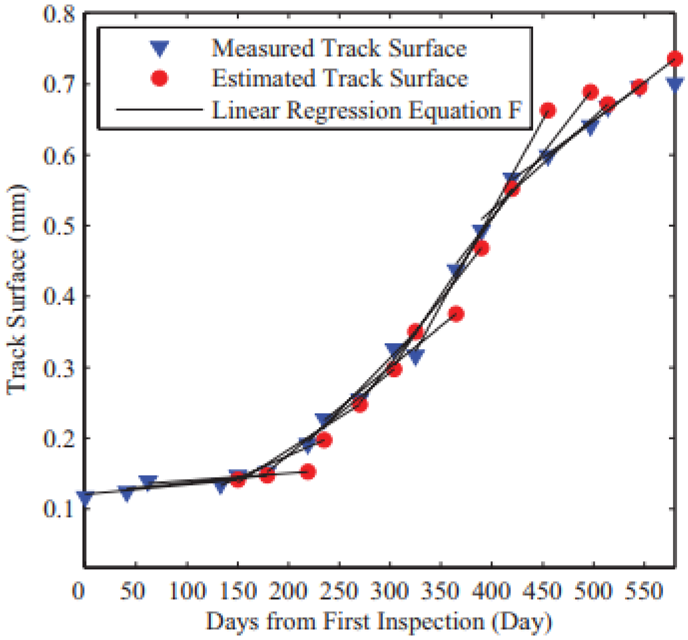


Figure 2-1 Schematic diagram of track surface SRPM for unit track section [12].

Track inspection refers to routine inspection work for track equipment in which track equipment is inspected during train outage time at dayshift. Initially the track inspection process was done by manual process or simply by visual inspection. Gradually, there are a number of automated inspection and monitoring systems developed over the years such as internal rail inspection, track geometry inspection and gage restraint measurement systems (GRMS) [20].

Table 2-1 Sample Researches on Track Degradation Model

Researcher and year	**Title**	**Methodology**	**Degradation model**
Andrade, A.R and Teixeira, P.F. (2011).[3]	Uncertainty in rail-track geometry degradation: Lisbon–Oporto line case study.	Statistical	Linear regression
Andrade, A.R and Teixeira, P.F. (2012).[2]	A Bayesian model to assess rail track geometry degradation through its life-cycle.	Statistical	Linear regression
Andrade, A.R and Teixeira, P.F. (2015).[4]	Statistical modeling of railway track geometry degradation using Hierarchical Bayesian models	Statistical	Hierarchical Bayesian
Sadeghi, J A.and Askarinejad, H. (2010).[8]	Development of improved railway track degradation models.	Statistical and Engineering Approaches	Correlation analysis
Vale, C. and Lurdes, S.M. (2013).[9]	Stochastic model for the geometrical rail track degradation process	Statistical Stochastic Model	Dagum model
Quiroga, L.M. and Schnieder, E. [13]	Monte Carlo simulation of railway track geometry deterioration and restoration.	Statistical	Exponential function
Chang, H., *et al.* (2011).[14]	Multi-stage linear prediction model for the irregularity of the longitudinal level over unit railway sections.	Statistical	Multi-stage linear regression

Karimpour, M., *et al.* (2018).[5]	Fuzzy Approach in Rail Track Degradation Prediction.	Artificial Intelligence	Fuzzy Approach
Guler, H.(2016).[1]	Optimisation of railway track maintenance and renewal works by genetic algorithms.	Artificial Intelligence	Genetic algorithms.
Yousefikia, M., *et al.* (2014).[15]	Modeling degradation of tracks for maintenance planning on a tram line.	Statistical	Markov chain
Iyengar, R.N.& Jaiswal,O.R.(1995).[16]	Random field modeling of railway track irregularities.	Statistical	Random field
Meier-Hirmer, C., *et al.* (2006).[17]	A decision support system for track maintenance.	Statistical	Gamma process

2.2 Track irregularities

Deviations from the design track geometry are called track irregularities [18, 19].Track defects are classified in to two major groups [20].

A. Track structure defects: are defects occurring in one of the structural part of the track.

B. Track geometry defects: include deviation from the ideal gage measure, deviation of curved/tangent track and misalignment during re-laying of tracks etc.

2.2.1 Track Structure Defects

Defects on both super structure and sub structure part of the railway track are called track structure defects. These include defects in the rails, ballast structure, defects in the cross-ties, tie-plates, fasteners, bolts and rail-joints etc.

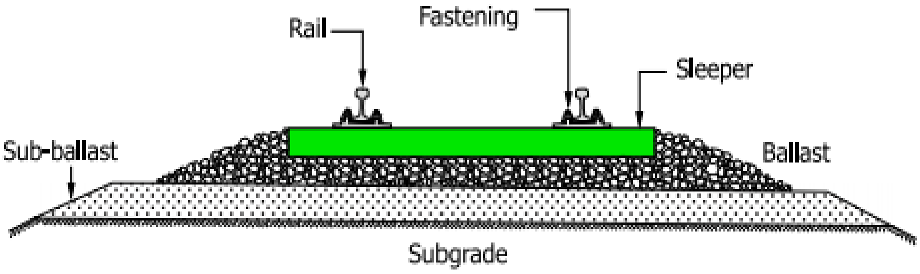


Figure 2-2 Track structure [21].

2.2.1.1 Rail Defects

Rail defects develop in any type of rail, or rail welds, as a result of several conditions. These conditions normally will originate from the rail manufacturing process, cyclical loading and impact from rolling stock, rail wear and plastic flow [22].

There are several factors that can influence the expected duration of rail service; chemical composition of the rail, track maintenance programs, speed, and tonnage. All of these factor into the development of vertical and lateral head wear, plastic flow or deformation of the rail head and development of rail defects [22].

Track maintenance programs: contains any track maintenance procedure that can confirm the track can maintain adequate support to decrease the amount of rail flexing, provide proper friction control and provide rail profile maintenance that will considerably influence the rail service life.

Wear: Lateral wear occurs predominantly on the gauge face when the rail is placed on the high side of a curve due to the occurrence of high-wheel flange force. Vertical wear arises on the rail head running surface from the wheel/rail interaction through cyclical loading and rail grinding patterns.

Plastic flow: Plastic flow or mechanical deformation of the rail head can take place on high or low rail, and is normally associated in curves that carry higher axle load operations. Plastic flow is a result of wheel/rail contact stress that is exceeding the material strength of the rail steel.

Internal rail defects normally require certain forms of rail stresses to initiate progression and develop to a detectable size defect [22].The terminology that can be used to describe the planes of stresses in rail and rail locations are shown in Figures 2.3 & 2.4.

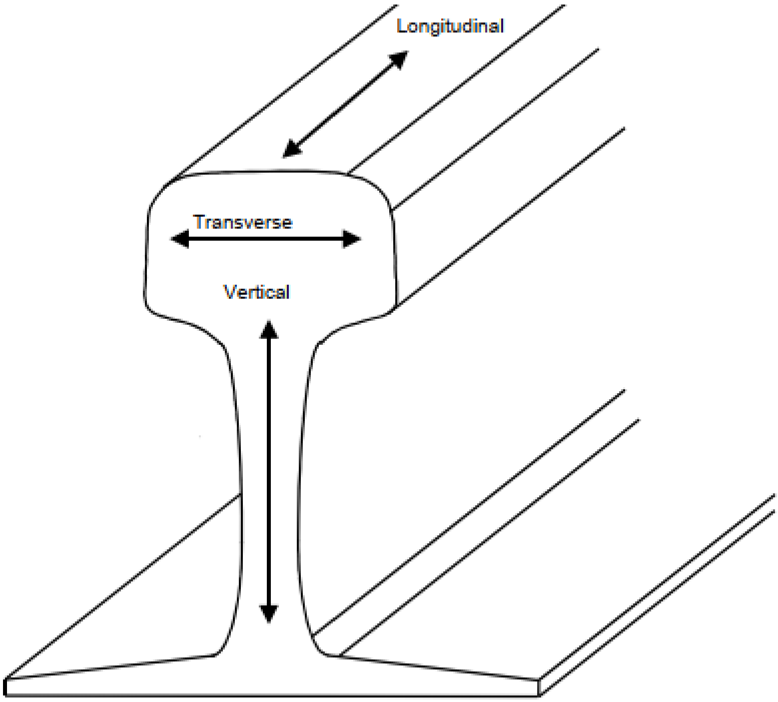


Figure 2-3 Terminology used for directions in rails [23].

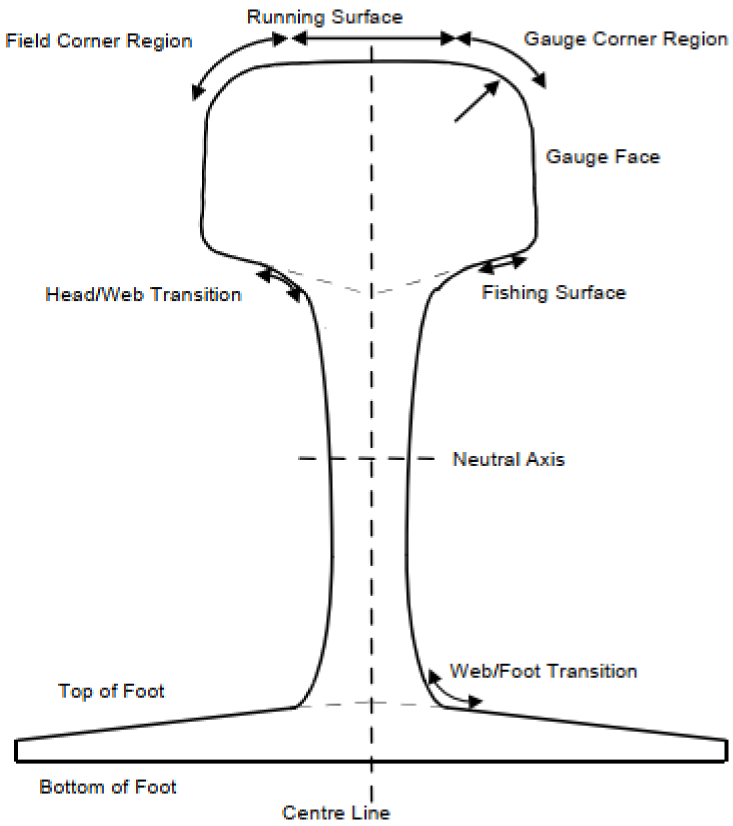


Figure 2-4 Terminology used for rail locations [23].

Irregularity development identification is determined by the type of irregularity, origin, and direction of development in relation to the planes of the rail section. These are identified as transverse, vertical and horizontal planes of development. The irregularities that develop in a transverse plane in relationship to the rail section are typically internal in origin and are not clearly identified until the defect development penetrates the rail head [22].

Internal transverse defect size can only be identified visibly by breaking the cross-section of the rail in a press. After the rail is broken, a transverse defect is measured against the cross-sectional area of the rail head. If half of the rail head cross-section shows signs of defective growth, the defect is called a 50-percent fracture. The three types of rail fracture growth are shown in Figure 2.5.

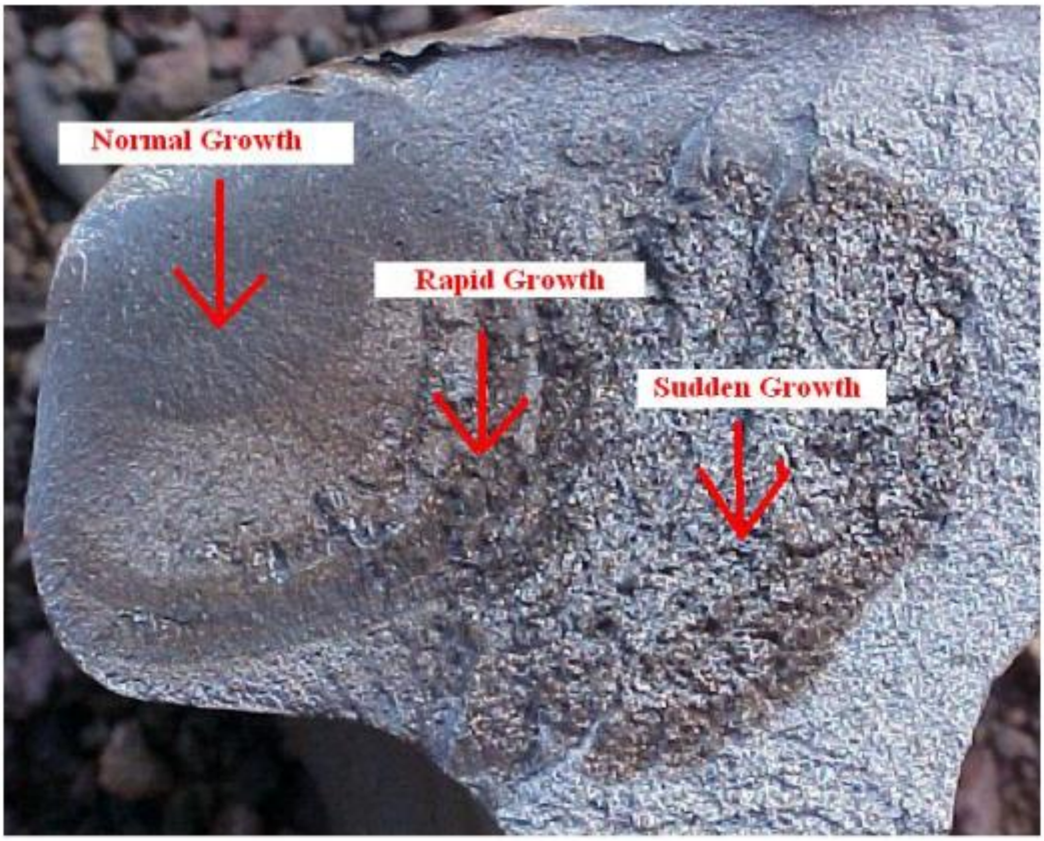


Figure 2-5 Detail Fracture Showing Normal, Rapid, and Sudden Growth Patterns [22].

