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MODELLING AND ANALYSIS OF THE LIFE CYCLE COST OF A/A – DJIBOUTI RAILWAY TRACK

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Modelling and Analysis of the Life Cycle cost of Addis Ababa- Djibouti Railway Track

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Approved By Board of Examiners

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STATEMENT OF DECLARATION

I, Abiselom Mehari, declare that this thesis entitled "*Modelling and Analysis of the Life Cycle Cost of Addis Ababa to Djibouti Railway Track*" is carried by myself with the close guidance & support of my advisor Ato Yusuf. I have followed all ethicality standards while conducting the research and all references and sources are properly acknowledged. The study is original and has not been used as a partial fulfillment for any sort of educational qualification at this university.

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Researcher	Signature	Date

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Abstract

Rail infrastructure is a large and costly investment, therefore infrastructure managers should manage the infrastructures properly to achieve the aim of the project. Ones the railway line is constructed it should be managed efficiently. In order to have an efficiently management system the infrastructure manager should know all cost during railways life time. Life cycle cost analysis help the infrastructure manager to know the cost of maintenance, risk, renewal, organization, Train delay and initial cost.

The aim of this research is to analyze the Life cycle cost of Addis Ababa – Djibouti Railway track. In this research rail, Sleeper and ballast LCC models are developed separately. For the rail and Sleeper LCC model, an existing model is used, whereas for the ballast LCC model, a new model is proposed based on a track geometry degradation model. This paper also describes a decision support system approach for railway track maintenance and renewal management system to analyze the track components and suggests methods for helping the track managers and help engineers decide when maintenance is necessary and when is the best time for renewal.

In this Thesis, the Life cycle cost of the track is determined and the results shows that the maintenance cost of rail using lubrication has less LCC than without use lubrication. The analysis also shows the best Grinding interval, Inspection interval, Tamping interval and Renewal interval which give the least LCC of the line.

List of Abbreviation

AAR: – Association of American Railroads
A/A: - Addis Ababa
ASCE: – American Society of Civil Engineers
CSA: - Central Statistical Agency
CWR: – Continuous Welded rail
D/D: - Dire Dawa
ERA: – Ethiopia Road Authority
ERC: – Ethiopia Railway Corporation
ERRI: – European Railway Research Institute
FRA: – Federal Railroad Administration
IM: – Infrastructure Manager
LCC: – Life cycle cost
m :- Gross tonnage per year in MGT
M: - Life period of track in MGT (Million Gross Tons)
M&R: – Maintenance and Renewal
MGT: – Million Gross Tons
MoFED: – Ministry of Finance and Economic Development
MRT: – Mean Repair Time
MTTF: – Mean Time to Failure
N: - Life period of track (equivalent to M) in years
NDT: – Non-Destructive Testing
ORR: – Office of Rail Regulation
P-F: – Potential failure to Functional failure
PSI: – Present Serviceability Index
r :- Discount Rate
RAMS: – Reliability, Availability, Maintainability and Safety
RCF: – Rolling Contact Fatigue
RTA: - Road Transport Authority
UIC: – Union Internationale des Chemins (International Union of Railway)

Chapter 1 Introduction

1.1 Background

Ethio – Djibouti railway line should work in safe and reliable network with sufficient capacity and availability is a prime requirement. Ethiopian and Djibouti Railway Corporations are playing their parts in achieving this requirement in its system of life cycle. To fulfill this requirement in an effective manner, one needs to examine the various phases of the life cycle such as inception, design, manufacturing, installation, operation, maintenance and disposal. Once the infrastructure is installed, it is very difficult to modify the initial design. Therefore, the performance of the infrastructure depends largely on the maintenance and renewal decisions taken during its life cycle. The main goal of this paper is to analyze the Life cycle cost of the track and to determine the maintenance and renewal strategy which give the minimum Life cycle cost.

1.2 Problem Statement

The new Ethio-Djibouti Railway line was constructed at the initial cost of USD 4,273,890,000.00. The capital ratio of railway corporations is 15% (funded by both Ethiopia government and Djibouti government), while the remaining capital obtained through loan from bank(s): 25% loan from commercial bank of Ethiopia; 60% loan initially intended by Import and Export Bank of China, with length of maturity of 20 years and grace period of 5 years According to Ethiopian Railway Corporation (ERC) study, interest should be paid during the year; and the interest rate agreed by Ethiopian and China Government is 6%. Since the loan payment at the time it specified, the ERC and railway company in Djibouti must know the income and the life cycle cost of the line. According to Patras (2009) the life cycle cost of the line is the sum of operation cost, Maintenance cost, Delay cost and risk cost. Therefore, by analyzing the life cycle cost and optimization of the maintenance strategy the companies can minimize the LCC. Generally, this thesis is essential because the two countries do not have future study on the maintenance and the life cycle cost of the new track.

Some of the other points elaborating the need for the current research are:

- To determine the effective maintenance strategy in order to decrease the maintenance cost,
- Better prediction of inspection interval, grinding interval, tamping intervals and renewal for the development of an effective maintenance procedure, and
- Determine the impact of availability and reliability of the railway line on the life cycle cost.

1.3 Objectives

The objective of this research is to provide support for the two Countries when making decisions on the maintenance strategy and future plan.

The specific objectives of the thesis are:

- To develop model and analyze the life cycle cost of Ethio- Djibouti railway track
- To optimize the Maintenance strategy and identify an effective maintenance plan which reduce the LCC cost,
- To predict the life time of the track component and determine the renewal cost,
- To analyze the impact of lubrication as well as grinding on the rail life and compare life cycle cost of rail with or without lubrication,
- Calculate the inspection interval effect on rail brake, rail Defect, derailment and train delay cost,
- Determine the minimum rail life cycle cost by optimizing the best inspection interval which give the lowest cost on rail defect and broken repair, derailment cost and train delay cost,
- To determine the Life cycle cost of sleeper, and
- To determine optimal renewal of ballast and analyze the LCC of ballast.

1.4 Scope of the Research

Rail infrastructure consists of various sub-systems such as track system, signaling and telecommunication system and power system. Each of these sub-systems contributes to LCC of the infrastructure. In this research it considers only the track system; Although LCC activities are applicable in all the phases of the system life cycle, this thesis considers the RAMS and LCC methodologies only in the operation and maintenance phase. The thesis presents different maintenance models for the railway infrastructure. However, the models consider track component failure prediction separately instead of track failure prediction as a whole. The reason for this limitation is the immensity and complexity of the research area. The models provide decision support for the two Country when making decisions on the inspection and maintenance so as to achieve the RAMS targets for the infrastructure.

1.5 Structure of the Thesis

This thesis consists of seven chapters. The content of each chapter is described as follows:

Chapter 1: starts with an introduction giving a brief background of the research area followed by problem statement. Then the purpose of the study and the limitations have also been outlined in this chapter.

Chapter 2: review of previous literature which focused on the life cycle cost, maintenance work and track Degradation

Chapter 3: describes the degradation behavior of track component and the maintenance action that applied to reduce or prevent the track failure.

Chapter 4: This chapter discusses in detail LCC Modelling and the component of the LCC. It express the factor of LCC, discount rate, Steps of LCC and Data collection and analysis. Finally, forecasting the transportation shared by Ethio –Djibouti railway line and determine the traffic load on the line.

Chapter 5: is the core of the thesis which analyze the Life cycle cost of Ethio – Djibouti railway track. In this chapter the LCC of Rail, Sleeper, Fasting and Ballast are analyze.

Chapter 6: conclusions and recommendations.

Chapter 7: recommended future studies.

Chapter 2 Literature Review

2.1 Introduction

Railway infrastructure is a large and complex system with a long useful life with respect to availability demand. In order to guarantee optimal long-term results for the railway systems the effects of decision should be systematically evaluated (Zoeteman, 2001).

The infrastructure manager is responsible for the design, construction, maintenance, renewal and upgrading of the infrastructures; has a clearly defined role and is confronted by increasing performance of the actors. Budgets are reduced as reliability and availability have to be increased without endangering the traffic safety. A systematic approach is needed to facilitate the communication between the infrastructure manager and the government in order to guarantee a defined levels of performance of the infrastructure. Therefore, the performance of the infrastructure depends largely on the maintenance and renewal decisions taken during its life cycle. The design phase of the track needs to consider not only the cost, but also aspects like Reliability, Availability, Maintainability, and Safety and Life Cycle Cost, with respect to technological advancements and changes. After the installation, during the operation and maintenance phase, LCC and RAMS are considered when making effective maintenance decisions.

According to Patras (2009) emphasis based on the applicability of RAMS and life cycle cost analysis in order to develop maintenance decision models for railway infrastructure. Patra (2009) also examines how different maintenance strategies affect the RAMS requirements of the infrastructure. The overall goal is to achieve the RAMS levels stipulated for the railway infrastructure at a lower maintenance cost. He also demonstrates different approaches and models for achieving a more cost effective maintenance strategy for the railway infrastructure. An important aspect of the rail infrastructure is that the assets have a long useful life. If the railway line is installed, the reliability and availability of the track mainly depends on the maintenance policy therefore LCC and RAMS are considered in order to make effective decisions.

RAMS analysis will help to identify different maintenance alternative to be applied on to the infrastructure. It provides a system that can guarantee the achievement of goals of the infrastructure. LCC analysis will help in optimizing the cost effectiveness of the maintenance action delivered from RAMS analysis. In addition, LCC analysis should not only be as an approach for determining the cost of the system but also as an aid for decision making in design and maintenance. LCC cost can be presented in net present value cost.

2.2 Life Cycle Costs (LCC)

Life cycle cost is defined as all costs associated with the system life cycle or "the cost of an asset throughout its life cycle, while fulfilling the performance requirements (Tzanakakis, 2013).

Which includes:

- Production and construction cost;
- Operation and maintenance cost; and
- System retirement and phase out cost.

Life cycle benefit is a methodology for the systematic economic consideration of life time costs and benefits over a period of analysis. Life cycle benefit is equivalent to LCC plus external costs, thereby defining as a comprehensive term included within it life cycle cost and covering a wide range of analysis.

Life cycle benefit is a tool, to assist in making decisions between different options with different cash flows over a period of time. In this respect it is a form of investment analysis. LCC consider construction cost, operation cost, Maintenance Cost, Occupancy and end of life, whereas Life cycle benefit consider LCC, non-construction cost, income and Externalities.

In order to be able to estimate life cycle costs of the rail infrastructure, factors influencing the performance of the railway infrastructure and their relationship need to be identified. The driving factor causing failures and maintenance is the deterioration of the asset. Track deterioration depends on many factors, such as initial quality of construction, the quality of the substructure and the loads on the track. Besides asset deterioration, the factors that also influence the life cycle costs are RAMS targets for the track, the amount of preventive maintenance, market prices of labor, shadow price, materials and machines, and the operational characteristics of the line such as axle loads, traffic intensities and the duration of train down time (Zoeteman, 2001).

Since the cash flows occur during different operational years, to take these into account all future costs are discounted to present values of cost, Patra (2007). According to Esveld (2001) total present value cost (TPVC) is the sum of all discounted cash flows which is calculated as:

$$TPVC = \sum_{i=0}^{N} \frac{C_i}{(1+r)^i} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.1$$

Where:

TPVC = Total present value cost
C_i= Sum of all costs incurred in year i
i= initial year of analysis period
r = Discount rate
N = Last year of the analysis period

The larger TPVC, the less attractive investment compared to other alternative investments or maintenance.

2.2.1 The Purpose of LCC

For the maintenance management of the railway asset, cost modelling of railway infrastructure has three major purposes:

- To estimate costs of a maintenance/renewal work,
- To assist in the selection of the best maintenance option/strategy in terms of capital return under specified time and financial constraints, and
- To assist scheduling of maintenance works in the most effective way.