Multiple stage ruptures is defined as development of defects in an oblique, angular, or longitudinal direction in relationship to the rail section can also produce identifiable stages of development.

American Railway Engineering and Maintenance-of-Way Association (AREMA 2010) manual for railway engineering classify the rail defect in seven groups [24] (Figures are available in Appendix A).

a. Transverse Defects in the Rail Head
    - Detail Fracture (from Shelling, Head check or other surface defect)
    - transverse fissure
    - compound fissure
    - engine burn fracture and
    - welded burn fracture
b. Defective welds
    - Plant Welds (Head)
    - Plant Welds (Web)

  - Field Welds (Head)
  - Field Welds (Web)

c. Longitudinal Defects in the Rail Head
  - Horizontal split head
  - Vertical split head

d. Web Defects
  - Head and web separation
  - Split web

e. Piped rail

f. Web Defects in Joint Area
  - Bolt hole crack
  - Head and web separation

2.2.1.2 Sleeper Defects

Railway sleepers are the main structural elements of railway track. The causes of sleeper failures are classified in three major groups [25].

a. Deteriorations during production and coupling
  - Longitudinal crack (Figure 2.6)
  - Muscle crack
  - Crack in head zone
  - Decayed concrete sleeper
  - Concrete sleeper tear
  - Filled plug

b. Defects during transportation & installation
  - Chipped sleepers
  - Bending cracks
  - Cutting cracks
  - Sleeper instability in fastening point

c. Defects during operation and maintenance
  - Bending cracks
  - Sleeper breakage due to derailments (Figure 2.7)
  - Cutting cracks

Figure 2-6 Longitudinal crack in Concrete Sleeper [25].

Figure 2-7 Sleeper breakage due to derailment [25].

Dyk et al. [26] surveyed and ranked the most common causes of concrete sleeper failures based on the results obtained from North America and worldwide studies (Figure 2.8). The study identified that the most critical cause of failure in concrete sleeper is rail-seat degradation in the North America and the installation or tamping damage globally. However, these failure modes can vary from place to place as geometry and operation practices are different [27].

The most critical concrete crosstie and fastening system problems are ranked from 1 to 8, with 8 being the most critical [26, 27].

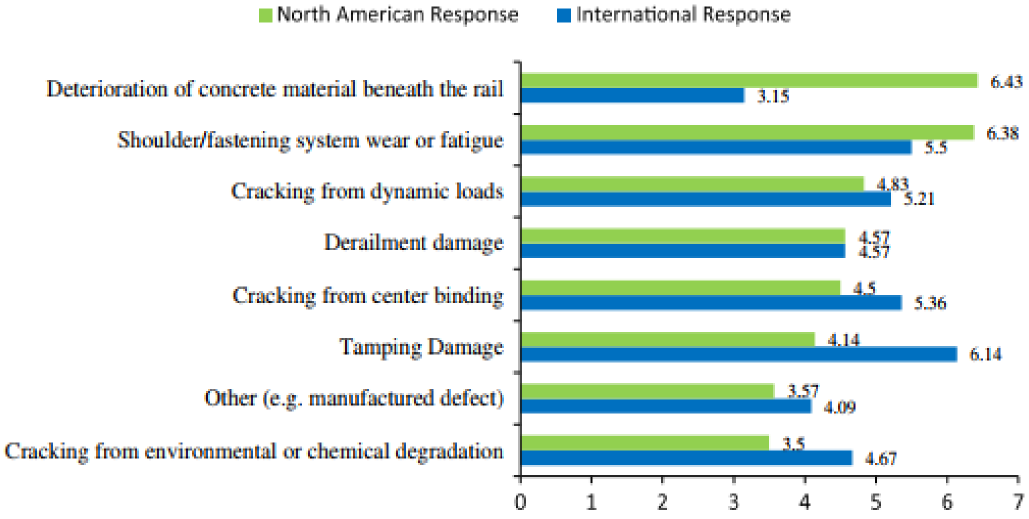


Figure 2-8 The most critical concrete crosstie and fastening system problems [26, 27].

2.2.1.3 Fastener Defects

The railway track fasteners play a critical role in fixing the track on the ballast bed. The defects of the fasteners are resulted from the elastic bar fracture of the fastener or missing of the main fastener components [28].

Figure 2-9 Broken Fastener [28].

Figure 2-10 Missing Fastener [28].

2.2.1.4 Ballast Defects

Ballast defects that are not maintained early can lead to future defects. According to FRA study it is important for track inspectors to be aware that ballast defects and conditions can cause track components to degrade rapidly and compromise the stability of the track structure, and that inspectors are trained to identify and repair ballast defects [21].

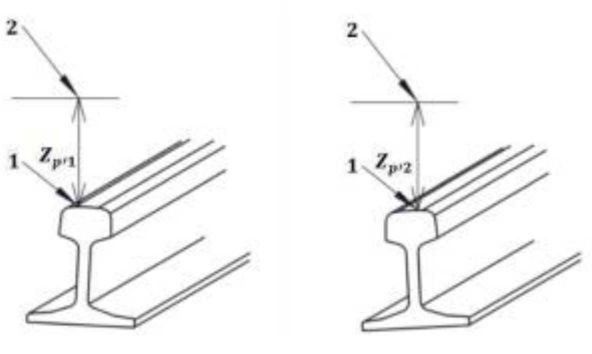
The main ballast failures include [29]

- Ballast Settlement
- Ballast Fouling
- Abrasion and breakdown of ballast

Figure 2-11 Ballast Fouling [30].

2.2.2 Track Geometry Defects

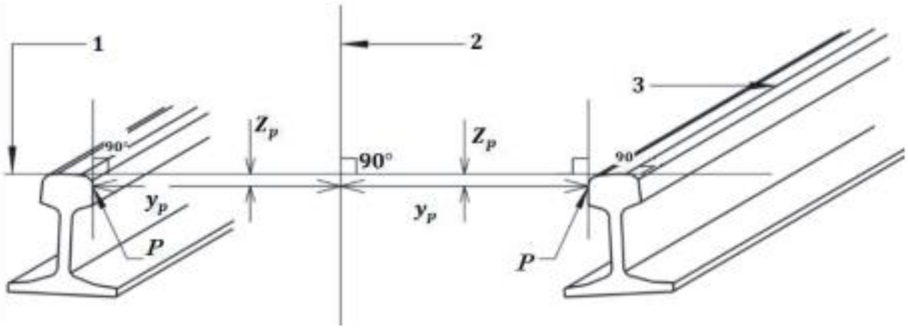
According to EN 13848-1 [31] the track irregularities are defined below.
• Longitudinal level irregularities are the track irregularities in the vertical direction and defined as the mean value of both rails' vertical deviations from their nominal vertical position to their running Tables.



1-running Table and 2- reference line

Figure 2-12 Longitudinal Level [31]

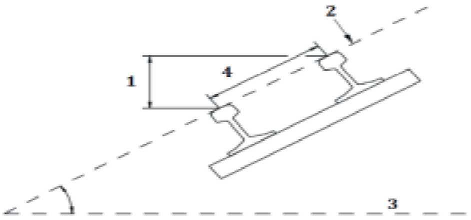
- Alignment irregularities are the track irregularities in the lateral direction, defined as the mean value of both rails’ lateral deviations from the nominal track center.



1-running Table and 2- reference line 3- center line of running Table

Figure 2-13 Alignment [31]

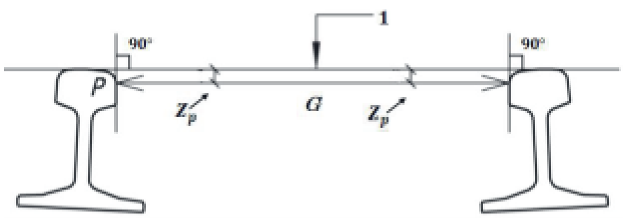
- Cant irregularities (called cross level irregularities in EN 13848) are the unintentional rotation of the track around its longitudinal axis, defined as the difference in height between both rails. In curves, the cant irregularities are the deviations from the nominal cant.



1-cant 2-running surface 3-horizontal reference plane 4-hypotenuse

Figure 2-14 Cross Level [31]

- Track gauge is the smallest distance between the inside of the two rails, measured within 14 mm below the running surface. The deviation from the nominal track gauge is the track gauge irregularity.



1-running surface

Figure 2-15 Gauge [31]

- Twist is the algebraic difference between two cant values measured at positions located at a specified distance from each other.

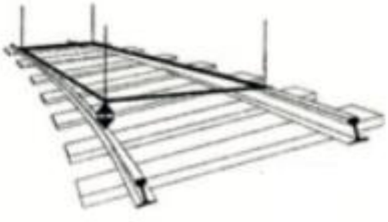


Figure 2-16 Twist [32]

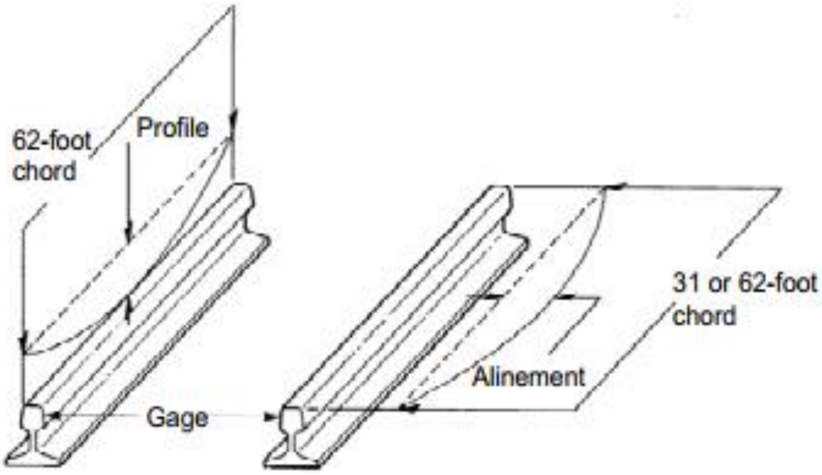


Figure 2-17 Basic track geometry elements [28].

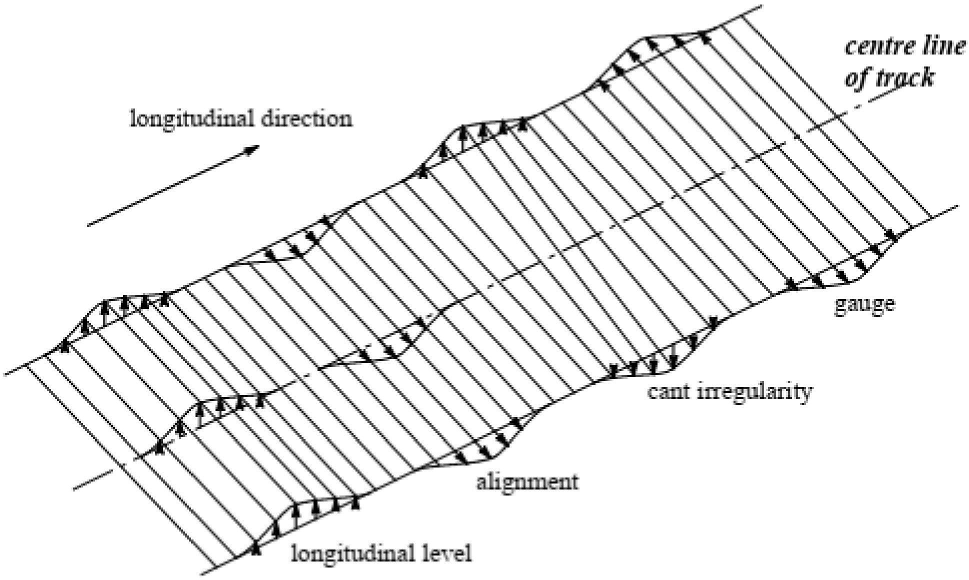


Figure 2-18 Basic track geometry elements [28, 31].

2.3 Track Quality Index

Track Quality Index (TQI) is the parameter that objectively quantify the condition of the track. It has been developed to be more flexible in the application of degradation of parameters evaluation and to become more efficient and optimal to indication or description of various behaviors correctly [33]. Currently, different countries have their own methods to determine the condition of the track as well as to predict the future probability. Some of the common indices are summarized in Table 2.2 from different literatures. [34, 35, 36, 37].

Table 2-2 Track Quality Indices

Index	Formula	Description	Country
Track Quality Index (TQI)	$TQI = \sum_{i=1}^{n} \sigma_i$ $\sigma_i = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(x_{ij}^2 - \bar{x}_i^2\right)}$ Where $\bar{x}_i = \sum_{j=1}^{n}\frac{x_{ij}}{n}$	σ_i =standard deviation $\bar{x}$ =mean	China
Track Quality Index (TQI)	$TQI = \left[\frac{L_s}{L_0} - 1\right] \times 10^6$ $L_{s=\sqrt{\Delta x^2+\Delta y^2}}$	L_s = traced length of space curve L_0 =theoretical length of section Δx = Sampling space Δy = difference of two consecutive measures	USA
Track Quality Index (TQI)	$TQI_i = 1000 - C(\sigma_i^2)$ $TQI = \frac{\sum_{i=1}^{n} TQI_i}{n}$	C = 700 for mainline track	Canada
Track Geometry Index (TGI)	$TGI = \frac{2UI + TI + 6AI + GI}{10}$ Where $UI, TI, AI, GI = 100 \times e^{-(SD_m - SD_N)/(SD_u - SD_N)}$	SD_m=SD of measured parameter SD_N = SD of new track SD_u = SD of track needing urgent maintenance $UI, TI, AI, GI = \mathit{Unevenness, Twist, Alignment\ and\ gauge\ irregularities}$	India
Q index	$Q = 150 - 100\left[\frac{\sigma H}{\sigma H_{lim}} + 2 \times \frac{\sigma s}{\sigma s_{lim}}\right]/3$	$\sigma H = \mathit{Average\ of\ left\ \&\ right\ SDs}$ σs=Average of gauge, cross level & alignment SDs σH_{lim}=Allowable value of σH	Sweden

Index	Formula	Description	Country
		σs_{lim} = Allowable value of σs	
J index	$J = \frac{S_Z + S_Y + S_W + 0.5S_e}{3.5}$	$S_Z = SD\ of\ track\ gauge$ $S_Y = SD\ of\ horizontal\ irregularities$ $S_W = SD\ of\ track\ twist$ $S_e = SD\ of\ vertical\ irregularities$	Poland
Track Roughness Index (R)	$R^{2=\sum_{i=1}^{n}\frac{d_i^2}{n}}$	$d_i = Amount\ of\ deviation\ measured$ n = number of measurements	USA
SD index	$\sigma_i = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(x_{ij}^2 - \bar{x}_i^2\right)}$ Where $\bar{x}_i = \sum_{j=1}^{n}\frac{x_{ij}}{n}$	σ_i =standard deviation $\bar{x}$ =mean	UK, Australia
Q index	$N = 10 \times 0.675^{\frac{\sigma_i}{\sigma_i^{80}}}$	σ_i =standard deviation σ_i^{80}= 80th percentile of standard deviation	Netherlands

2.4 Tolerance limit

The tolerance limit values for different measurement parameters of track and turnout sections are specified in the maintenance regulations of line facilities version A manual of Addis Ababa Light Rail Transit (AALRT) shown in the following Tables. The regulations of the tolerance management values of static geometric dimension of track and turnout sections are for speed V≤80km/h [38].

Table 2-3 The tolerance management values of static geometric dimension of track [38].

Items		Acceptance of operation (mm)		Regular maintenance (mm)		Urgent repair (mm)	
		Main track and auxiliary track	Yard track	Main track and auxiliary track	Yard track	Main track and auxiliary track	Yard track
Gauge		+6 -2	+6 -2	+7 -4	+9 -4	+9 -4	+10 -4
Level		4	5	6	8	10	11
High-low		4	5	6	8	10	11
Direction		4	5	6	8	10	11
Twist of track (twisted)	Easement curve	4	5	5	7	7	8
	Straight line and circular curve	4	5	6	8	9	10

Note: gauge deviation does not include the widening value of gauge set by rules, but the maximum gauge (including widening value and deviation) shall not exceed 1456mm; alignment deviation and high-low deviation are the maximum vector value measured by 10m string; twist of track deviation does not include the torsion caused by curve super elevation downslope, the girth in inspecting twist of track is 6.25m long, but there is no twist of track that exceeds the ones listed in Table within the range of extended 18m; testing track is handled as main track [33].

Table 2-4 The tolerance management values of static geometric dimension of turnout [38].

Items		Acceptance of operation (mm)		Regular maintenance (mm)		Urgent repair (mm)	
		Main track and auxiliary track	Yard track	Main track and auxiliary track	Yard track	Main track and auxiliary track	Yard track
Gauge		+3 -2	+3 -2	+5 -3	+5 -3	+6 -3	+6 -3
Level		4	6	6	8	9	10
High-low		4	6	6	8	9	10
Direction	Straight line	4	6	6	8	9	10
	Offset	2	2	3	3	4	4
Twist of track (twisted)		4	5	6	8	9	10

Note: ① Gauge at the tip of switch rail, acceptance standard of operation is ±1mm.

② Offset deviation is the difference between site offset and calculated offset.

③ Limiting value of lead curve lower strand being higher than the upper strand: acceptance of operation is 0, regular maintenance is 2mm and urgent repair is 3mm.

④ No twist of track that exceeds the ones listed in Table.

⑤ Testing track is handled as main track [38].

The threshold value for track quality index is the summation of the standard deviation of each track geometry parameters. The management or limit value of TQI for Chinese railway is presented in Table 2.5 [39].

Table 2-5 Limit Value for TQI

Speed (km/h)	Longitudinal level (mm)	Alignment (mm)	Gauge (mm)	Cross-level (mm)	Twist (mm)	TQI_{lim} (mm)
$v_{max} \leq 160$ km/h	2.5*2	2.2*2	1.6	1.9	2.1	15
160 km/h $< v_{max} \leq$ 200 km/h	1.5*2	1.6*2	1.1	1.3	1.4	10
200 km/h $< v_{max} \leq$ 250 km/h	1.4*2	1*2	0.9	1.1	1.2	8
250 km/h $< v_{max} \leq$ 300 km/h	0.8*2	0.7*2	0.6	0.7	0.7	5

Based on the track quality index maximum limit value the track geometry condition is described in Table 2.6 [39].

Table 2-6 Track Geometry Condition

Condition	Determining standard	Track geometry condition
1	Less than the management value ($TQI \leq TQI_{lim}$)	qualified
2	More than the management value but the excess value ≤10% ($TQI_{lim} < TQI \leq 1.1TQI_{lim}$)	bad
3	More than the management value but the excess value ≤20% ($1.1TQI_{lim} < TQI \leq 1.2TQI_{lim}$)	worse
4	The excess value is more than 20% ($TQI > 1.2TQI_{lim}$)	worst

2.5 Rail track degradation prediction models

According to Falamarzi *et al*. [10] rail track degradation models can be divided into three main categories: statistical models, mechanistic models and AI models.

2.5.1 Mechanistic Model

This model is the oldest model for predicting degradation in railway tracks and can be divided into two categories: conventional mechanistic models and empirical mechanistic models. Conventional mechanistic models can predict track degradation with a small amount of geometrical data. Empirical mechanistic models are a combination of mechanistic and statistical models and because they consider observations and extensive data records, are able to predict the degradation of the entire network rather than a section. Ballast settlement is a significant factor in mechanistic degradation models. The main disadvantage of conventional mechanistic models is their inability to deal with the inherent uncertainty of track degradation behavior. In addition, this type of model is applicable to a limited number of track sections rather than a whole network. In other words, these models cannot be used for rail tracks with the same operational, maintenance and environmental conditions but different behavior in the rate of degradation. However, this limitation can be resolved by applying empirical mechanistic models [10].

2.5.2 Statistical Models

A statistical model is a type of mathematical model which can deal with a large amount of data. To establish a statistical model, sufficient historical data are required. Statistical models can be employed to cope with a large number of descriptive factors that can affect rail track degradation. Statistical models can be classified into three main groups: deterministic models, stochastic models and probabilistic models [10].

2.5.3 Artificial Intelligence (AI) Models

In recent years, AI-based models have become popular, as they overcome the deficiencies of current mechanistic models in the prediction of rail track degradation. AI models involve activities and developments relating to human-like intelligence reproduced by computer applications. AI models can be categorized into different sub-categories, including Artificial Neural Networks (ANNs), Adaptive Neuro-Fuzzy Inference Systems (ANFIS), Decision Support Systems (DSSs) and machine learning models [10].

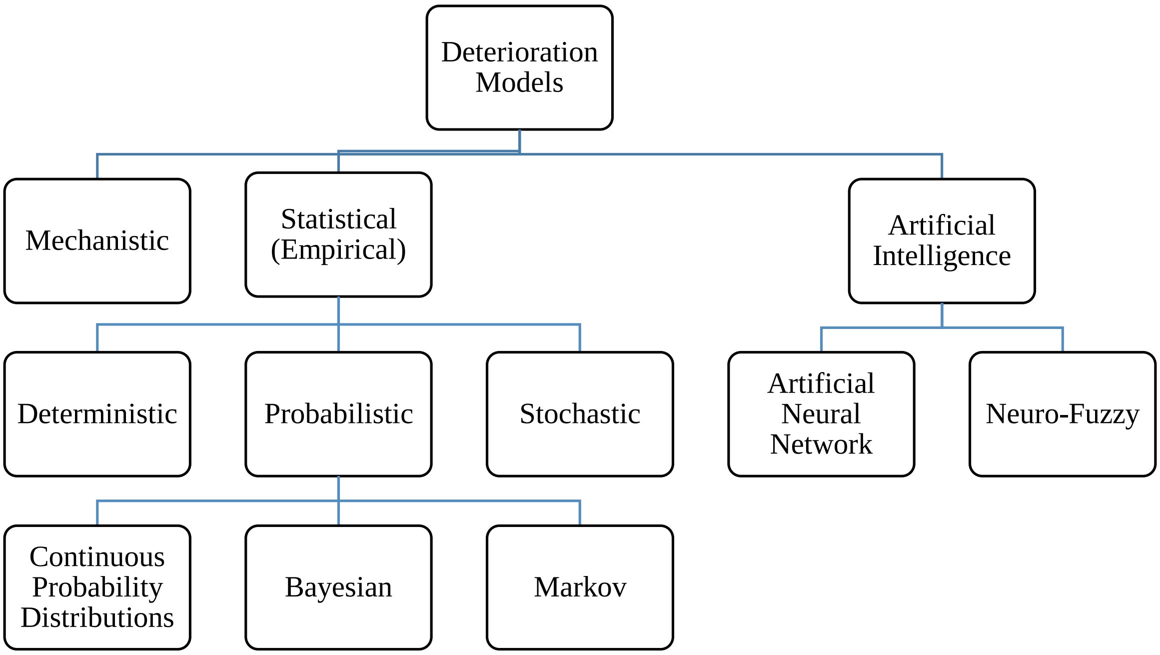


Figure 2-19 Track degradation models [10].

Table 2-7 Comparison of different track deterioration models [7].

Approach		**Variables**	**Strengths**	**Weaknesses**
Mechanistic		• Track settlement, • Track deformation, • Track geometry (e.g. gauge), • Track Quality Index (TQI).	• Based on laboratory experiment data sources, • Clearly address track settlement and degradation, • SuiTable for maintenance of a particular section of rail track.	• Challenging, intensive, time consuming. • Measurement of the affecting variables of rail structure may be difficult or poorly understood. • Materials of rail structure are not homogenous. • Difficulties in applying the model for different sections of rail track.
Statistical (Empirical)	Deterministic	• Traffic volume, • Dynamic axle, • Speed, • Accumulated tonnage (MGT), • Axle loads.	• Work well for large data sets.	• Potential to miss important degradation factors during application, • It does not account for uncertainty (i.e. input parameters and model geometry are not well known).
	Probabilistic	• Speed restrictions or line closure, • Track Quality Index (TQI), • Standard deviation of longitudinal level defects (SDLL) and horizontal alignment defects (SDHA), • Number of cracks	• Reasonable procedure and realistic findings, • Ability to deal with large numbers of datasets to achieve more accurate results.	• Not common due to lack of historical data, • Difficulties in predicting probability of track deterioration, • Bayesian models rely on Markov models especially when high numerical dimensions occur.

Approach		Variables	Strengths	Weaknesses
		missed by USI per year, • Rail breakage.		
	Stochastic	• Time, • Degradation rate of longitudinal level.	• Ability to deal with large numbers of datasets to achieve more accurate results	• No evidence to validate the claim of an exponential deterioration pattern.
Mechanical-empirical		• Track Quality Index (TQI), • Traffic parameters, • Maintenance parameters (EMGT), • Degradation Coefficient • Time.	• Applicable to different track sections (e.g. curves, turnouts, tangents), • Applicable to more precise and less costly future maintenance techniques.	Result in a higher degradation rate of lines in bridges, curve-bridges and turnouts in comparison with other model types
Artificial Intelligence	Artificial Neural Networks (ANNs)	• Number of layers, • Nodes, • Type of the network and functions.	• Calibrating model with an optimization algorithm, • Optimizing parameters of model.	• Presence of many effective factors resulting in more errors, • Validation of membership functions.
	• Neuro-Fuzzy	Fuzzy sets, • Fuzzy membership functions.	• Finding fuzzy rules from numerical data, • Considering human imprecise perception, • Categorizing variables into different categories	• Complexity in abstracting fuzzy rules, • Connections of a proposition may be imprecise, • Difficulty in calibrating model parameters.

2.6 Identified Gaps

There are a number of researches conducted in the area of track irregularities and track quality index using statistical modeling methods in different countries. This paper fills the following identified gaps of the selected studies.

Table 2-8 Identified Gaps

Researcher and year	**Title**	**Methodology**	**Purpose**	**Gap**
Sadeghi, J A. *et al.,* (2010).	Development of improved railway track degradation Models	Statistical and Engineering Approaches	to improve current track deterioration modelling techniques	There is no evaluation of the accuracy of the developed models.
Vale, C., *et al., (2013).*	Stochastic model for the geometrical rail track degradation process in the Portuguese railway Northern Line	Statistical Stochastic Model	To develop geometrical rail track degradation using stochastic model	The analysis does not consider alignment, cross level, gauge and twist (consider only longitudinal level).

3 RESEARCH METHODOLOGY

CHAPTER THREE

3.1 Study Area

The research was conducted in Addis Ababa, the capital city of Ethiopia. The specific task is performed in Addis Ababa Light Rail Transit (AALRT). It was the first light rail and rapid transit in eastern and sub-Saharan Africa [40, 41].