2.2.2 LCC Process

In order to develop a robust LCC model, it is imperative to consider all the factors that influence the LCC as well as the risks associated with it. Life cycle costing of the track infrastructure is a continuous process as cost-effective solutions are not reached within budget constraints and without affecting safety and availability of the track. The value of LCC, which is generally modelled in the design phase changes when the system enters into the operation and maintenance phase due to change in stakeholders' requirements and the costs incurred during the operation and maintenance phase become predominant. The operation and maintenance costs become the basis for taking decisions on the maintenance and renewal actions of the track. The figure 2.1 shows the different steps for estimating the life cycle cost of the track infrastructure during the operation and maintenance phase. The input parameters for each step in the LCC process and the corresponding outputs are described (Patra, 2007).

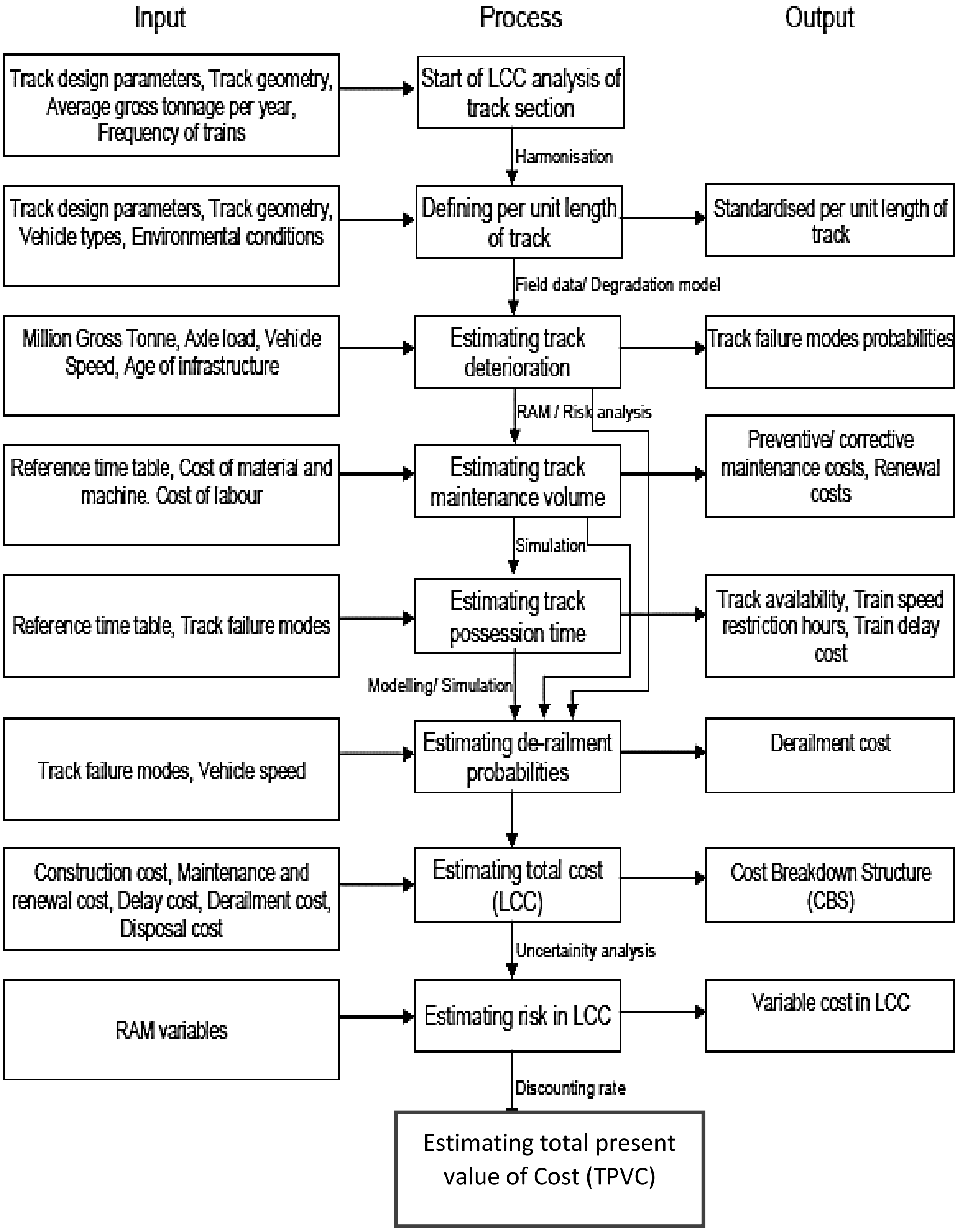


Figure 2.1 Life Cycle cost Analysis

2.3 Track Maintenance and Renewal

Generally, railways are used very frequently and they play an important role in transporting thousands of people as well as large amount of goods on a daily basis. The integrity of railway tracks is challenged by the friction forces caused by trains passing over them and corrosive effects of the surrounding environment. Because of that, railway tracks require regular maintenance in order to function properly. There are several maintenance operations that aim to increase a railway's life span, but in some cases none of these operations is sufficient and the entire railroad section needs to be renewed. Railway organizations generally use different maintenance and renewal (M&R) techniques due to their existing facilities e.g., technologies, human resources, and collaborations with universities and research institutes (Guler, 2013).

Maintenance is defined as the combination of all technical and administrative actions, including supervisory actions, intended to restore it to a state where it can perform a required function (Tzanakakis, 2013).

Maintenance action can be classified into two categories they are:

- Preventive Maintenance; and
- Corrective Maintenance.

2.3.1 Renewal

Railways maintain their infrastructure using a combination of ordinary and renewal maintenance techniques. Ordinary maintenance generally includes the replacement of small quantities of infrastructure components using relatively small track gangs and small equipment, whereas renewal maintenance techniques involve the replacement of larger quantities of components with larger gangs and bigger, more sophisticated, and more expensive equipment (Grimes et al, 2006).

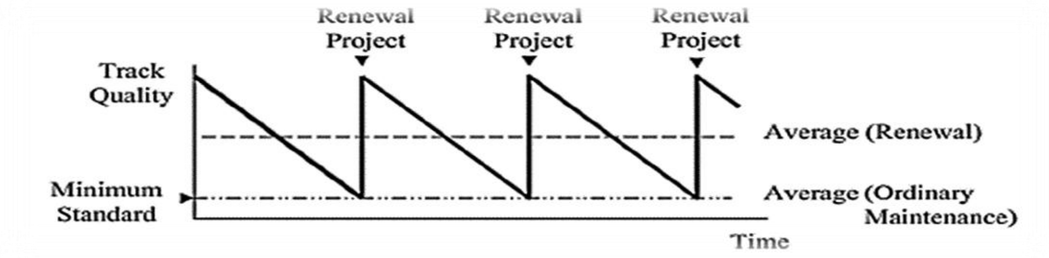


Figure 2.2 Comparison of temporal relationship between renewal and ordinary maintenance and track quality

The objective of track component renewal is to inform and support decisions that considers not only the railway track LCC but also the track occupation times required to perform interventions. Track renewal also minimizes railway track unavailability caused by railway track maintenance (Andrade, 2008).

2.4 Track Deterioration

Track geometry deterioration is a complex phenomenon that occurs under the influence of dynamic loads and is normally calculated as a function of traffic in millimeter/MGT, or time in millimeter/year. Some factors that can affect the track geometry deterioration are shown in the Ishikawa diagram in Figure 2.3. These factors are classified as Design, Construction, Operation, and Maintenance (Khouy et al, 2014).

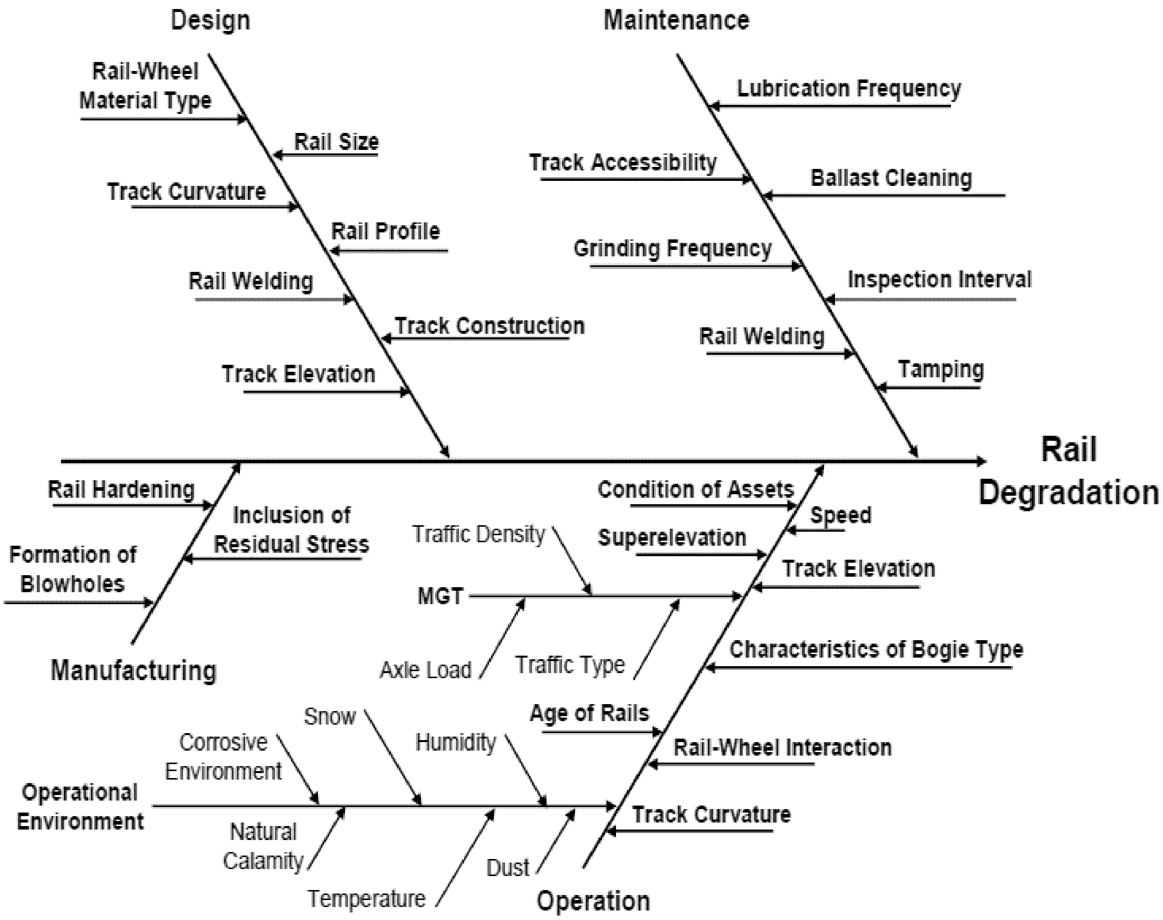


Figure 2.3 Ishikawa diagram (cause and effect diagram) for the factors influencing rail degradation (Kumer, 2006)

The deterioration of rail tracks is a complex process, where each major component may degrade and fail due to several modes. Deterioration of one component also affects another component, in addition several deterioration modes often occur concurrently. Most deterioration modes of track components and degradation of the whole track, are dependent on traffic and operating conditions.

2.4.1 Deterioration of Rail

Rail degrades in terms of wear (primarily in curves), fatigue (in the form of various defect types), and plastic flow (in the form of corrugation in rails, together with mushrooming of the rail head) (Zhang et al, 1997).

Wear Excessive gauge face: wear has been the major problem in curves on heavy haul railway tracks and a controlling factor of rail life in many cases (Kalousek, 1987).

Surface/Subsurface Defects: Surface initiated defects include head checking and surface cracking. Surface checking or surface initiated rolling fatigue does not itself represent a significant loss of material from the rail surface, unless it results in material removed (Kalousek, 1987).

Rail Corrugation: gives rise to dynamic forces, causing noise, discomfort to passengers, possible damage to freight, accelerated wear of rails, and damage to sleepers, fastenings and ballast. Because the formation of corrugations is a complex process, studies into the cause of rail corrugation often lead to discrepant conclusions. One study concluded that “soft” rail materials are vulnerable to corrugations (Zhang et al, 1997).

Kumar (2006) stated that Wear and fatigue in rails are significant problems for rail industries. These are major contributors of rail deterioration depending on operational conditions such as train speed, axle load, rail-wheel material type, size and profile, track construction, characteristics of bogie type, Million Gross Tones (MGT), curvature, traffic type and weather.

Rail break is the last phase of crack development process. As the crack goes on increasing in length as well as in depth, stress concentration also goes on increasing and finally rail break occurs, but this does not happen in all cases. Sometimes rail head material removal takes place and a portion of rail material comes out as crack develops. The end result of a crack is governed by its development path. It is very difficult to predict the crack development path as it depends on several factors. Some of the cracks are removed by wear process during initial stages of crack development while most of them are removed in grinding campaigns. Not all cracks impose derailment risk, but they are the major contributors to rail Deterioration.

2.4.2 Deterioration of Sleepers

Concrete sleepers could become a dominant deterioration mode. The area under rail pads can cause concrete sleeper degradation due to intrusion of fines, dust, and moisture, the area can also be worn out, resulting in settlement of rail pads, and looseness of fastenings (Reiff, 1993).

2.4.3 Ballast Deterioration

Ballast fouling, which is a major degradation mode, is a process of ballast voids being filled with fines, from either ballast particle abrasion or foreign substance intrusion such as windblown dust, spillage from wagons, and pumped fine from underlying subgrade Most researchers suggest that the majority of fines are from the ballast itself, as a result of abrasion, impact and physical and chemical weathering (Selig et al, 1988). The deterioration process is influenced by track loading, particle size distribution, and particle shape and surface characteristics.

2.5 Track Failure Prediction and Maintenance Optimization

The first step of the track maintenance planning process is to determine the condition of the track at some future point when maintenance may need to be performed. This is done through a track degradation model that predicts the condition of the track at a specified point in the future. For model development, a simplified degradation model based on Normal Distribution, Log normal Distribution and Weibull distribution was used, but more advanced models will be applied as they are identified or developed. Most research suggest that Weibull distribution is the best probability graph for track failure. The Weibull distribution is commonly used to represent the distribution of the time to failure for similar components including most aspects of railroad track (Lovett et al, 2013).

One reason for selecting the Weibull distribution from other distribution is its ability to provide reasonably accurate failure analysis with extremely small sample size. The cumulative distribution function (CDF), given in equation 2.2, describes the percentage of the component population expected to have failed prior to a given age. The shape factor, α, determines the probability distribution and the scale factor, β, is based on the average life of the component. The variable x is the age of the track in either years or million gross tons (Lim et al, 2004).

$$F(x) = 1 - e^{(\frac{x}{\beta})^{\alpha}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 2.2$$

Where:

F(x) = cumulative failure distribution

e= 2.72

α= shape factor

β= scale factor

x= Age of the track

2.5.1 Rail Failure Prediction and Maintenance Action

Developing Rail Failure Prediction approach is based on the factors influencing the rail degradation process .This will help to better estimate the risk associated with rails, providing better understanding of the existing rail maintenance procedure, prevent the occurrence of rail failures by taking the required action at the right time and extend rail life expectancy by developing an effective rail maintenance procedure. An approach to rail break prediction has been developed and described. Rail break data have been extracted from different databases, classified according to a classification framework developed and analyzed over a period of time based on Million Gross Tones (MGT) of traffic using Weibull distribution. During the process of data evaluation and analysis, a method of extracting useful information from incomplete data has been identified. This will help to better estimate risk in rails, better understand existing rail maintenance procedures, prevent occurrence of the predicted rail failures by taking the required actions at the right time and extend rail life by developing an effective rail maintenance procedure (Kumar, 2006).

Rolling contact fatigue defects (head checks, gage corner cracks, squats, and shells) are reported to be a major problem on the larger railways. These types of defects are dangerous in that they appear in groups, and a single break may lead to consequential breaks and catastrophic rail failure (Reiff, 2000). According to Liu et al (2012) Broken rails are a major cause for Derailment many things must generally go wrong to cause a rail break such as Transverse defects, Thermite welds, Vertical split, internal fatigue, Bolt holes, Squats and Weld Joint.

Bolts generally fail due to yielding, and bars usually fail due to fatigue. The discontinuity in the running surface of the rail creates conditions that can accelerate track degradation around the joint. At a minimum, the gap at the rail ends within the rail joint is a source of impact loading from passing wheels. If left unchecked, these impact loads increase rail end batter, thereby deteriorating the foundations, which further increase the impact forces generated by passing wheels (Akhtar et al, 2010).

The defect must be missed or wrongly sized by inspection; and a high dynamic load may be needed to cause final fracture. For this reason, broken rails can be considered random events. The Weibull statistical approach has been used in North America to predict broken rails. Taking out increasing numbers of defective rails does not appear to lead to lower numbers of broken rails. Similarly, taking out reducing numbers of defective rails does not necessarily lead to higher numbers of broken rails.

2.5.1.1 Optimization of Rail Defect Inspection

The effectiveness of rail inspection depends on the efficiency and accuracy of the inspection equipment. It also depends on skills and experience of inspectors. Errors in inspection are important issues and its reduction is a big challenge. This mainly depends on the technological limitation of the inspection equipment and skill level of the rail inspectors. Figure 2.4

shows the Venn diagram of inspection and detection rail breaks and derailments. The Venn diagram shows the percentage of defect detected by different inspection procedures. By improving the inspection techniques and more efficient equipment, reduction in undetected defect and false detection is possible (Kumar et al, 2006).

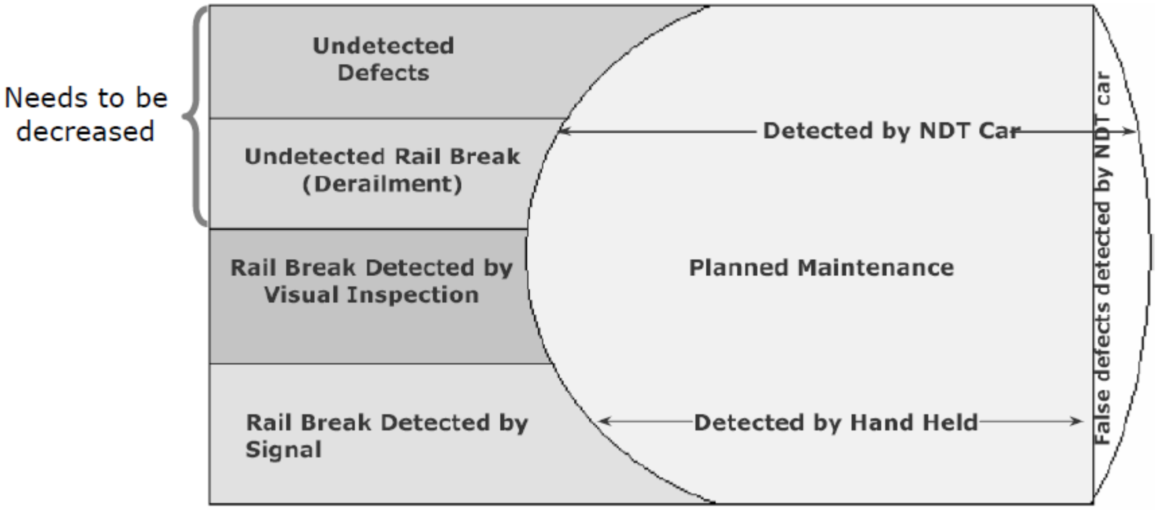


Figure 2.4 Venn diagram of inspection and Detection rail breaks and Derailment (Chattopadhyay et al, 2005)

Ultrasonic inspection is the principal technology used by North American railroads to identify certain types of rail defects before they grow large enough to cause a broken rail, FRA (2014). The occurrence and growth of rail flaws is a stochastic process, but the probability of defect formation is positively correlated with the cumulative tonnage passing over a rail (Orringer et al, 1988). Probabilistic estimation of the formation of rail fatigue defects is generally modeled using a Weibull Distribution, which describes the probability that a rail has a defect at a given time or tonnage (Davis et al, 1987; Orringer, 1990).

The U.S. Department of Transportation Volpe Transportation Systems Center (hereinafter referred to as the Volpe Center) developed an engineering model to estimate the number of broken rails between two successive inspections given inspection interval and rail age (Orringer et al, 1988; Orringer, 1990; Jeong and Gordon, 2009). The model was further enhanced and implemented by ZETA-TECH Associates (Palese and Wright, 2000). The model recommends the frequency of rail defect inspections, and its use on at least one railroad is reported to have helped them reduce broken rail caused derailments (Zarembski and Palese, 2005). Total annual inspections increases, broken rail caused train derailment likelihood decreases, at a diminishing rate.

In addition to derailment risk, operational and train delay costs related to rail defect inspection are also important (Davis et al, 1987). The rail defect inspection cost model (INSPEC) developed by the Association of American Railroads (AAR) in the late 1980s predicted annual costs related to rail defect inspection, including derailment damage costs and costs for repairing a detected rail defects or broken rails (Davis et al, 1987). However, the data used in that model needed to be updated, in part because of changes in traffic volume, axle load, improved rail steel, and better rail maintenance practices. Liu et al (2014) developed a model to optimize rail defect inspection frequency accounting for both transportation safety and efficiency given specified operating characteristics.

2.5.2 Optimization of the Maintenance Strategy

The cost effectiveness of any system depends on the operational availability and life cycle cost. In order to make the system more cost effective, higher availability should be attained at a lower LCC. However, there are numerous challenges in attaining the desired cost effectiveness of the system over a period of time, because of deterioration of the systems, changes in traffic scenario etc.

Optimization of the maintenance policy is one of the major ways to attain the desired cost effectiveness of the system in the long run. All such optimizations should aim at maximum system availability and minimum life cycle costs, as well as minimum train delays for a specific traffic scenario and minimum accident.

Optimization of the maintenance is a process that, as its name implies, seeks the best solution by setting priorities and making compromises to achieve what is most important (Campbell and Jardine, 2001). The first step in optimization is to specify which objectives are most desirable, such as maximizing availability, minimizing cost, etc. In maintenance optimization, objectives are usually defined by maintenance purposes (Cui, 2008). All constraints should be considered before the optimal solution is determined. When it is not possible to achieve all objectives simultaneously, a choice should be made between the objectives to find the best solution. Techniques for maintenance optimization include Figure 2.5 which shows the elements of a decision support system for track maintenance planning. An important element of such a model is the explicit inclusion of risk variables to deal with the impact of track condition on train transit times, reliability of arrivals, accident/derailment potential, and ultimately rail business revenue (Maria, 2011).