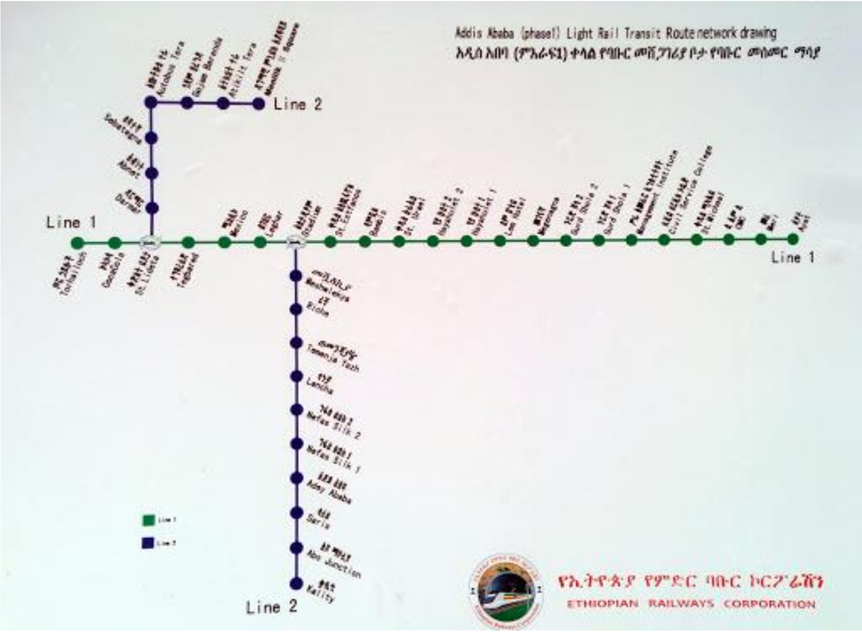


Figure 0-1Map of AALRT [41]

AALRT project has two lines; the east-west line and the north- south line with a total length of 31.048 km. From this 2.662 km is the sharing section for both E-W route and N-S route, which has the greatest traffic flow.

The E-W Line connects the two ends of Torhailoch and Ayat which has a total length of 17.017 km; from which 12.896 km lies on the subgrade section, 3.905 km elevated section, and the rest 0.197 km in the underground section. This line has 22 stations, 6 elevated (including 5 common-track stations), 2 underground and the rest on the ground level. The maximum and minimum interval between stations is 1.26 km and 0.435 km respectively, with an average interval of 0.798 km. There are 41 curved sections in this line (5.53 km or 31.8% of the line) with a maximum radius of curve 3004 m and the minimum radius of curve 154 m [43].

The N-S Line connects the two ends of St. George church and Kaliti which has a total length of 16.693 km; from which 10.075 km lies on the subgrade section, 5.944 km elevated section, and the rest 0.655 km in the underground section. This line has 22 stations, 8 elevated (including 5 common-track stations), 1 underground and the rest on the ground level. The maximum and minimum interval between stations is 1.972km and 0.435km respectively, with an average interval of 0.775 km. There are 46 curved sections in this line (6.589km or 39.8% of the line) with a maximum radius of curve 2004m and the minimum radius of curve 50 m[43].

The LRT network was designed to carry 15,000 passengers per hour per direction (PPHPD) and 115000–153,000 passengers per day (PP/PD). Whereas the closest mass public transport like the Anbessa city buses carry 730,500 passengers per day, was for now only 21% (153,405) of the LRT. This justifies the plan by the ERC to purchase more LRT vehicles and open more routes, to accommodate the high travel demand [44].

The general characteristics of AALRT is summarized in Table 3.1 [20, 43].

Table 0-1 General characteristics of AALRT

Items	Descriptions
Route kms	31.048km
Gauge	1435mm(standard gauge)
Electrified track kms	31.048km
Maximum Running Speed	70kmph
Level crossing numbers	12 (7 EW & 5 NS)
Tunnels length	655 m
Maximum allowable unbalanced transverse acceleration	0.4m/s^2
Train axle load	≤ 11t
Number of Horizontal curves	87 (41 EW & 46 NS)
Number of sleepers per km in straight track	1600
Rail type	50kg/m
Maximum Longitudinal Gradient	5.5%
Maximum cant	120mm
Sleeper spacing	0.6 m on straight track
Sleeper type	Concrete
Rail length	25m
Rail joint type	Bolted & CWR
Number of stations	44
Year of construction completion	2015
Number of main lines	Double Lines
Minimum curve radius	For main line 50m and that of depot is 25m

3.2 Study Design

In order to conduct this research deterministic statistical method has been used.

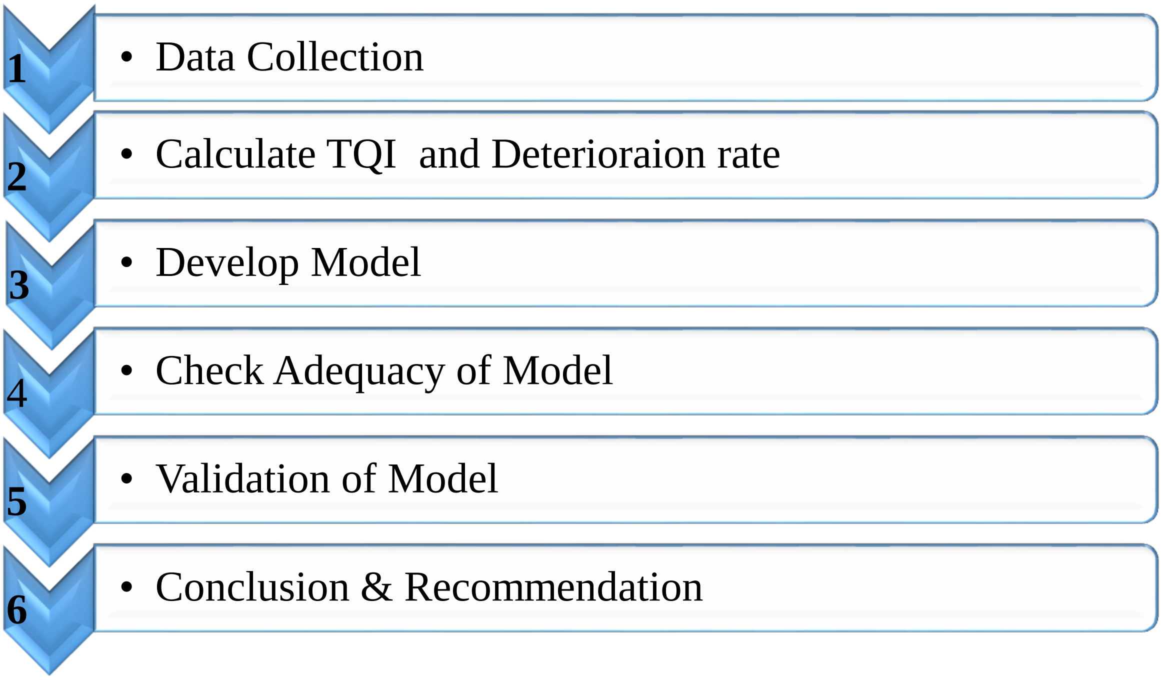


Figure 3-2.Study Design

3.3 Data Collection Process

The data for the purpose of this research was collected through secondary sources. The secondary data is obtained from AALRT office. The AALRT office performs daily, monthly and annual track inspection for the Addis Ababa railway route. For this research monthly track inspection data for alignment, cross level, gauge and twist collected by the AALRT office is used.

3.4 Sampling

For this research simple random probability sampling techniques are used to select the study area. Therefore, the railway lines running from Kaliti to St. George is selected for this study. Totally 13.54 km track section is used for the analysis. In order to get representative result for all types of section totally 12 samples from curves in embankment, curves in bridges, tangents in embankment and tangents in bridges are considered. For detail analysis sections located at Autobis Tera, Darmar, Lideta, Stadium, Riche, Lancha, Nifas Silk 1, Nifas Silk 2, Adey Abeba, Saris, Abo Junction and Kaliti are used.

3.5 Data Processing and Analysis

After the data is collected according to the previous section, the track quality index has been calculated alignment, cross level, gauge, and twist. The collected data is analyzed, the relation between different track geometry parameters is determined and finally the statistical degradation model has been developed. For statistical analysis in this research MS-excel 2013 is used.

Finally, the performance of the developed model was assessed and the result was analyzed and summarized to put the important measurable actions as well as to give hint for further researches.

CHAPTER FOUR

4 STATISTICAL MODELLING

4.1 Track Geometry Irregularities

AALRT office conducted daily, monthly, quarterly, semi-annual and annual track inspection for identification of track irregularities. Generally, there are four types of track irregularities inspected by the AALRT office; cross level, alignment, twist and gauge. The longitudinal level inspection is performed through visual inspection and by the help of 20 m string method but there is no recorded data till now by the office about longitudinal level defects.

The AALRT monthly track inspection data in the North-South route which is from Kaliti to St. George Church in the left direction has been used for this paper. The monthly track inspection data obtained from the AALRT office is summarized in MS-excel. The data were collected in five meter (5m) interval during May 2020 G.C. In addition to that data collected during June 2020 G.C for 12 samples from curves in embankment, curves in bridges, tangents in embankment and tangents in bridges are used. According to Chinese standard segment length 200 m is used for light rail transit [36], so the track length has been segmented in 200 m interval. Therefore, there are 68 segments for the 13.54 km track length considered in this research. The sample track inspection data is presented in Appendix E. The average track irregularities for the considered length of track, which is 13.54 km is summarized in Table 4.1.

Table 4-1 Average track irregularities

Segment No.	Millage (km)	Cross Level	Alignment	Twist	Gauge
1	0.20	1.10			0.28
2	0.40	1.19			-0.33
3	0.60	0.34			0.39
4	0.80	0.98			0.13
5	1.00	1.45			0.60
6	1.20	1.07			0.68
7	1.40	1.38			0.93
8	1.60	1.64			0.59
9	1.80	0.68			0.38
10	2.00	-0.43			0.63
11	2.20	0.53			0.63
12	2.40	0.93			0.53
13	2.60	0.49		6.00	0.41
14	2.81	0.24			0.14
15	3.01	1.25			0.48
16	3.21	-0.22		5.33	0.73
17	3.41	0.45			0.98
18	3.61	0.18			0.45
19	3.81	-0.78			0.45
20	4.01	1.10			0.53
21	4.21	1.11			0.69
22	4.41	0.34			1.24
23	4.60	-0.10			0.68
24	4.81	-0.54			0.25
25	5.01	0.51			0.14
26	5.21	0.68			-0.34
27	5.41	1.71		6.00	-0.05
28	5.61	0.56			-0.14
29	5.81	1.05			-0.03
30	6.01	0.75			-0.05
31	6.21	-1.18		3.75	1.13
32	6.41	0.67			0.29
33	6.61	1.05			0.15
34	6.81	1.40			0.14
35	7.01	0.78			0.32
36	7.21	0.51			0.14
37	7.41	1.95		5.00	0.23
38	7.61	-0.18			0.08

Segment No.	Millage (km)	Cross Level	Alignment	Twist	Gauge
39	7.81	0.75		5.00	0.10
40	8.02	-0.05		5.00	0.07
41	8.21	1.90		5.50	0.25
42	8.41	2.14		5.50	0.71
43	8.62	1.28			0.03
44	8.82	0.50			-0.24
45	9.02	0.46			-0.03
46	9.22	1.48	1.78		-0.15
47	9.42	2.14	2.85		-0.13
48	9.62	0.71			-0.05
49	9.82	0.63			-0.18
50	10.02	0.63			-0.17
51	10.22	1.20			-0.13
52	10.42	1.08			-0.30
53	10.62	1.08			-0.05
54	10.82	1.20			-0.10
55	11.02	0.15			-0.05
56	11.22	0.55			0.13
57	11.42	0.83			0.38
58	11.62	-0.60		5.00	0.70
59	11.82	0.93		5.00	-0.08
60	12.02	1.78			-0.03
61	12.22	0.78			0.23
62	12.43	1.00			-0.02
63	12.63	1.05			0.10
64	12.83	1.31			0.23
65	13.03	0.62			-0.14
66	13.23	-0.15			-0.68
67	13.43	0.91			0.70
68	13.54	0.55			-0.23

4.2 Track Quality Index

Since the standards of AALRT is similar with Chinese manual, the TQI calculation is based on the Chinese TQI method. The Chinese track quality index is calculated as the sum of the standard deviations of all track geometry parameters and is calculated over 200 m for conventional railway lines and 500 m for high speed lines. The AALRT monthly track inspection data in the North-South route which is from Kaliti to St. George Church in the left direction is segmented in 200 m interval for this analysis of track quality index. The number of track geometry parameters considered in this paper are four; cross level, alignment, twist and gauge.

$$TQI = \sum_{i=1}^{4} S_i$$

$$S_i = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}\left(x_{ij}^2 - \bar{x}_i^2\right)} \quad \text{Where } \bar{x}_i = \sum_{j=1}^{n}\frac{x_{ij}}{n}$$

The standard deviation for each track geometry parameter and the corresponding TQI for each segment is summarized in Table 4.2.