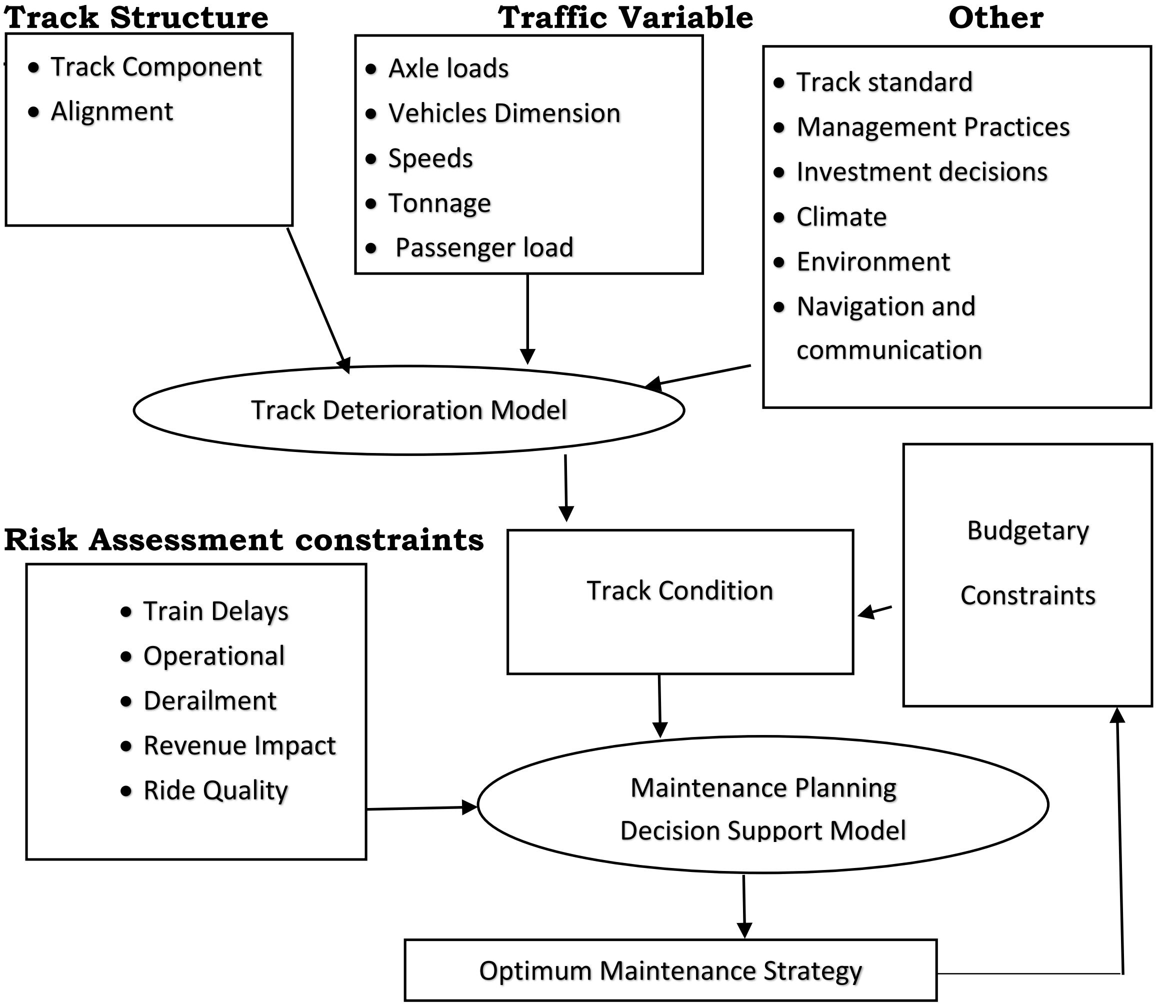


Figure 2.5 Optimization maintenance strategy

Chapter 3 Track Degradation and Maintenance

3.1 Track Deterioration

Deterioration is the reduction of the original quality due to various influences. By far, the most significant factor contributing to the deterioration is the Traffic load. The Traffic load is directly related to the axle load and track geometry. The main processes of track deterioration are:

- Wear;
- Fatigue; and
- Settlement.

Three main groups of factors may be distinguished that contribute to the deterioration of railway infrastructure:

- **Use**: wear by physical contact, static and dynamic load;
- **Environment**: climatic influence, water; and
- **Failures**: faulty components, bad construction.

The deterioration curve of the railways track component is shown in Figure 3.1 below.

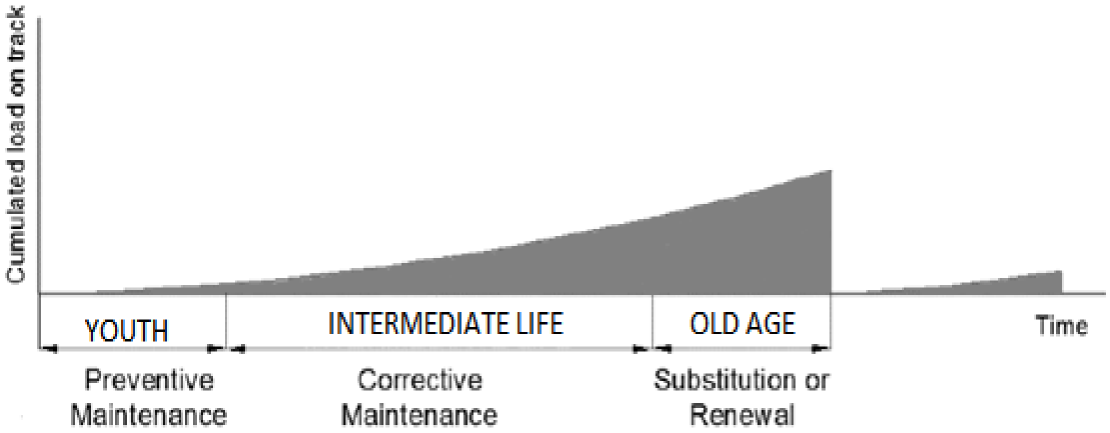


Figure 3.1 Degradation Curve (Tzanakakis, 2013).

The life of such components can be divided into three distinctive parts:

- **The youth period**: During the youth, the component experiences substantial deterioration due to track settlements.
- **The intermediate life**: After a while, the importance of degradations diminishes and the component starts its intermediate life.
- **The old age period**: When reaching the end of its lifetime, the component undergoes higher degradations.

3.1.1 Deterioration of Rails

Rail is mainly affected by surface defects due to the interaction between wheel and rail under various operation conditions. Rail deterioration will result in a rougher rail surface and increases in dynamic forces of high frequencies. The key Deterioration that limit the serviceable life of rail are:

- Loss of rail profile;
- Rolling Contact Fatigue (RCF); and
- Rail breaks and defectives from various sources.

3.1.1.1 Loss of Rail Profile

The loss of rail profile is a cause for premature replacement of rail in track. This loss of rail profile can be through vertical wear, 45° (side) wear and Plastic deformation of the rail. Most research investigations disclosed that vertical wear is maximum rail life determining factor for the majority of tangent line. Wear increases with increasing rail curvature (decreasing radius), with curve radii of less than 1000m exhibit significant amounts of 45° wear than for vertical wear.

3.1.1.2 Rolling Contact Fatigue (RCF)

Rails are subjected to cyclic loading in service, the stress range and the magnitude of stresses being dependent on a range of variables including the rail and wheel profile, the contact patch position and size, and the dynamic track forces from the vehicle. Therefore, the phenomenon of fatigue is of critical importance to longevity of rails. The two major classifications of rolling contact fatigue (RCF) that are primarily of interest to mixed traffic railways are "squats" and "head checks" both of which can be associated with early propagation of crack and crack development process consists of three phases:

- crack initiation;
- crack propagation; and
- Fracture or rail break face or near surface initiated rolling contact fatigue cracks.

Crack initiation: When the wheel passes over a rail section, the axial load continues to increase and decrease cyclically. This process continues for a certain number of cycles until plastic deformation begins, usually at a relatively weak location. These deformations take place as a result of compressive and shear forces. This process goes on for a few cycles until a micro-crack is formed in the rail surface. These micro-cracks develop into cracks when stress is repeatedly applied (micro-cracks may not always develop into cracks). Once a crack is initiated, stress concentration occurs at both ends of the crack causing it to continue to grow. Cracks initiate in a very thin surface layer of the rail and develop inside the rail head (P.L.Barkan, 2008).

Crack Propagation: The Crack propagation depends on the rail material, the point of crack initiation and the kind of metallurgical processing or the heat treatment method adopted for that particular rail section. If the crack propagation is in an upward direction towards the rail surface, pieces of rail material detach from the rail surface, but if these cracks propagate downwards, they may cause a rail break. Crack propagation rate is accelerated by fluid entrapment. The presence of water, snow or lubricant on the rails may increase the crack propagation rate. When these small head checks are filled with water or lubricants they do not dry up easily. During wheel-rail contact, these liquids get trapped in the crack cavities and build up very high localized pressure, which may even be greater than the compressive stress. If head checks are in the direction of train traffic, crack growth takes place due to liquid entrapment, but when head checks are in the opposite direction of train traffic, the liquid is forced out before its entrapment (P.L.Barkan, 2008).

Rail break is the final result of the crack development process. The first two phases of crack development are critical for railway engineers, as it is during this phase that the crack should be detected by the inspection techniques and consequently rectified by suitable implementation of maintenance or replacement measures.

Investigation observed that surface crack lengths of less than 17mm the crack depth is less than 5mm, but above 17mm the crack length increase up to a maximum of 10mm. The reason for this is the mechanism by which RCF cracks grow, illustrated in Figure 3.2 whereby cracks initially grow at a shallow angle to the surface after propagating to a certain length, observed experimentally to be approximately 5mm, after which the cracks branch and turn down into the rail (P.L.Barkan, 2008).

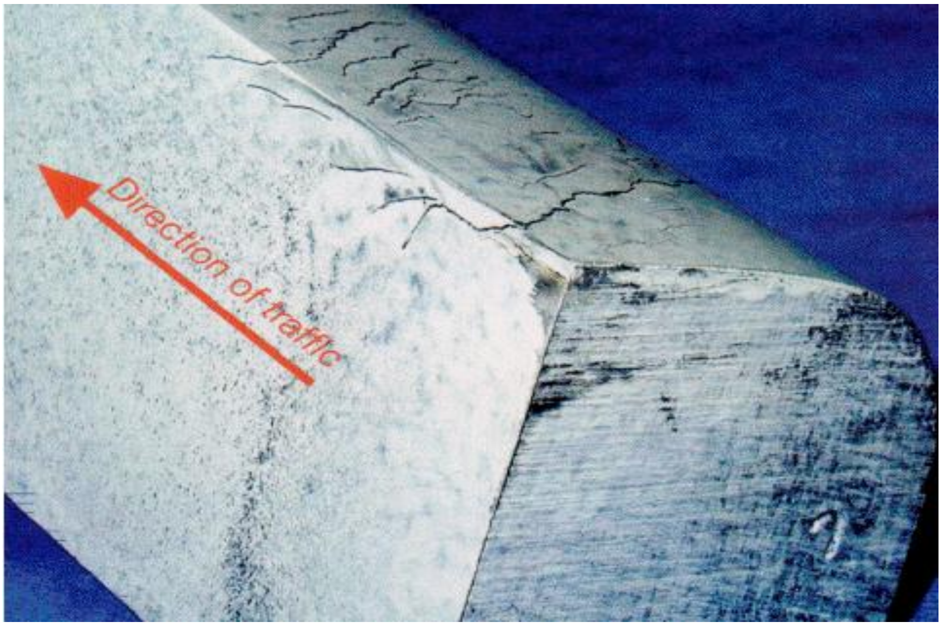


Figure 3.2 RCF crack growth

3.1.1.3 Rail Breaks and Defectives

Rail breaks are serious defects that lead to rail failure and derailment. Depending on severity of occurrence maintenance must be initiate within 24-48 hours or do a temporary repair, Examples:

- Fractures;
- Head/web separations;
- Cracks;
- Horizontal/vertical split head;
- Base Defect;
- Transverse Defect;
- Broken Base;
- Original Break; and
- Broken rail.

3.1.2 Deterioration of Sleepers and Fastenings

The sleeper and fastening deterioration depends on traffic and operational factors such as axle loads, speeds, and accumulative tonnage and maintenance practices. Concrete sleepers deterioration composes:

- Sleeper cracking;
- Loosening of fastenings when support of the sleeper is inadequate; and
- Abrasion of the soffit due to excessive movement of sleepers or bad ballast conditions.

A vital factor for the fastenings in track to function successfully is the condition of the sleepers. Deterioration of fastenings such as loose, broken or missing fasteners influences other track components. Also track geometry irregularities arise and other deterioration modes become apparent on track components.

3.1.3 Ballast Deterioration

A newly produced ballast bed consists almost entirely of the skeletal grain. Due to the operating loads from the trains, the edges of the new ballast will be highly stressed. The rolling of the wheel on the rail causes just before reaching the sleeper a slight lifting and then by rolling over the sleeper a hammering of the sleeper to the ballast. This leads to crumbling (splintering) of the ballast grains at the contact points. This continues until the contact areas are so numerous, that the loads can be transferred through the gravel to the sub-ballast and the subgrade. Over time however, the proportion of grain distance, forming an additional finer material, the filling grain that after an operating load of several million cycles encloses the skeletal grains. Thus, the internal friction angle of the material is going to be smaller, the shear strength is reduced and so the carrying capacity. Filling grain can also enter into the ballast bed by rising grains from fine-loamy or clayey subsoil.

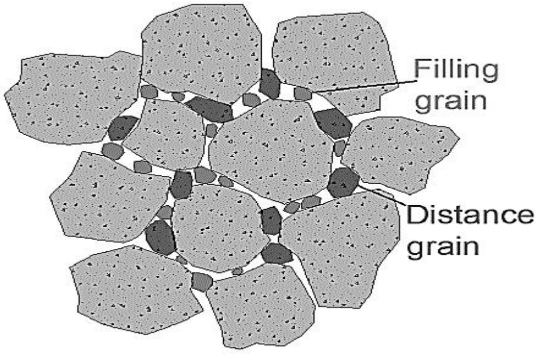


Figure 3.3 Dirty Ballast

3.2 Track Maintenance

Maintenance is define as the combination of all technical and administrative actions, including supervision actions, intended to retain or restore a state in which it can perform a required function (Tzanakakis, 2013).

Maintenance strategy can be described as “an arrangement of the “types” of Maintenance, which is to be done to the track and its components, at a specific Rate or frequency, under specific operating conditions” (Tzanakakis, 2013).

The maintenance plan presents "a description of the preventive and predictive maintenance and inspection tasks to be performed at maintenance objects. The maintenance plans describe the dates and scope of the tasks". A maintenance plan in the rail infrastructure sector is a yearly schedule defining when, where and by whom (Infrastructure Managers and/or contractor) a specific type of rail infrastructure maintenance has to be carried out. The maintenance planning is only related to renewal activities and preventive predictive maintenance, since corrective maintenance cannot be planned in advance (Tzanakakis, 2013).

Maintenance planning process is "the process of identifying maintenance needs, material availability and available budget in order to provide useful and realistic data input for rail infrastructure maintenance planning systems" (Tzanakakis, 2013).

Upgrading means any major modification work on a subsystem or part subsystem which improves the overall performance of the subsystem (Tzanakakis, 2013).

Renewal means any major substitution work on a subsystem or part subsystem which does not change the overall performance of the subsystem. The term "renewal" includes "all activities involved in replacing a rail infrastructure part or object by a same or similar type of rail infrastructure part or object" (Tzanakakis, 2013).

3.2.1 Types of Maintenance Strategies

There are many general types of maintenance strategies, such as

- Preventive Maintenance (PM);and
- Corrective Maintenance (CM).

3.2.1.1 Preventive Maintenance (PM)

Preventive Maintenance is "a set of activities that are performed on plant equipment, machinery, and systems before the occurrence of a failure in order to protect them and to prevent or eliminate any degradation in their operating conditions". By this type of maintenance, work is performed at predefined intervals on a routine basis regardless of whether functionality or performance of the asset is degraded. At the assets age, the frequency and number of checkpoints may need to be re-evaluated. These tasks require a relatively constant amount of labor and materials. The factors that affect the efficiency of this type of maintenance are: (Tzanakakis, 2013).

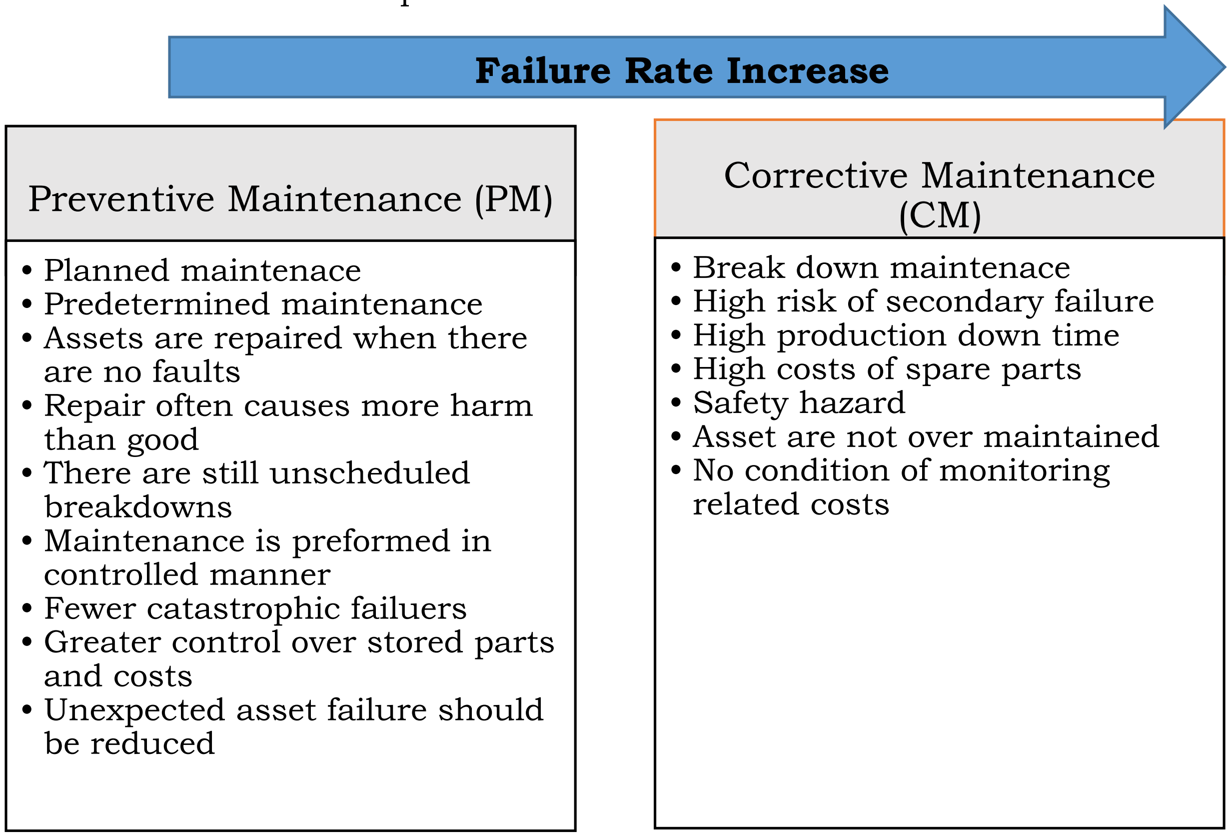
- The need for an adequate number of staff in the maintenance department in order to perform this type of maintenance,
- The right choice of production equipment and machinery that is suitable for the working environment and that can tolerate the workload of this environment,
- The required staff qualifications and skills, which can be gained through training,
- The support and commitment from executive management to the PM program,
- The proper planning and scheduling of PM program, and
- The ability to properly apply the PM programed.

3.2.1.2 Corrective Maintenance (CM)

Corrective maintenance is defined as: "the maintenance carried out after recognition and intended to put an item into a state in which it can perform a required function". In this type, actions such as repair, replacement, or restore will be carried out after the occurrence of a failure in order to eliminate the source of this failure or reduce the frequency of its occurrence. Corrective maintenance has several requirements in order to be carried out effectively:

- Accurate identification of incipient problems,
- Effective planning which depends on the skills of the planners,
- Availability of the required labor skills, specific tools, parts and equipment,

- Proper repair procedures,
- Adequate time to repair, and
- Verification of repair.



Failure Rate Increase

Preventive Maintenance (PM)

- Planned maintenace
- Predetermined maintenance
- Assets are repaired when there are no faults
- Repair often causes more harm than good
- There are still unscheduled breakdowns
- Maintenance is preformed in controlled manner
- Fewer catastrophic failuers
- Greater control over stored parts and costs
- Unexpected asset failure should be reduced

Corrective Maintenance (CM)

- Break down maintenace
- High risk of secondary failure
- High production down time
- High costs of spare parts
- Safety hazard
- Asset are not over maintained
- No condition of monitoring related costs

Table 3-1 Maintenance strategy and the failure rate

3.2.2 Maintenance Actions

Various types of maintenance actions are presented as encoded in a relevant technical specification of the Railways Organization.

3.2.2.1 Rail Grinding

Rail grinding is wearing and formation of crack on the rail head to reduce wear and rolling contact fatigue (RCF) (Reddy et al, 2007). Rail grinding allows the correction of the rail profile in the case of rolling contact fatigue (RCF) defects which arise on the rail surface. The purpose of rail grinding is to eliminate surface-initiated cracks which are in an initial stage. It is especially indicated in the case of corrugations, and is also able to correct or prevent cases of wheel burns, shelling, head checks, loss of rail head material and plastic flow. Preventive grinding also remove the corrugations that have grown since the last grinding cycle. If corrugations cannot be removed in a single pass, then multiple passes are applied (Reddy et al, 2007).

Most investigations in Figure 3.4 show that Rolling contact fatigue, in the form of head checks, is most prevalent on curves of 700-3000m radii. Curves less than 300m side wear is higher which results in the cracks being removed without grinding and effectively provides an RCF free rail, in which the life determining factor will be wear.

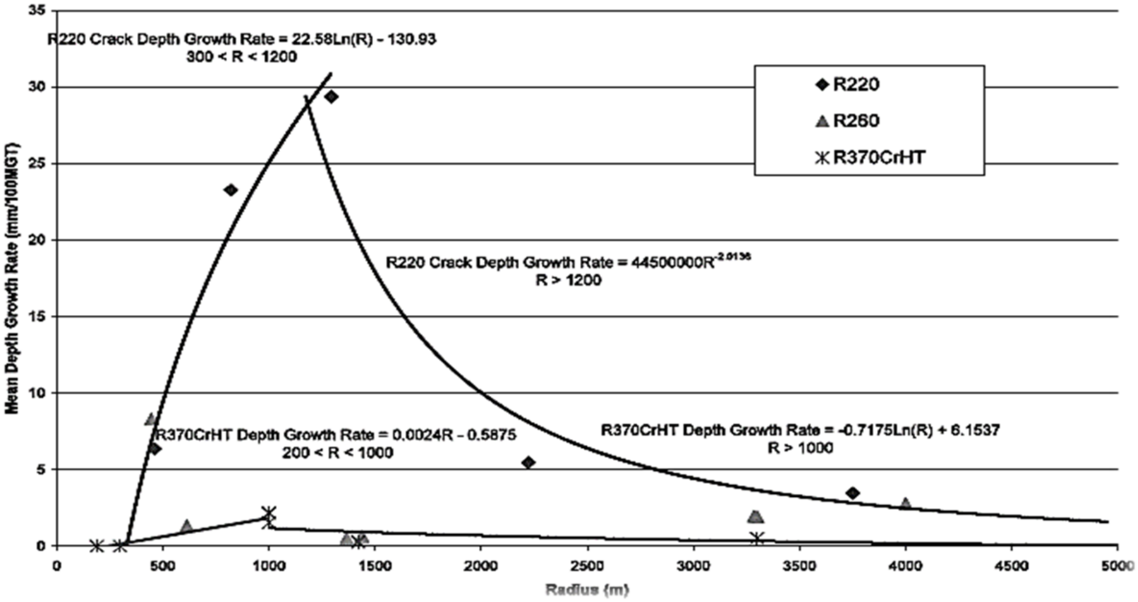


Figure 3.4 Mean crack depth growth rates for all rail grades

After grinding, wheel-rail relation is improved, incidence rate of damage is reduced and corresponding maintenance workload is decreased. Maintenance cost is also cut down at the different grinding interval, that the grinding is operated in different degree of rail damage and the condition of heavy damage or rail breaking is different, so the workload of corresponding emergency maintenance is decreased. Rail service life is also extended after grinding.