Table 4-2 Standard deviation and TQI

Segment No.	Total Length (km)	measured level	horizontal deviation	Twist	measured gauge	TQI
1	0.20	1.0953			0.9986	2.0940
2	0.40	1.8111			0.9795	2.7905
3	0.60	0.9902			1.2425	2.2327
4	0.80	1.2297			0.7574	1.9871
5	1.00	1.1536			0.7779	1.9315
6	1.20	1.3855			0.9859	2.3713
7	1.40	1.0048			0.9711	1.9759
8	1.60	1.2245			1.1634	2.3879
9	1.80	1.3085			0.7403	2.0488
10	2.00	1.6154			0.8679	2.4833
11	2.20	1.0619			0.8679	1.9297
12	2.40	1.2483			0.8469	2.0953
13	2.60	1.5186			0.9741	2.4926
14	2.81	1.9103			0.7831	2.6934
15	3.01	1.7505			0.6789	2.4294
16	3.21	1.9302		0.5774	0.7080	3.2155
17	3.41	1.3578			0.6975	2.0553
18	3.61	0.8439			0.8149	1.6588
19	3.81	1.1206			0.9044	2.0250
20	4.01	0.8102			0.7157	1.5259
21	4.21	1.0896			1.0091	2.0987
22	4.41	1.3343			0.9429	2.2772
23	4.60	1.3989			1.4777	2.8765
24	4.81	1.5598			1.0734	2.6332
25	5.01	1.3340			0.7426	2.0767
26	5.21	1.6649			0.6561	2.3210
27	5.41	2.2050		0.0000	0.8352	3.0402
28	5.61	1.6291			0.7983	2.4274

Segment No.	Total Length (km)	measured level	horizontal deviation	Twist	measured gauge	TQI
29	5.81	1.5844			0.4797	2.0641
30	6.01	2.1092			0.5524	2.6616
31	6.21	2.2175		5.9090	1.3810	9.5075
32	6.41	1.9464			0.5962	2.5426
33	6.61	1.3388			0.6622	2.0009
34	6.81	1.0833			0.6466	1.7300
35	7.01	1.1729			0.8197	1.9926
36	7.21	1.1536			0.7442	1.8978
37	7.41	1.8250		0.0000	0.6597	2.4848
38	7.61	1.4830			0.7642	2.2472
39	7.81	1.5317			0.4961	2.0279
40	8.02	1.5961			0.5653	2.1614
41	8.21	2.0730		0.7071	0.5883	3.3685
42	8.41	1.8815		0.5774	0.9183	3.3771
43	8.62	1.5357			0.5305	2.0662
44	8.82	1.3113			0.6917	2.0030
45	9.02	1.7748			0.4860	2.2607
46	9.22	1.5464	1.5635		0.4830	5.1564
47	9.42	0.6901	2.8845		0.5158	6.9748
48	9.62	1.7499			0.5455	2.2954
49	9.82	1.6123			0.3848	1.9971
50	10.02	1.1137			0.5137	1.6274
51	10.22	1.2026			0.5633	1.7659
52	10.42	1.0952			0.5164	1.6116
53	10.62	0.9971			0.5970	1.5941
54	10.82	1.1140			0.5905	1.7045
55	11.02	1.5115			0.7143	2.2258
56	11.22	2.1237			0.7906	2.9143
57	11.42	1.4480			0.9789	2.4270
58	11.62	1.7802			1.0178	2.7980
59	11.82	1.4916			0.6155	2.1071
60	12.02	1.7020			0.7334	2.4354
61	12.22	1.5440			0.6975	2.2415
62	12.43	1.0488			0.7241	1.7730
63	12.63	1.1536			0.9001	2.0537
64	12.83	0.8732			0.7334	1.6066
65	13.03	1.7223			0.7703	2.4926
66	13.23	1.2142			0.8780	2.0923
67	13.43	1.5348			0.9261	2.4610
68	13.54	2.1096			0.8125	2.9221

In order to show the rate of change of track quality index, twelve segments were used. The data were collected for June 2020 G.C from curves in bridge (ballasted track), curves in embankment (slab track), tangents in bridge (ballasted track) and tangents in embankment (slab track) and three segments from each were considered.

Table 4-3 Standard deviation and TQI for June 2020

Segment No.	Total Length (km)	measured level (mm)	horizontal deviation (mm)	Twist (mm)	measured gauge (mm)	TQI (mm) June	Remark
24	97.19	1.7956			1.2354	3.0310	Curves in slab track
43	270.75	1.2689			1.1792	2.4481	
44	106.21	1.5132			0.8146	2.3278	
47	179.11	0.9821	2.6900		0.9574	7.3195	Curves in ballasted track
58	200.43	1.3734			1.5298	2.9032	
66	256.94	1.3755		0.6589	0.6859	2.7202	
12	196.37	1.3512			1.1387	2.4899	Tangents in slab track
17	195.00	1.5436			0.7132	2.2568	
20	195.00	1.0142			0.8780	1.8923	
29	195.00	1.1360		0.5298	0.9679	2.6337	Tangents in ballasted track
51	195.00	1.4715			0.7679	2.2394	
53	195.00	0.7736			1.0431	1.8167	

4.3 Modeling

Since there were four independent variables (predictors); the average cross level, alignment, twist and gauge irregularities and one dependent variable which was track quality index considered in the analysis therefore multiple linear regression modeling was used to predict the condition of the track.

In order to use multiple linear regression modeling the correlation between the four track geometry irregularities and track quality index is presented in Table 4.4.

Table 4-4 Correlation Matrix of Track Geometry Parameters

	Cross Level	Alignment	Twist	Gauge	TQI
Cross Level	1				
Alignment	0.2859	1			
Twist	0.0174	-0.0739	1		
Gauge	-0.1902	-0.1619	0.1599	1	
TQI	-0.1175	0.5512	0.2649	0.1771	1

The multiple linear regression model has the form [45];

$$y_i = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4 + \varepsilon$$

Where y_i = Response β_0 = Intercept β_i, i = 1,2 ... 4 were regression coefficients, x_i, i=1, 2…4 were predictors (regressors) and ε was a random error. The errors were assumed to have mean zero and unknown variance σ2. In this study there are four independent variables (predictors); the average cross level, alignment, twist and gauge irregularities and one dependent variable which is track quality index (TQI).

Assumptions of Multiple linear regression [45]

- There is a linear relationship between the predictors and the response.
- The independent variables are not too highly correlated with each other.
- Residuals should be normally distributed with a mean of 0.
- The error term ε has constant variance σ2.
- The errors are uncorrelated.

The multiple linear regression is analyzed using data analysis tool of MS-excel and the result is summarized in Tables 4.5 & 4.6.

Table 4-5 Regression Analysis Output

Regression Statistics	
Multiple R	0.7213
R Square	0.5203
Adjusted R Square	0.4898
Standard Error	0.8447
Observations	68

ANOVA

	Df	*SS*	*MS*	*F*	*Significance F*
Regression	4	48.7485	12.1871	17.0800	0.000000002
Residual	63	44.9524	0.7135		
Total	67	93.7009			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	2.414454	0.178447	13.530376	2.65043E-20	2.05786	2.77105
Cross Level	-0.493402	0.161364	-3.057708	0.003271506	-0.81586	-0.17094
Alignment	1.999417	0.268589	7.444147	3.34977E-10	1.46268	2.53615
Twist	0.176992	0.054075	3.273099	0.001729279	0.06893	0.28505
Gauge	0.585117	0.282471	2.071424	0.042420205	0.02064	1.14959

Table 4-6 Residual and Probability Outputs

RESIDUAL OUTPUT				PROBABILITY OUTPUT	
Observation	**Predicted TQI**	**Residuals**	**Standard Residuals**	**Percentile**	**TQI**
1	2.03547947	0.058492	0.07140972	0.735	0.87321246
2	1.6320312	1.158484	1.41433057	2.206	1.525858656
3	2.4743138	-0.24158	-0.294931	3.676	1.594112264
4	2.00652648	-0.01938	-0.0236572	5.147	1.611550269
5	2.05009107	-0.1186	-0.1447941	6.618	1.627382237
6	2.28454149	0.086799	0.10596819	8.088	1.658832157
7	2.27725941	-0.30141	-0.3679724	9.559	1.704536757
8	1.94983735	0.438065	0.53480983	11.029	1.729965307
9	2.30082656	-0.252	-0.3076551	12.500	1.765862081
10	2.9898486	-0.50654	-0.6184125	13.971	1.772956792
11	2.52111627	-0.59137	-0.7219767	15.441	1.897798123
12	2.26524356	-0.16997	-0.2075086	16.912	1.929742126
13	3.47832964	-0.98569	-1.203378	18.382	1.931489583
14	2.38056562	0.312831	0.38191819	19.853	1.975851657
15	2.07563189	0.35372	0.43183785	21.324	1.987148787
16	3.89485221	-0.67935	-0.829381	22.794	1.99259022
17	2.76291254	-0.7076	-0.8638717	24.265	1.997060408
18	2.59141159	-0.93258	-1.1385358	25.735	2.000935247
19	3.06014392	-1.03513	-1.2637313	27.206	2.003048316
20	2.17889813	-0.65304	-0.7972606	28.676	2.025016271
21	2.27256077	-0.17384	-0.2122335	30.147	2.027854919
22	2.97380425	-0.69657	-0.8504097	31.618	2.048824941
23	2.85874868	0.017793	0.021722	33.088	2.053732154
24	2.8279932	-0.1948	-0.2378222	34.559	2.055311639
25	2.24366002	-0.16701	-0.2038906	36.029	2.064095669
26	1.87770024	0.443333	0.54124156	37.500	2.066167756
27	2.60546738	0.434772	0.53079005	38.971	2.076652396
28	2.05907542	0.368337	0.44968239	40.441	2.092266436
29	1.88175369	0.182342	0.22261146	41.912	2.093971474
30	2.01514649	0.646436	0.78919878	43.382	2.095272415
31	4.31617784	5.191315	6.33779608	44.853	2.098719403
32	2.25269562	0.289897	0.35391899	46.324	2.107148185
33	1.98414923	0.016786	0.02049314	47.794	2.161362169
34	1.80492943	-0.07496	-0.0915196	49.265	2.225816764
35	2.21488462	-0.22229	-0.2713872	50.735	2.232734549
36	2.24015529	-0.34236	-0.4179653	52.206	2.241535512
37	2.46892909	0.01585	0.0193505	53.676	2.247205742

RESIDUAL OUTPUT				PROBABILITY OUTPUT	
Observation	**Predicted TQI**	**Residuals**	**Standard Residuals**	**Percentile**	**TQI**
38	2.54468343	-0.29748	-0.3631744	55.147	2.260737421
39	2.98787236	-0.96002	-1.1720334	56.618	2.277230106
40	3.36629434	-1.20493	-1.4710365	58.088	2.295404389
41	2.59672298	0.771758	0.94219757	59.559	2.321033476
42	2.74855831	0.628562	0.76737673	61.029	2.371340478
43	1.799994	0.266174	0.32495713	62.500	2.387902327
44	2.02843931	-0.02539	-0.0309985	63.971	2.426976388
45	2.17172698	0.08901	0.10866803	65.441	2.427412154
46	5.14906083	0.007343	0.00896517	66.912	2.42935209
47	6.97933372	-0.00458	-0.0055953	68.382	2.435359789
48	2.03691991	0.258484	0.31556972	69.853	2.46096415
49	2.00368212	-0.00662	-0.0080841	71.324	2.483304315
50	2.00400967	-0.37663	-0.4598041	72.794	2.484779168
51	1.74923158	0.016631	0.02030328	74.265	2.492581437
52	1.70851134	-0.09696	-0.1183745	75.735	2.492637702
53	1.85479069	-0.26068	-0.3182482	77.206	2.542592156
54	1.76385952	-0.05932	-0.0724239	78.676	2.633192032
55	2.31118796	-0.08537	-0.1042251	80.147	2.661582524
56	2.21622252	0.698083	0.85225215	81.618	2.693396416
57	2.22681619	0.20016	0.24436475	83.088	2.790515307
58	4.0050361	-1.20701	-1.473576	84.559	2.798023814
59	2.79913139	-0.69198	-0.8448049	86.029	2.87654126
60	1.52403691	0.911323	1.11258479	87.500	2.914305842
61	2.16371871	0.077817	0.09500233	88.971	2.92206402
62	1.90678059	-0.13382	-0.1633782	90.441	3.040239735
63	1.95489336	0.098839	0.12066694	91.912	3.215502716
64	1.89851489	-1.0253	-1.2517363	93.382	3.36848097
65	2.02723372	0.465348	0.56811785	94.853	3.377119819
66	2.09454756	-0.00228	-0.0027849	96.324	5.156404246
67	2.37099449	0.08997	0.10983909	97.794	6.9747506
68	2.01234436	0.90972	1.11062751	99.265	9.507493234

CHAPTER FIVE

5 RESULT AND DISCUSSION

5.1 Track Irregularities

Based on the collected monthly track inspection data in Addis Ababa Light Rail Transit (AALRT) the average track geometry irregularities for the four geometry parameters is presented in the Figure 5-1.

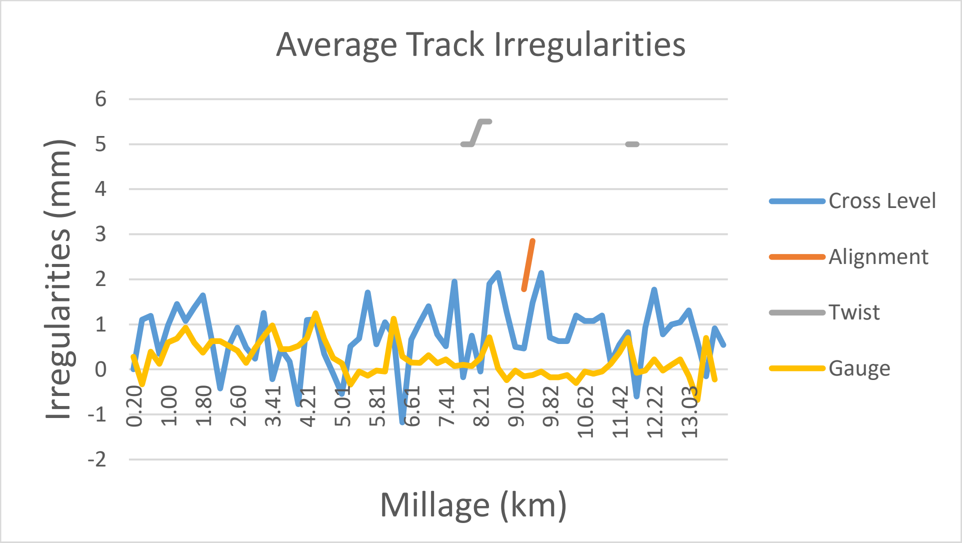


Figure 5-1 Average Track Irregularities

Similarly, the track irregularities distribution is summarized in Figure 5.2.

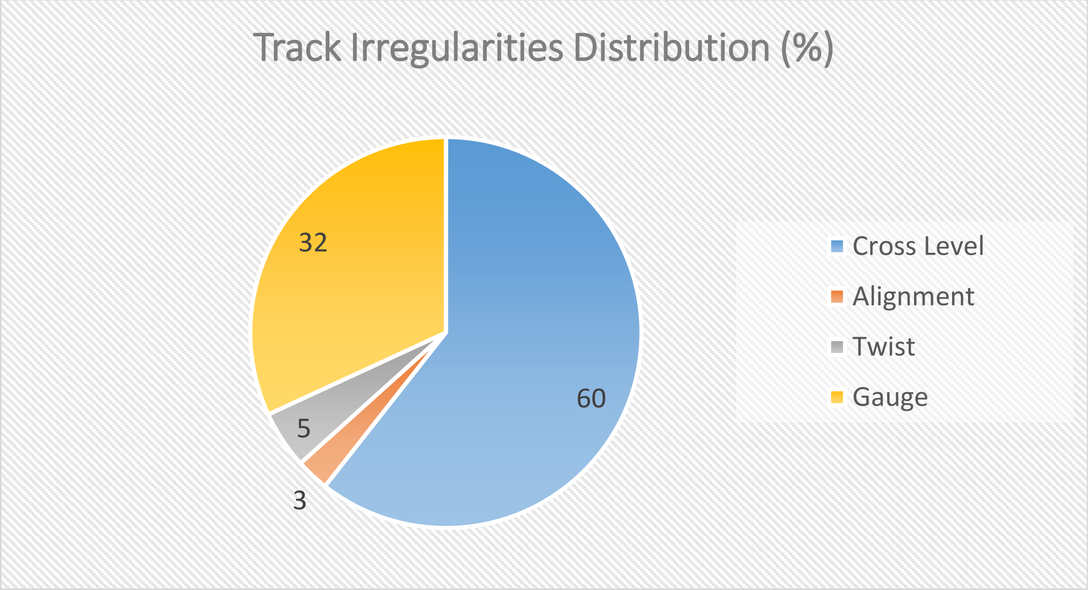


Figure 5-2 Track Irregularities Distribution

The result shows that the most common track geometry irregularities of Addis Ababa Light Rail Transit (AALRT) were cross level and gauge irregularities. From the four collected track geometry parameters the cross level irregularity covers 60 % and the gauge irregularity covers 32 % of the total irregularity percentage whereas the twist and alignment irregularities covers small proportion numerically 5 % and 3 % respectively. Also the twist and alignment problems were observed on some specific locations whereas the cross level and gauge irregularities were observed over the whole track length.

5.2 Track Geometry Quality Index (TGQI)

Since the Track Geometry Quality Index (TGQI) result of the inspected track length is depend on the standard deviations of each track geometry parameters, so it is better to show the standard deviation variations of each parameter in Figure 5.3.

Figure 5-3 Standard Deviations of Track Geometry Irregularities

Similar with the average track geometry irregularities the standard deviations of cross level and gauge irregularities distribution is over the whole track whereas twist and alignment irregularities are on specific location. The sum of the standard deviations of the four track geometry irregularities gives the track geometry quality index (TQI) and it is presented in Figure 5.4.

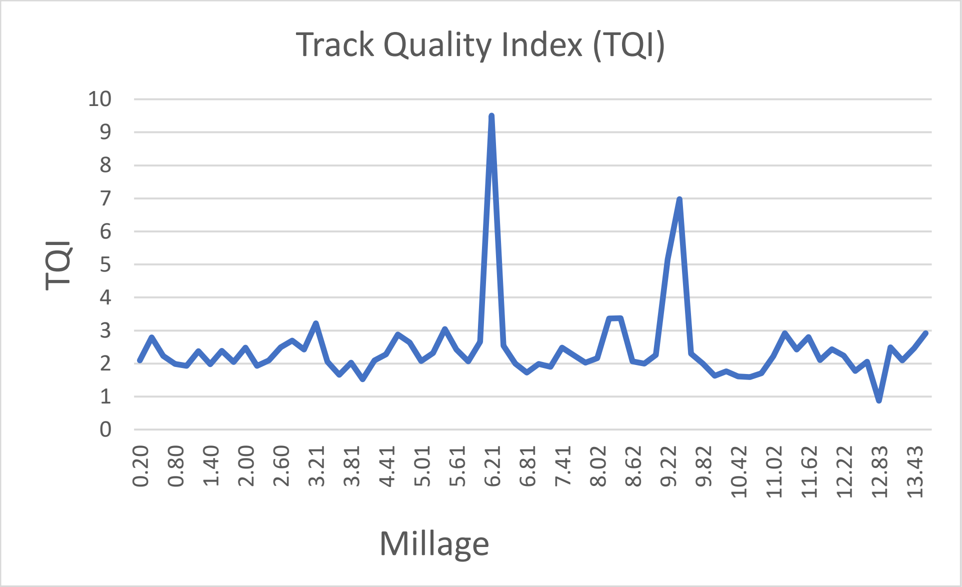


Figure 5-4 Track Quality Index

The maximum design speed of Addis Ababa Light Rail Transit (AALRT) is 70 km/hr. Therefore, according to the track quality index limit value stated in Table 2.5 the maximum limit value of track quality index for AALRT is 15 mm. The result shows that the maximum value of track quality index is 9.51 mm which was 63.4 % of the threshold limit and the minimum value was 1.5 mm. Since the track quality index was less than track quality index limit ($TQI \leq TQI_{lim}$), according to the track geometry condition standard described in Table 2.6 the track geometry condition of AALRT was qualified.

Based on the collected data on June 2020, the rate of change of track quality index (track deterioration rate) was calculated as:

$$\text{Rate of change of TQI} \left(\frac{\text{mm}}{\text{year}}\right) = \frac{\Delta\ \text{TQI}}{\Delta\ \text{Time}}$$

$$= \frac{\text{TQI June} - \text{TQI May}}{1/12}$$

The track quality index rate of change was calculated for curves in embankment, curves in bridges, tangents in embankment and tangents in bridges. The result for each segments is summarized in Table 5.1.

Table 5-1 (A-D) Track Deterioration Rates

A. Curves in Bridge (Slab Track)

Segment No.	Curve Starting millage (m)	Curve Ending millage (m)	Curve Length (m)	Curve Radius (m)	TQI (mm) May	TQI (mm) June	Rate (mm/year)
24	9+599.367	9+696.561	97.194	55	2.6332	3.0310	4.77
43	13+097.281	13+368.026	270.745	350	2.0661	2.4481	4.58
44	13+569.869	13+676.076	106.207	304	2.0030	2.3278	3.90

B. Curves in Embankment (Ballasted Track)

Segment No.	Curve Starting millage (m)	Curve Ending millage (m)	Curve Length (m)	Curve Radius (m)	TQI (mm) May	TQI (mm) June	Rate (mm/year)
47	14+136.76	14+315.869	179.109	460	6.9747	7.3195	4.14
58	16+333.318	16+533.747	200.429	230	2.7980	2.9032	1.26
66	17+898.577	18+155.513	256.936	146	2.0922	2.7202	7.54

C. Tangents in Bridge (Slab Track)

Segment No.	Tangent Starting millage (m)	Tangent Ending millage (m)	Tangent Length (m)	TQI (mm) May	TQI (mm) June	Rate (mm/year)
12	4+585	4+781.37	196.37	2.0952	2.4899	4.74
17	5+595	5+790	195	2.0553	2.2568	2.42
20	6+195	6+390	195	1.5258	1.8923	4.40

D. Tangents in Embankment (Ballasted Track)

Segment No.	Tangent Starting millage (m)	Tangent Ending millage (m)	Tangent Length (m)	TQI (mm) May	TQI (mm) June	Rate (mm/year)
29	10+495	10+690	195	2.0641	2.6337	6.83
51	14+910	15+105	195	1.7658	2.2394	5.68
53	15+310	15+505	195	1.5941	1.8167	2.67

The research found that the maximum rate of change of track quality indices (track deterioration rates) for curves in bridges, curves in embankment, tangents in bridges and tangents in embankment were 4.77 mm/yr, 7.54 mm/yr, 4.74 mm/yr and 6.83 mm/yr respectively. The overall maximum track quality index was 7.54 mm/yr which was found in curves in embankment (ballasted track).

5.3 Track Quality Index Model

According to the multiple linear regression analysis result from MS-excel data analysis tool, the following points are observed.

5.3.1 Correlation Matrix

Higher absolute value of the correlation coefficient indicates a stronger the relationship. The extreme values of -1 and 1 specify a perfectly linear relationship where a change in one variable is results a perfectly reliable change in the other. For these relationships, all of the data points occur on a line. A coefficient of zero signifies no linear relationship between variables. When r is in-between 0 and +1/-1, there is a relationship, but the points don't all fall on a line. When the value of r approaches -1 or 1, the strength of the relationship increases and the data points tend to fall closer to a line. The correlation matrix of the four track geometry irregularities and track quality index shows that alignment irregularity has highest correlation with track quality index when compare to the other types of irregularities.

Additionally, the higher the correlation coefficient parameter leads to less acceptance of the multiple regression analysis [45] but in this study the maximum correlation coefficient was 0.28 or 28%, there was no high correlation between the independent variables; low collinearity and hence the good model.

5.3.2 Coefficient of Determination

The coefficient of determination or multiple correlation coefficient (R-squared) is a statistical metric that is used to measure how much of the variation in outcome can be explained by the variation in the regressors. The value of R^2 always increases as more regressors are added, although the regressors may not be related to the outcome variable. R^2 by itself cannot hence be used to isolate which regressors should be included in a model and which should be excluded. R^2 can only be between 0 and 1, where 0 shows that the outcome cannot be predicted by any of the regressors and 1 shows that the outcome can be predicted without error from the regressors.

Simply R^2 indicates that the correlation between the observations $\boldsymbol{y}_{\mathbf{i}}$ and the fitted values y. Adjusted R square is calculate R square from only those variables whose addition in the model which are significant. So always during a multiple linear regression model it is better to look at adjusted R square instead of R square.In this track quality index multiple linear regression model R^2 is 0.52 and adjusted R^2 is 0.49; it means 49 % of the variation in the output variable (track quality index) is explained by the input variables (average track geometry irregularities).

5.3.3 P-Value

The p-value result from the track quality index multiple linear regression analysis is shown in Table 5.2.

Table 5-2 P-Value

Predictor	P- Value
Cross Level	0.00327
Alignment	3.3E-10
Twist	0.00173
Gauge	0.04242

A p-value is a measure of the probability that an observed difference could have occurred just by random chance. The lower the p-value, the greater the statistical significance of the observed difference. In this multiple linear regression analysis the assumed confidence level is 95 %, therefore the independent variables with p- value greater than 5 % or 0.05 should be removed because it does not have any significance for the model. The result shows that the p- values for all independent variables (track geometry parameters) are less than 0.05, indicates that all the four parameters are significant in the analysis.

5.3.4 Multiple Linear Regression Model

From the multiple linear regression analysis output Table [Table 4.5] the regression coefficients are obtained and finally the multiple regression model for track quality index is developed.

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_4 x_4$$

Where $\beta_0 = 2.41$ $\beta_1 = -0.49$ $\beta_2 = 2.00$ $\beta_3 = 0.18$ $\beta_4 = 0.59$, and $X_{i,}$ i=1, 2, 3 & 4 were the average cross level, alignment, twist and gauge irregularities respectively.

$$y = 2.41 - 0.46x_1 + 2x_2 + 0.18x_3 + 0.59x_4$$

Figure 5-5 Track Geometries Line Fit Plot

5.3.5 Model Adequacy

Model adequacy checking includes residual analysis, testing for lack of fit and other internal analyses that indicate the fit of the regression model to the available data. Graphical analysis of residuals is a very effective way to examine the adequacy of the fit of a regression model and to check the essential assumptions of multiple linear regression model. Residual plot is one of the most important parameter to show the adequacy of the model. The residual plots of the regressors is shown in Figure 5.6.

The result from residual plots in Figure 5.6 indicates that the residuals for the track geometry parameter points in a residual plot are randomly dispersed around the horizontal axis, a linear regression model is appropriate for the data. Therefore, the developed model is adequate.