Meanwhile, considering that when grinding interval is larger, crack propagation is much deeper, and mental removal is large, repeat grinding is needed, which increases the difficulty of actual operation (Jianxi et al, 2014).

A typical rail grinding consists of a series of vehicles equipped with grindstone, which form a grinding effect on the rails surface, thus producing smooth surface and specific profile.

3.2.2.2 Rail Lubrication

Lubrication is used to reduce the friction and wear that occurs between the flange part of the wheel and the gauge side of the rail on curves with low radii. It also reduces railway locomotive fuel consumption and noise levels. Lubrication may however cause RCF defects to develop due to the presence of fluids (fluid entrapment), so it should be used cautiously. Another problem which may arise is the migration of lubricant material from the gauge face corner to the rail head surface, leading to wheel slipping – this may stimulate the appearance of head checks. Several lubrication materials are available, such as grease or oil based, solid lubricants, or combinations of several types. These may be applied by on-bogie mounted systems, or more frequently, by track-side permanent systems with automatic grease dispensing units.

The rail wear rate decreases with increase in curve radius for both high and low rails as shown in Figure 3.5. The wear rate ratio between non-lubricated and lubricated sites decreases for the curves with larger radius. Therefore, most research recommend that lubrication increase the rail life for curve radius up to 3000m but for greater radius lubrication effect is low.

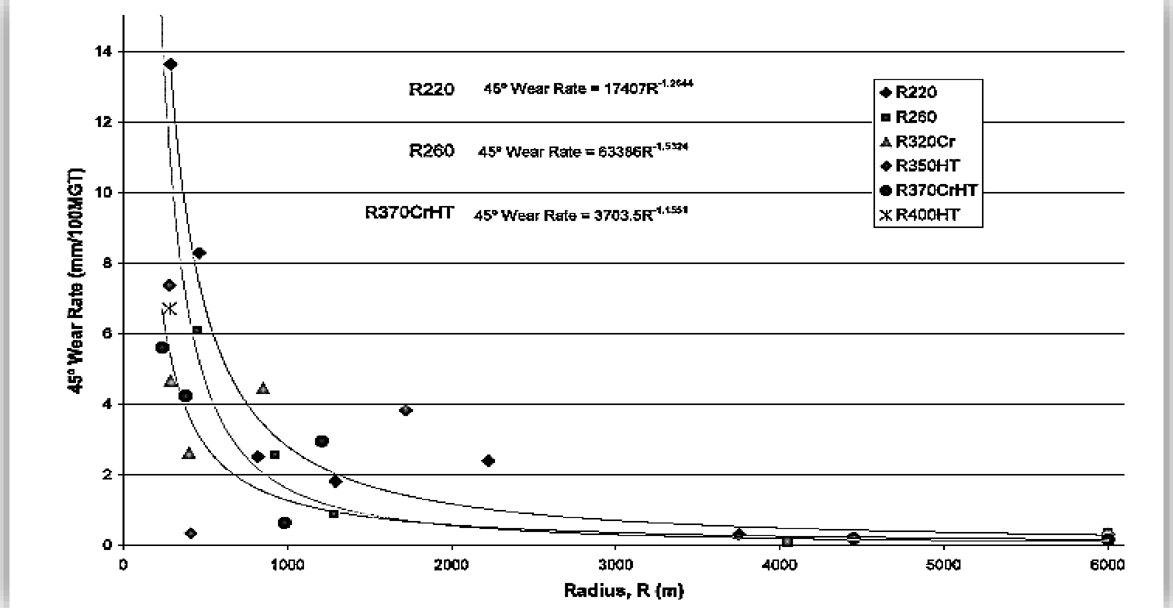


Figure 3.5 Mean 45° wear rate for all rail grades

3.2.2.3 Rail Replacement

Rail is replaced due to rail wear, fatigue defect or derailment damage. Appropriate field data is required to predict the rail life and to plan the replacement action.

3.2.2.4 Sleeper and Fastening Replacement

The cracking of the sleeper and missing of fastener will results in replacement of Sleeper and fastening.

3.2.2.5 Ballast Tamping and Renewal

The quality of the track geometry is highly dependent on ballast and substructure conditions. Currently, railways frequently use ballasted track, incurring high annual expenses for ballast maintenance and renewal. Track geometry maintenance (tamping) is used to compact ballast and correct track geometry faults including incorrect alignment (lateral deviation) and incorrect longitudinal level (vertical deviation).

Chapter 4 Modelling Life cycle cost of Ethio-Djibouti Railway Track

LCC Analysis is an engineering economics technique that can be utilized to focus on maintenance strategy to minimize the life cycle cost. LCC can be used as a tool to make cost-effective decision on investment, renewal and maintenance to adjust the three parameters to optimize the infrastructure performance. Also life cycle cost analysis calculates the cost of a system or product over its entire life span. The method is one of the most recommended for investment projects, assessment of different solutions over the whole life cycle and comparison of various strategy options.

LCC analysis will help in optimizing the cost-effectiveness of maintenance actions derived from RAMS analysis. Cost estimations through LCC help in foreseeing the cost implications of maintenance actions over the service life of the track not just in the short term. This chapter describes the utilization of RAMS and LCC methodologies in track maintenance planning. Proper RAMS analysis can help in effective maintenance planning of the track, it also answers the question which is the best way to maintain the track by analysis of Reliability, Availability, Maintainability and Safety:

- **Reliability**: - When should the track be maintained? (Predict “when” to take maintenance actions depending on the failure modes of the track).
- **Availability**: - how can railway traffic be least disturbed? (Predict the frequency and duration of track possession periods due to maintenance actions carried out on the track).
- **Maintainability**: - What maintenance activities should be performed? (Determine “what” maintenance actions need to be taken on the event of failures occurring on the track and “how” much time is taken to carry out those maintenance actions).
- **Safety**: - How can hazards be minimized during maintenance works? (Estimate the risk of carrying out different maintenance actions on the track in terms of severity and cost).

How can we be assured that over time the current maintenance practice is the most effective one and it can be answered by LCC analysis? LCC analysis is a method for calculating the total cost of a system or a product over its total lifespan. A very central target is the systematic process for evaluating and quantifying cost impacts. LCC analysis is primarily a method for decision making through economic assessment, comparison of alternative strategies and design. Within a LCC analysis all payments - also future payments - will be referred to a reference date using the discount rate.

Life-cycle Cost of the Railway Infrastructure includes construction costs (CC), spot maintenance costs (MC), maintenance and renewal costs (RC), delay costs (DC), organizational costs (OC) and hazard cost (HC). Every single cost is estimated for a specific year y and discounted to the base year considering a constant discount rate r, throughout the life-cycle, Esveld (2001).

$$LCC = \sum_{j=0}^{N} \frac{CC+MC+RC+DC+OC+HC}{(1+r)^{j}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.1$$

Construction Costs (CC): are those incurred during an initial phase, including design, materials, labor, equipment and risk.

Spot Maintenance Costs (MC): differ from periodic maintenance and renewal costs (RC). Spot maintenance is not planned and scheduled in advance throughout the infrastructure life-cycle, whereas, periodic maintenance is supposed to be planned in advance.

Maintenance and Renewal Costs (RC): maintenance costs in general comprise maintenance and renewal of track (rails, sleepers, ballast) and subgrade; maintenance of electrification, signaling and telecommunications facilities and substations; maintenance of tunnels and bridges; and also maintenance of platforms. All the components of the railway infrastructure, here understood in a wider definition, will start deteriorating once the operational phase commences, more slowly or rapidly depending on the specific component.

Delay Costs (DC): Basically unavailability of equipment due to failures requiring unplanned corrective maintenance, may also infer costs related to the operation of the trains, essentially delay costs. Thus, unavailability costs are here grouped into the following two categories. Short Term Delay Cost, i.e. costs of delays of relatively short duration (e.g. up to 30 minutes) while corrective actions are carried out. Long Term Delay Cost, i.e. cost due to any unavailability of rather long duration, requiring certain measures to be taken by the railway company in order to be able to get through the traffic.

Organizational Costs (OC): These should be included only if they change significantly due to a different decision alternative. Organizational costs are the annual flat costs required for inspection, overhead cost, maintenance planning and incident response.

Hazardous Costs (HC): Failure/unavailability of equipment may also cause hazardous events, giving the hazard cost: cost of hazards to humans (e.g. personal injuries, fatalities), cost of hazards to environment, cost of possible rebuilding (after accidental event), cost of clean-up (after accidental events).

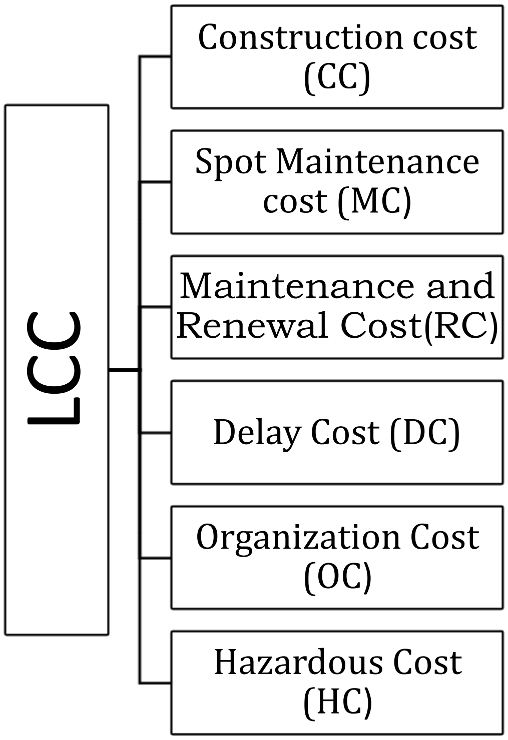


Figure 4.1 LCC cost component

4.1 Discount Rate and Economic Cost

The LCC is the expected total cost over life period, so all costs in the life converted to present time by a Discount rate. Discount rate is metric that determines the present value of a future cost.

The ministry of Finance and Economic development (MoFED) of Ethiopia calculate the discount rate for different sector of the project in order to make uniform comparison of projects. Therefore, the discount rate of Road/Rail infrastructure in Ethiopia at 2015 G.C is 10%.

The life cycle cost is an economical cost analysis which help to make decision on investment, maintenance etc. Therefore, all costs considered in the LCC analysis should be convert to economic cost. The costs prevailing in the market is a financial cost which include taxes and transfer payment that have to be converted to economic costs using conversion factor as provide by MoFED. So, the conversion factors for use from Financial to Economic costs show on table 4.1.

item	Conversion Factor World price (USD base)	Conversion factor domestic Price (Birr base)
Road/railway Construction cost	0.74	0.823
Road/railway maintenance cost	0.74	0.820
Construction plant and equipment	0.92	1.019
Local material	0.69	0.760
Import material	0.70	0.950
Labor – Expatriate	1.05	-
Labor – Skilled	0.76	0.840
Labor – unskilled	0.33	0.350
Gasoline(benzene) fuel	0.68	1.050
Diesel Fuel	0.94	1.050
Lubrication	0.60	-

Table 4-1 Financial to Economical Conversion Factors at 2015 G.C (Source *MoFED)*

4.2 Factor of LCC

Many factors influence the costs of railway track. Such as the quality of track asset (life time expectancy and failure chance) and the maintenance strategy applied (such as the amount of preventive maintenance and the number of incident repair teams). The factors that influence the cost level are:

- The initial quality of the infrastructure;
- The quality of substructure;
- Load on the track;
- RAMS target;
- Maintenance strategy;
- Market price of labor, machine and materials;
- Shadow price;
- Operation characteristics;
- Discount rate;
- Safety and risk; and
- Noise and vibration.

4.3 Steps of LCC

In this thesis, it help Ethiopia Railway Cooperation (ERC) make the decision on the best technical-operating and on most economical maintenance strategy in the future. The calculation of the life cycle cost of the Addis Ababa –Djibouti track takes place in processes as described below. The figure 4.2 are only meant to illustrate the calculation step.

Calculation Process 1: Estimating the loads on the infrastructure- the starting point of the estimation is an analysis of the transportation forecast. Traffic forecasting is used to get annual estimated tonnages in the line and to determine the timetable. The timetable can be specified for different time intervals in order to express traffic growth or decline on the line and contains the expected number of trains and train-sets for the different services, specified to e.g. axle-loads and train weights, as well as the number of operational hours per day. This timetable is also used for calculating the (annual) scheduled journey time.

Calculation Process 2: Estimating track deterioration- depends both on various tracks as well as vehicle characteristics. Estimation of total track failures will be done by means of track failure data and degradation models of track and vehicle.

Calculation Process 3: Estimating Track maintenance volume- Track maintenance volume consists of all the corrective and preventive maintenance as well as renewal activities. This is estimated by means of RAMS analysis of the various failure modes.

Calculation Process 4: Estimating Track possession time- A reference timetable describes the type of traffic frequency of trains as well as the train operational hours per day. Track possession time determines the track availability, train speed restriction hours and train delay by means of track failure modes and maintenance cost. Track possession times can be calculated based on the corrective and preventive maintenance actions.

Calculation Process 5: Estimating derailment probabilities- Train derailment probabilities are estimated by track failure modes, maintenance volumes and track possession time

Calculation Process 6: Estimating the life cycle costs- In process the total costs of ownership (life cycle costs), and the reliability and availability estimates are made. The construction costs are included in the total cash flows. Another choice is to include or exclude the specific risks. Finally, the economic cost are calculated considering the value of Shadow price, labor, operation cost, initial cost and discount cost.

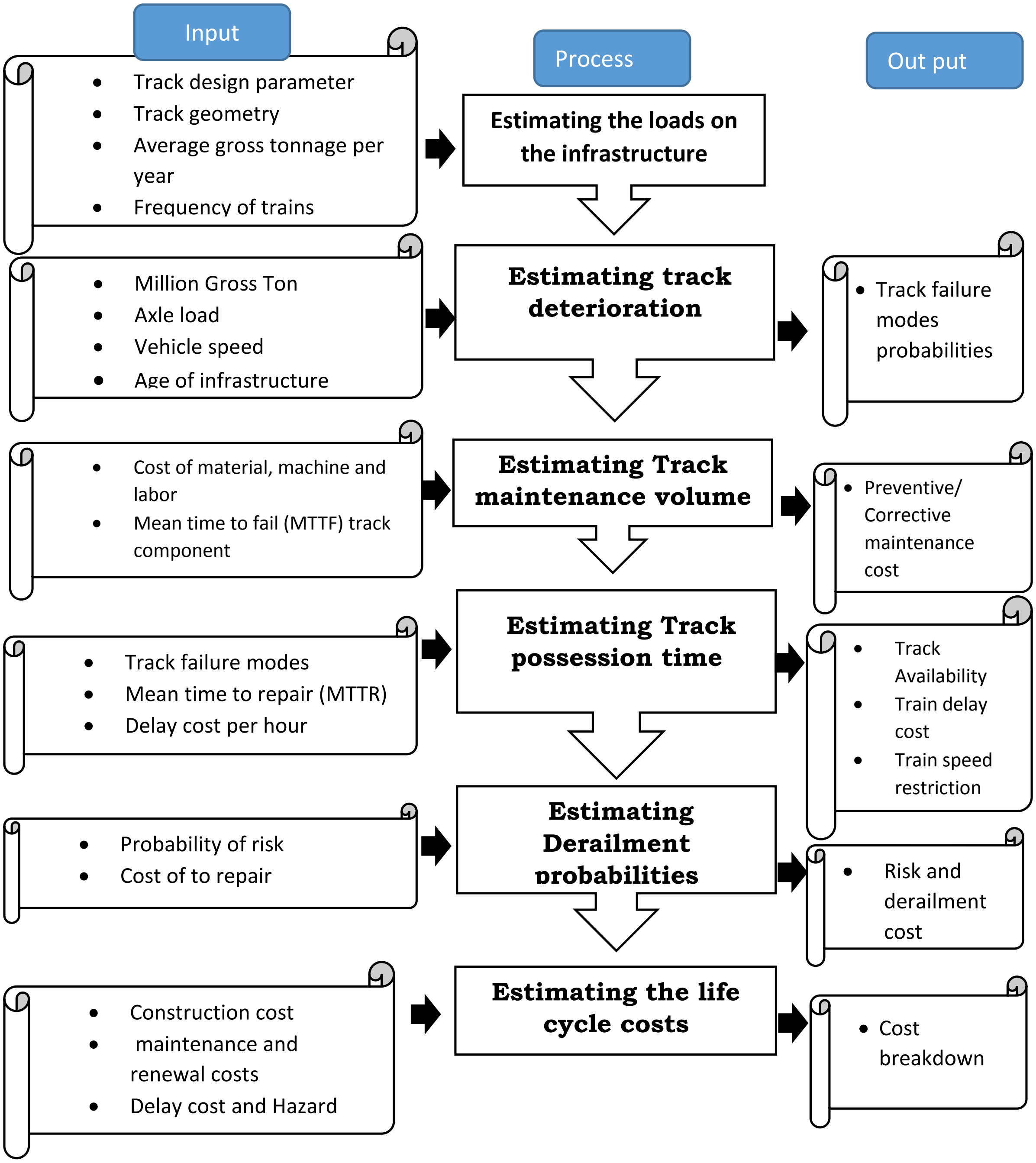


Figure 4.2 LCC analysis process

4.4 Data Collection and Analysis

The collected data for old Ethio- Djibouti railroad is not properly organized. In addition it is meter gage and different characteristics with the new line. Therefore, the data used for the new railroad is from other country which have the similar track type, operation speed, annual gross tonnage and the same characteristics.

Most of the rail players collect huge amounts of data when carrying out inspection and maintenance procedures. Analyzing these data to obtain meaningful information is a tedious job. At present, the rail maintenance data is interpreted through the experience of the technical people based on non-destructive testing and visual checks. The skill level of inspectors is important for assessing the criticality of the problem and taking appropriate maintenance decisions.

Different databases were searched to extract both qualitative and quantitative data. Relevant scientific papers and articles were extracted from online databases, such as ASCE library And Sage Journal. Some of the articles were searched from the references of other relevant articles. Different keywords were used for searching these articles, such as Life cycle cost analysis, rail defects, rail degradation, derailment, crack propagation, rail maintenance, inspection and grinding, rolling contact fatigue, Ballast tamping, Sleeper replacement etc. Different combinations of these keywords were tried to narrow down the number of hits. Some of the known articles were directly searched from the journal databases. Technical journals like European Railway Review were also examined. Some of the investigation reports were downloaded from the website of the Office of Rail Regulation (ORR), UK, Spoort (South Africa) and India Railway. Relevant books were searched from Lucia (Luleå university library's catalogue) and relevant reports, licentiate and PhD thesis from various universities were also studied.

The data required for transport demand forecasting were particularly secondary data. The secondary/historical data on particularly the economy, trade and transport sectors and the major sources of such data are public sectors such as ministry of finance and Economic Development (MoFED), Central Statistical Agency (CSA), National Bank of Ethiopia, Ethiopian Roads Authority (ERA), Road Transport Authority (RTA) and The Ethiopian Railway Corporation (ERC).

Data analysis in this thesis, failure analysis has been done in practice, components are subjected to different design, manufacturing, maintenance and operating conditions and will fail at different time intervals in future. Consequently, these times-to-failure obey a probability distribution which may, or may not be known and which describes the probability that a given component either fails within a certain specified time or survives beyond that time. Different probability distributions are used for failure analysis and prediction, but before using them, it is essential to conduct a formal verification that the failure data are independent and identically distributed. In reliability prediction and analysis, failure data are usually based on the assumption of being independent and identically distributed in the time domain.

Weibull distribution has been used in this thesis to analyze the data and predict the failure rate as it has the ability to provide reasonably accurate failure analysis and prediction with extremely small sample size. As the Weibull distribution is often used to represent the problems related to mechanical component aging, wear and degradation. A detailed analysis procedure has been described in in the following chapters.

4.5 Traffic Forecasting

The approach used to forecast the Addis Ababa – Djibouti Railway Line demand is based on past trip and travel characteristics that provide the basis for the “four-step process” of trip generation, trip distribution, modal choice, and traffic assignment

Theoretically transport traffic could be generated and forecasted at a macroeconomic level, at:

- Trip generation sub model: trip production and attraction based on population and import/Export activities,
- Trip distribution sub model: based on mainly “growth factor” type models,
- Modal split sub model: based on comparative costs, travel time and efficiency often using diverse logit model, and
- Traffic assignment sub model: based on future plan of using the port.

4.5.1 Freight Forecasting

Forecasting of freight transportation in Ethiopia mainly depend on the import and export volume which was gathered on the past years. The most appropriate approach for estimating the future volume of freight traffic for Ethiopian Railway Corporation along the Addis-Djibouti corridor consists of the following four steps.

- Estimation and projection (forecasting) the total volume of import and export by using Regression method.
- Determination of traffic passing through the port of Djibouti to different hinterlands.
- Assign the freight traffic to different part of Ethiopia.
- Modal split of the rail and road traffic.

4.5.1.1 Step One

To estmate the freight volume it has different method such as time, GDP and Trade. In this thesis the freight forecast by using least square regression method related of Time and import and Export data which was collected from the Ethiopian Revenues and Customs Authority(ERCA). In order to increase the accuracy use 13years import and export data from 2002 up to 2014G.C, were used the least Sequare Regression method to forecast the freight traffic is by using the following formula:

The equation of the regression line written as $y = a + bx$…………..4.2

Where: - a is the y intercept, b is the slope of the line, y is the tons and x is the year

$$a = \frac{(\sum_{j=1}^{n} y)(\sum_{j=1}^{n} x^2) - (\sum_{j}^{n} x)(\sum_{j=1}^{n} xy)}{n(\sum_{j=1}^{n} x^2) - (\sum_{j=1}^{n} x)^2} \qquad \text{4.3}$$

$$b = \frac{n(\sum_{j=1}^{n} xy) - (\sum_{j=1}^{n} x)(\sum_{j=1}^{n} y)}{n(\sum_{j=1}^{n} x^2) - (\sum_{j=1}^{n} x)^2} \qquad \text{4.4}$$

The correlation coefficient computed from the sample data measures the strength and direction of a linear relationship between two variables. The symbol for the sample Correlation coefficient is (r).

$$r = \frac{n(\sum_{j=1}^{n} xy) - (\sum_{j=1}^{n} x)(\sum_{j=1}^{n} y)}{\sqrt{[n(\sum_{j=1}^{n} x^2) - (\sum_{j=1}^{n} x)^2][n(\sum_{j=1}^{n} y^2) - (\sum_{j=1}^{n} y)^2]}} \qquad \text{4.5}$$

The import and export data is collected from ERCA. The data used in this thesis is for the period from 2002 up to 2014G.C and present in the Appendix-A and Figure 4.3