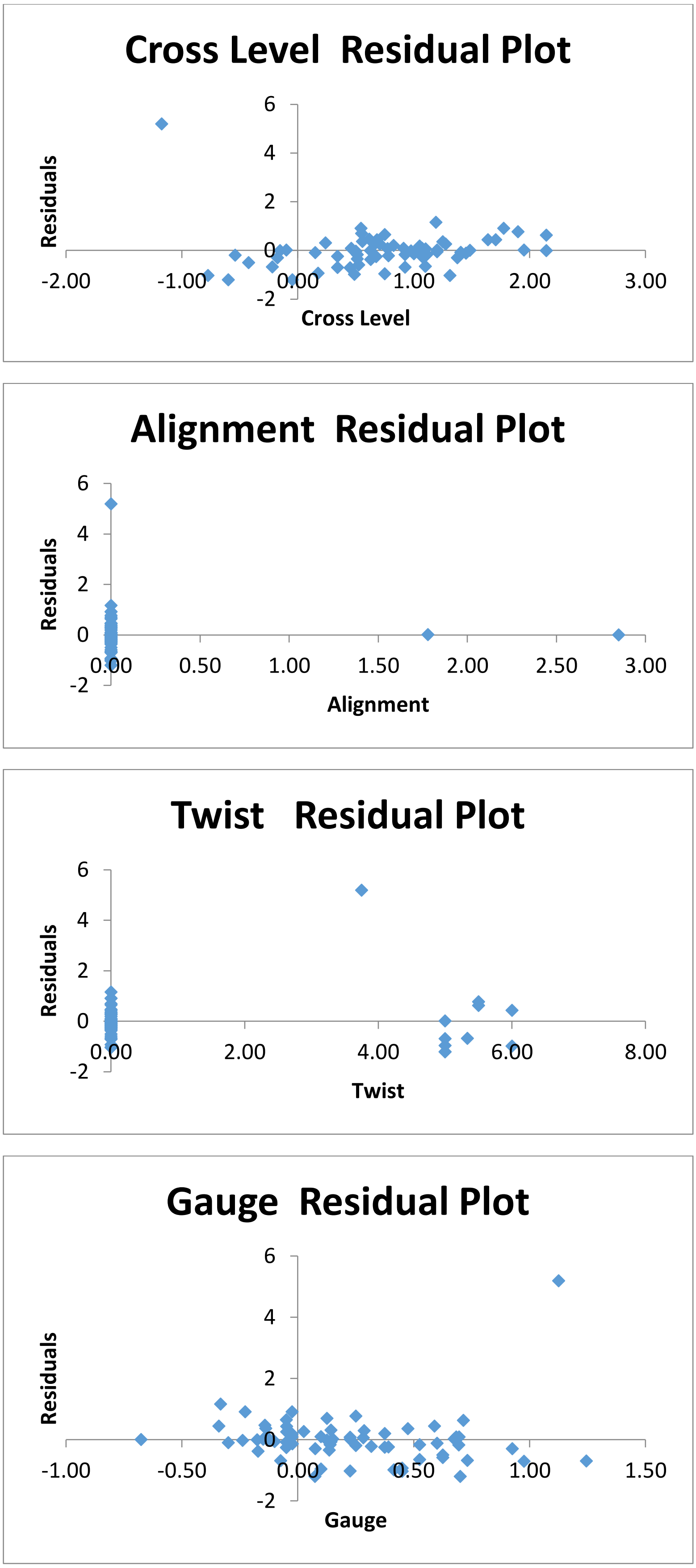


Figure 5-6 Residual plots

A plot of the standard residuals versus the corresponding fitted values (predicted TQI) is useful for detecting several common types of model inadequacies. If this plot resembles Figure 5.7, which indicates that the residuals can be contained in a horizontal band, then there are no obvious model defects. The patterns indicate that the variance of the errors is constant.

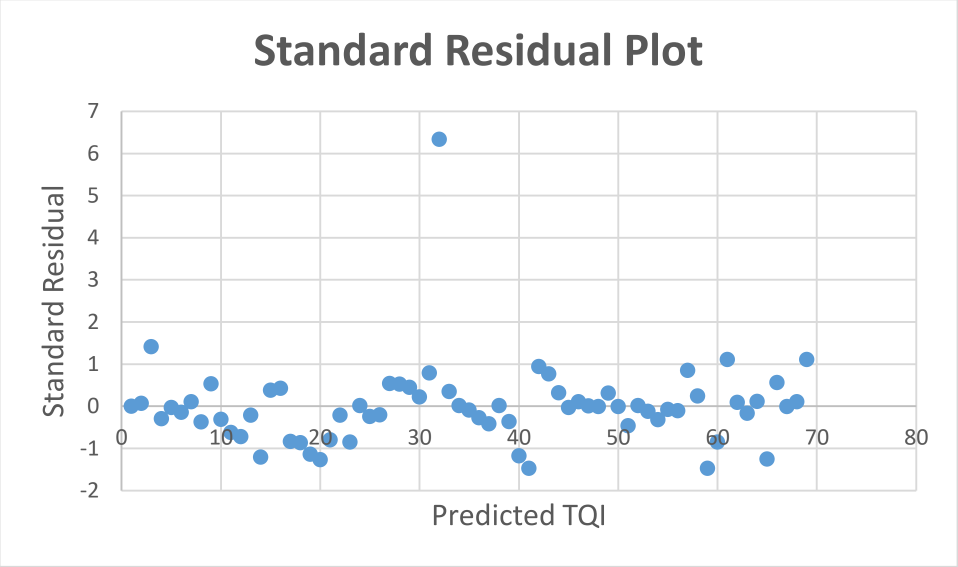


Figure 5-7 Standard Residual Plot

The normal probability plot is also used to check the adequacy of the model.

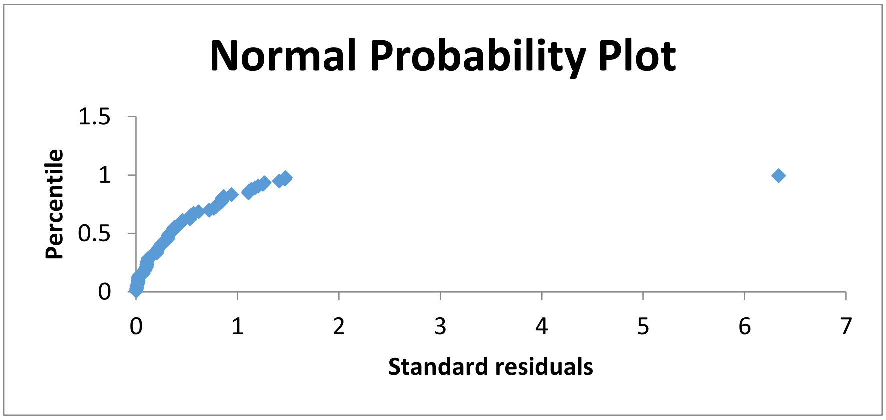


Figure 5-8 Normal Probability Plot

The normal probability plot is a plot of the ordered standardized residuals versus the percentiles the so-called normal scores. The normal scores are the cumulative probability. Points lie approximately on the straight line and indicate that the underlying distribution is normal.

5.3.6 Validation of the Model

Model validation refers to the process of approving that the model actually attains its proposed purpose. Usually, this will involve confirmation that the model is predictive under the conditions of its intended use. Proper validation of a regression model should include a study of the coefficients to determine if their signs and magnitudes are reasonable.

There are three types of techniques used to check the validation of developed models [45].

- ✓ Analysis of the model coefficients and predicted values including comparisons with past experience, physical theory and other analytical models or simulation results.
- ✓ Collection of new (or fresh) data with which to investigate the model's predictive performance
- ✓ Data splitting, that is, setting aside some of the original data and using these observations to investigate the model's predictive performance

Analysis of the model coefficients and predicted values

The sign and magnitude of coefficients in the final regression model should be checked in order to avoid errors in the model. One of the most important method to check the validation of the developed model regarding the coefficients and predicted values if there is multicollinearity is Variance Inflation Factor (VIF).

The VIF for each independent variables by performing a multiple linear regression analysis using one independent variable as the response variable and the other three as the regressors. For example VIF for cross level is calculated as by performing a multiple linear regression analysis using cross level as the response variable and the other three; alignment, twist and gauge as the regressors.

$$VIF_i = \frac{1}{1 - R_i^2}$$

Where R_i^2 is the R squared value from multiple regression analysis for the corresponding independent variables.

The VIF result is shown in Table 5.3.

Table 5-3 Variance Inflation Factors

Parameters	*R Squared*	VIF
Cross Level	0.10674433	1.12
Alignment	0.097514951	1.11
Twist	0.032004069	1.03
Gauge	0.072633464	1.08

The limit value for VIF is different in various literatures. The value of VIF starts at 1 and the upper limit value is 5 [46] or 10 [47]. A value of 1 indicates there is no correlation between a given explanatory variable and any other regressors (explanatory variables) in the model.

A value greater than 5 or 10 indicates potentially severe correlation between a given independent variable and other independent variables in the model. In this case, the coefficient estimates and p-values in the regression output are likely unreliable.

The VIF results of the developed model in this research indicating that VIFs are very small (less than 1.5) as a result no potential problems with multi-collinearity. Finally it can be concluded that predictive performance of the developed multiple regression model is good.

CHAPTER SIX

6 CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The result of the research shows that the common track geometry irregularities of Addis Ababa Light Rail Transit (AALRT) are cross level and gauge irregularities. Cross level irregularity covers 60 % whereas the gauge irregularity cover 32 % of the total track geometry irregularities percentage distribution. The research found that the maximum value of track quality index is 9.51 mm which was 63.4 % of the threshold limit (15mm). Since the track quality index was less than track quality index limit ($TQI \leq TQI_{lim}$) the track geometry condition of AALRT was qualified. The rate of change of track quality indices were calculated for twelve segments. The maximum rate of change of track quality indices (track deterioration rates) for curves in bridges, curves in embankment, tangents in bridges and tangents in embankment were 4.77 mm/yr, 7.54 mm/yr, 4.74 mm/yr and 6.83 mm/yr respectively. The overall maximum track quality index was 7.54 mm/yr which was found in curves in embankment (ballasted track).

The current track degradation models have been reviewed in this study and a new track quality index model has been developed using multiple linear regression method of analysis. For the developed model, the four track geometry irregularities parameter which are cross level, alignment, twist and gauge irregularities were used as independent variables or regressors whereas the track quality index was used as the dependent variable or response.MS-Excel data analysis tool was used for multiple linear regression analysis.

The developed model adequacy has been checked depending on the multiple linear regression analysis general assumptions. The residual plots of the independent variables indicated that points are randomly dispersed around the horizontal axis, a linear regression model is appropriate for the model. The plot which describes the relation between standard residual and the predicted track quality index shows that the points were distributed around the horizontal axis; indicating that the variance of the residual is constant which proofs the assumption of multiple linear regression. The model has also been validated by calculating the variance inflation factors for each independent variable. The variance inflation factor values for cross level, alignment, twist and gauge irregularities were much less than 5, which indicates that the developed track quality index model was valid.

6.2 Recommendation

- The maintenance team of Addis Ababa Light Rail Transit (AALRT) should give special attentions for checking the cross level and gauge irregularities because these irregularities cover the largest proportions of irregularities.
- In this study a track segment of 200 m was used for the analysis of data, but it is better to segment the track smaller than 200 m based on different parameters that make the segments characteristics similar like speed, types of structure, gradient, curvature, rail type and others.
- Since the track inspection method of AALRT is manual it is better to use modern track inspection strategies using vehicle.
- The AALRT office should improve the documentation system (especially in soft copy) of track inspection, maintenance and other relevant data for research and future use.

6.3 Future work

The following points are recommended for future study

- Develop a degradation model by considering speed, cost, traffic volume and other necessary parameters.
- Consider track structure defects in the model.

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APPENDICES

Appendix A-Rail Defects

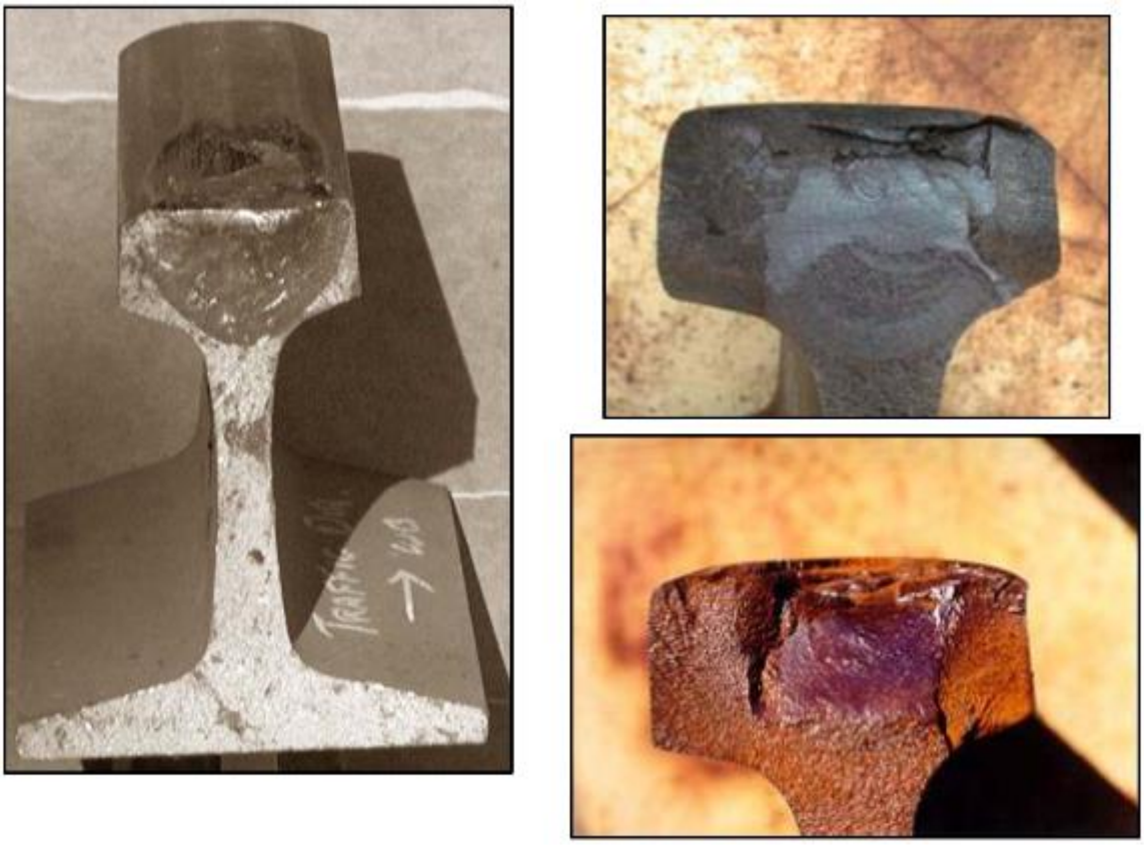
A. Transverse Defects in the Rail Head

Transverse defects are any progressive fractures occurring in the head of a rail and have a transverse separation, however slight. The followings are examples of transverse defects in the rail head.

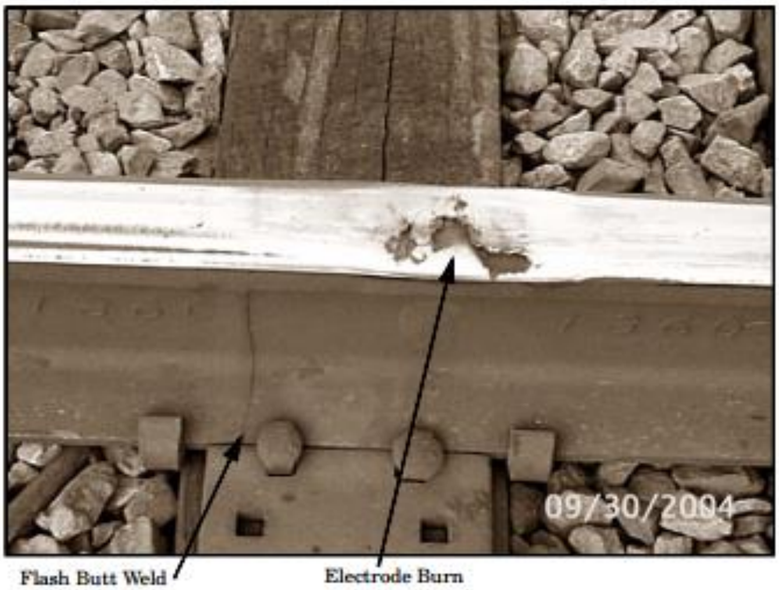
Detail Fracture

Transverse Fissure

Compound Fissure



Engine Burn Fracture

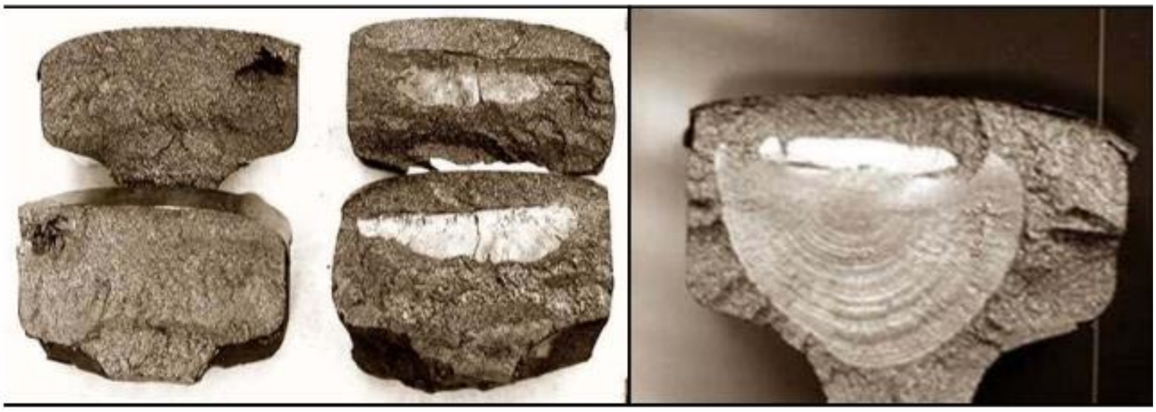


Welded Burn Fracture

B. Defective welds

Defect shows extreme rapid growth pattern (rail end view)

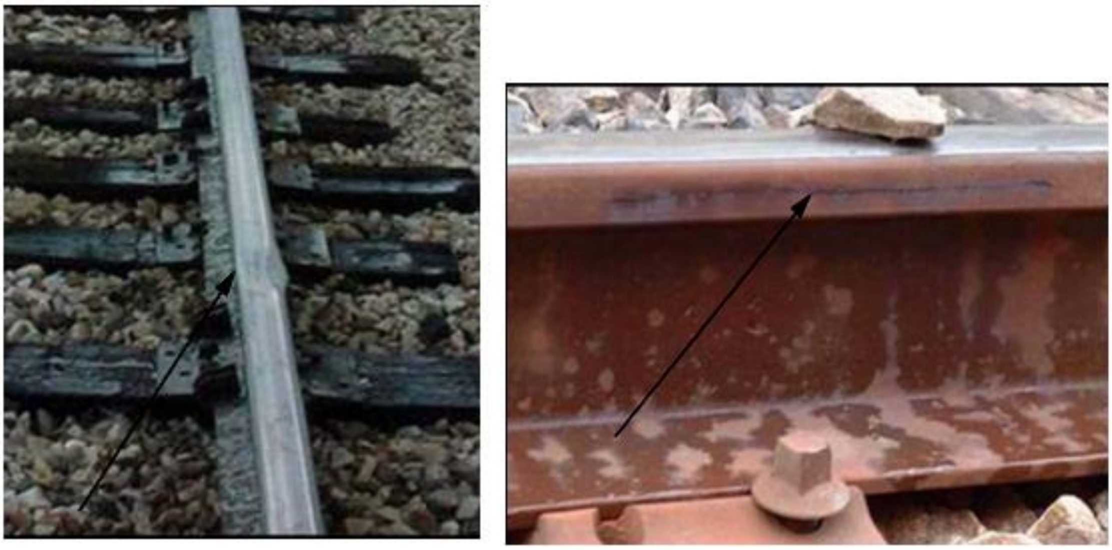
Plant Welds (Head)



Field Welds (Head) - Thermite Weld

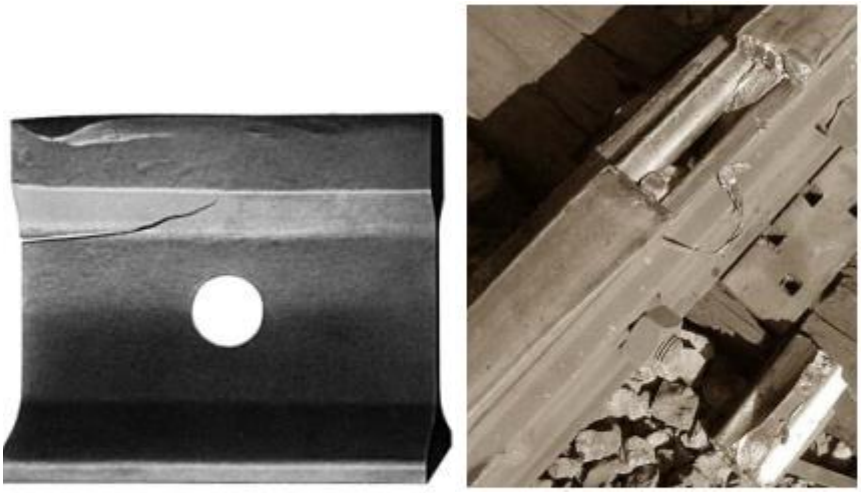
Field Welds (Web) – Web Shrinkage

C. Longitudinal Defects in the Rail Head



Horizontal split head

Vertical split head



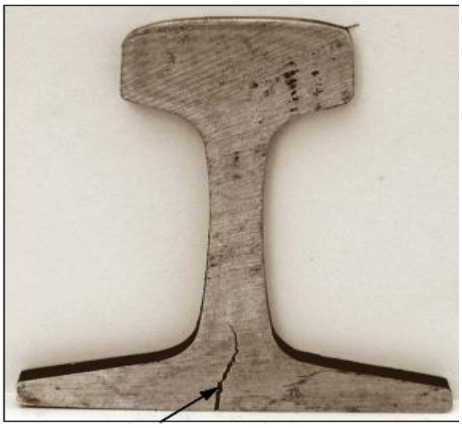
Head and web separation

Split web

E. Piped rail

Piped rail

F. Base Defects



Broken Base

Rail Batter: There are two types of rail batter; impact and friction batter. Impact batter is a result of a rail breaking exposing the fracture face to wheel impact from rolling stock. Friction batter is a result of sufficient rail section separation allowing the two fracture faces to make contact under load.

Impact Batter from Rolling Stock Wheels

Friction Batter from Fracture Face Contact

Appendix D-AALRT Track Geometry Inspection Form

Direction	Millage (m)	Point Spacing (m)	design level (mm)	Measured Level(Cross Level) (mm)	Horizontal Deviation (Alignment) (mm)	Twist (mm)	Gauge widening (mm)	Measured Gauge (mm)	Gauge deviation (mm)	remark

Record By: **Checked By:** **Date:**

Appendix E- Sample Track Inspection Data

Direction NS-R	Millage (m)	Point Spacing (m)	design level (mm)	Measured Level(Cross Level) (mm)	Horizontal Deviation (Alignment) (mm)	Twist (mm)	Meas ured Gauge (mm)	remark
	5790	5	0	1			3	
-1f	5793.028	3.028	0	0			1	
0f	5798.028	5	0	2			0	
1f	5803.028	5	-10	-1			1	
2f	5808.028	5	-20	0			0	
3f	5813.028	5	-30	0			0	
4f	5818.028	5	-40	0			0	
5f	5823.028	5	-50	-1			2	
6f	5828.028	5	-60	2			0	
7f	5833.028	5	-70	0			0	
8f	5838.028	5	-80	1			0	
9f	5843.028	5	-90	1			0	
10f	5848.028	5	-100	0			0	
11f	5853.028	5	-110	0			2	
12f	5858.028	5	-110	0			0	
13f	5863.028	5	-110	0			0	
14f	5868.028	5	-110	1			2	
15f	5873.028	5	-110	0			2	
16f	5878.028	5	-110	0			0	
17f	5883.028	5	-110	0			-1	
18f	5888.028	5	-110	0			2	

Direction NS-R	Millage (m)	Point Spacing (m)	design level (mm)	Measured Level(Cross Level) (mm)	Horizontal Deviation (Alignment) (mm)	Twist (mm)	Measured Gauge (mm)	remark
19f	5893.028	5	-110	2			0	
20f	5898.028	5	-110	2			0	
21f	5903.028	5	-110	0			1	
22f	5908.028	5	-110	-1			-1	
	5913.028	5	-110	0			0	
	5918.028	5	-106	1			0	
	5923.028	5	-96	0			0	
	5928.028	5	-86	0			0	
	5933.028	5	-76	0			0	
	5938.028	5	-66	-1			1	
	5943.028	5	-56	0			1	
	5948.028	5	-46	1			-1	
	5953.028	5	-36	1			0	
	5958.028	5	-26	-1			1	
	5963.028	5	-16	-1			1	
	5968.028	5	-6	0			1	
	5973.028	5	0	0			0	
	5978.028	5	0	0			1	
	5985	6.972	0	-1			1	
	5990	5	0	0			1	
	5995	5	0	-1			1	
	6000	5	0	0			1	
35f	6005.238	5.2398	0	2			0	

Direction NS-R	Millage (m)	Point Spacing (m)	design level (mm)	Measured Level(Cross Level) (mm)	Horizontal Deviation (Alignment) (mm)	Twist (mm)	Measured Gauge (mm)	remark
34f	6010.238	5	0	2			1	
33f	6015.238	5	3	0			1	
32f	6020.238	5	13	-1			-1	
31f	6025.238	5	23	-2			2	
30f	6030.238	5	33	-1			-1	
29f	6035.238	5	43	-2			1	
28f	6040.238	5	53	-1			1	
27f	6045.238	5	63	0			0	
26f	6050.238	5	73	-2			0	
25f	6055.238	5	80	-1			0	
24f	6060.238	5	80	0			2	
23f	6065.238	5	80	-1			0	
22f	6070.238	5	80	-1			0	
21f	6075.238	5	80	0			0	
20f	6080.238	5	80	-2			0	
19f	6085.238	5	80	-1			2	
18f	6090.238	5	80	-2			0	
17f	6095.238	5	80	1			0	
16f	6100.238	5	80	-1			1	
15f	6105.238	5	80	-2			0	
14f	6110.238	5	80	-1			0	
13f	6115.238	5	80	-2			2	
12f	6120.238	5	80	-1			1	

Direction NS-R	Millage (m)	Point Spacing (m)	design level (mm)	Measured Level(Cross Level) (mm)	Horizontal Deviation (Alignment) (mm)	Twist (mm)	Meas ured Gauge (mm)	remark
11f	6125.238	5	80	0			2	
10f	6130.238	5	80	-1			0	
9f	6135.238	5	80	-1			0	
8f	6140.238	5	80	-2			-1	
7f	6145.238	5	70	-1			0	
6f	6150.238	5	60	-2			1	
5f	6155.238	5	50	-1			-1	
4f	6160.238	5	40	-1			0	
3f	6165.238	5	30	-1			1	
2f	6170.238	5	20	-2			2	
1f	6175.238	5	10	-2			1	
0f	6180.238	5	0	1			-1	
1 n f	6185.238	5	0	1			0	
	6190	4.762	0	1			0	
	6195	5	0	1			0	
	6200	5	0	1			0	
	6205	5	0	1			1	
	6210	5	0	1			0	
	6215	5	0	1			0	
	6220	5	0	1			0	
	6225	5	0	2			1	
	6230	5	0	1			0	