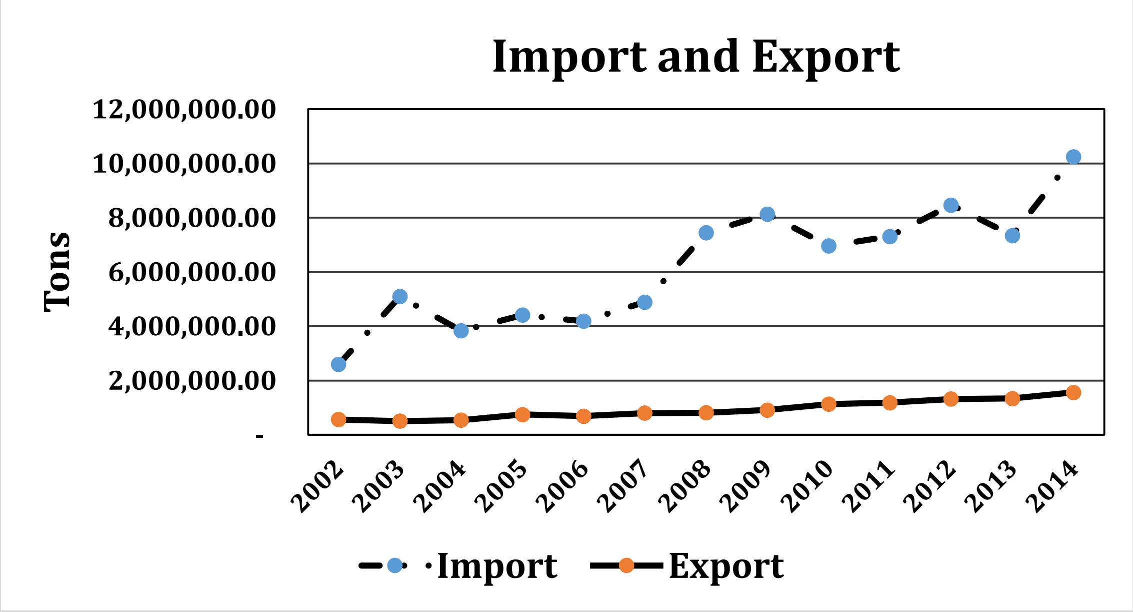


Figure 4.3 Import and Export of Ethiopian Trade Source (www.erca.gov.et)

The import tonnage varies each year depending on the situation of the country but it has been increasing from the starts year. The export increase is constantly from the start year but from figure 4.3 it is shown that the export tonnage is much less than the import tonnage. This tells us that the freight movement from Addis Ababa to Djibouti is less than from Djibouti to Addis Ababa.

The Regression values for Imports and Exports are shown in Table 4.2 below and the calculation presented in the Appendix-B.

	a	*b*	*r*
Import	-1021720267	511924.22	0.9015
Export	-170824298.5	85535.29569	0.971940613

Table 4-2 Regression value

Where the equation formulate using equation (4.2):

- $import \quad y = -1021720267 + 511924 * X$
- $Export \quad y = -170824298.5 + 85535 * X$

The *correlation* coefficients are 0.9 and 0.97 for imports and exports respectively which mean that strong linear relationship exist between the growth of import/export and the year. Therefore the projected import and Export value start from 2015 up to 2047 is present in Figure 4.4 and 4.5.

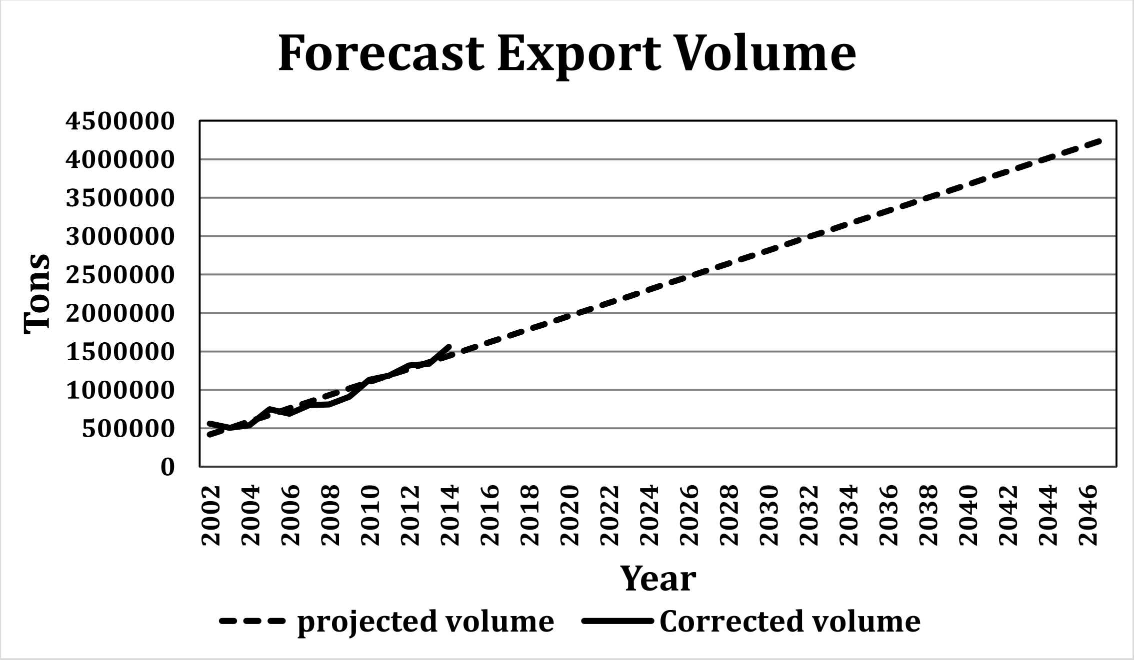


Figure 4.4 projected import value

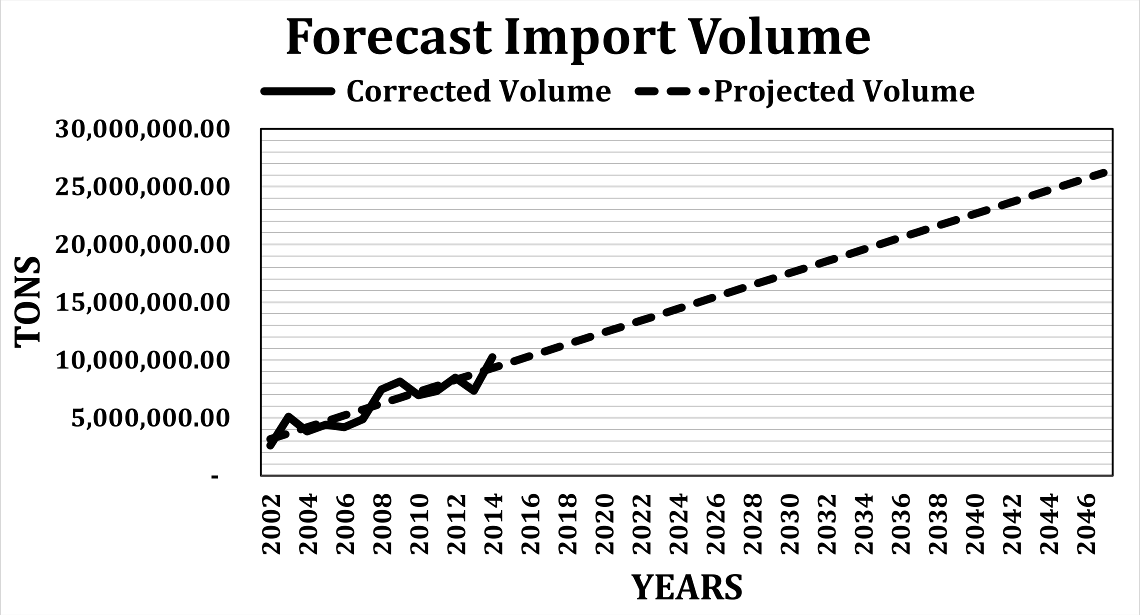


Figure 4.5 Projected Export Volume

4.5.1.2 Second Step

Prevalently, the international maritime transport of Ethiopia is almost completely dependent on the Port of Djibouti with some occasional supplementary support from Berbera and Port Sudan. The distribution pattern of import and export from each of the specified hinterlands are now frequently routed through Addis Ababa which puts them in a category of overlapping hinterlands. This is mainly determined by the organization of freight shipment, location of foreign trade business and the established pattern of import distribution and export collection within the country. Basically the port assignment is a function of available port capacity for Ethiopian foreign trade, relative costs of port charges and hinterland transport cost. The present and future share of different ports is mainly based on the above factors, the Ministry of Transportation (MOT) plan and other researchers estimate which envisages the following distribution:

1st level distribution of foreign trade (import) to three key sea ports will be as follows: (Transport Planning for BFS of Addis Ababa-Djibouti Railway Project)

- Djibouti port = 75%
- Berbera port =15%
- Port Sudan = 10%

4.5.1.3 Third step

3rd level assignment of foreign trade traffic concerns the distribution of Djibouti port traffic to Hinterlands (Transport Planning for BFS of Addis Ababa-Djibouti Railway Project)

- Northern Ethiopia = 15%
- Eastern Ethiopia = 10%
- Central Ethiopia = 75%

The distribution of freight based on the hinterlands is present on Appendix-B

4.3.1.4 Fourth step

Modal split is that aspect of the demand analysis process that determines the percentage of trips from Addis Ababa to Djibouti that are made by Truck and by Train. The selection of one mode or another is a complex process that depends on factors such as travel time, cost, and interval between departures. Logit model is used to split the modes which consider the relative utility of each mode as a summation of each modal attribute. Then the choice of a mode is expressed as a probability distribution

$$p = \frac{\exp(U1)}{\exp(\mathrm{U1})+\exp(\mathrm{U2})} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.6$$

Where

P = the percentage of mode 1 choice from mode 2

U1, U2 = the utility function of mode 1 and mode 2

To the extent that the selection of a mode is governed by its travel time, and general cost, a utility function may be written as:

$$\mathrm{Utility}_i = \mathrm{TT} + d\,{*}\mathrm{GC} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.7$$

Where;

Utility = utility function for mode *i*

Travel Time (TT) = Travel time that is the time require to travel between origin and destination, including in vehicle travel time and out of vehicle travel time.

General cost (GC) = the total cost of the trip and the out of pocket cost

Cost coefficient d is computed as follows:

$$d = \frac{(\mathrm{b})(1248)}{(\mathrm{TVP})(\mathrm{AI})} \qquad 4.8$$

Where;

TVP = the ratio of (value of one hour travel time)/ (hourly employment rate).

In-vehicle travel time (IVTT) =has a coefficient of b = -0.025

AI= the average annual household income, (USD)

1248 is the factor that converts USD/yr. to cents/min

Addis Ababa to Djibouti Railway Line is designed for both passenger and freight trains. Bulk cargo mainly includes petroleum, fertilizer, grains and containers transported from Djibouti port to Addis Ababa, Mojo, Adama, and Miseo. Indode Station is set as the technical station for freight trains, taking charge of the arrival-departure operation of cargoes in the capital and de-marshalling of Freight Trains to facilitate the technical operation of freight transportation. Therefore, Freight Train operate on the line between Indode to Port of Djibouti which is 742 km longer. According to ERC the average speed of freight train is 70km/h.

Almost all freight truck choose the Addis Ababa – Awash junction – Mille – Galafi – Djibouti port route based on ERA data. The total length of the road is 910Km and the speed of freight truck along the route is different on the section due to the road condition and speed limitation. Based on the researcher gathered data on the section and asked the drivers as well as the RTA data the route is classified in to three sections and the average speeds are.

- Addis to Adama: This section has two route expressways and highways road so the truck average speed is 70 km/hr.

- Adama to Awash is not good for driving; therefore, the average speed is 50 km/hr.
- Awash to port of Djibouti is with less congestion; so, the truck speed is 77km/hr.

Due to the above reasons the modal split between train and truck on the line is divided into three section that is Addis Ababa - Adama, Adama – Awash and Awash – Port of Djibouti. Ethiopian Railway corporation study regarding freight cost is 0.046USD/ton/Km and in case of truck the average tariff is 0.047USD/ton/km. (from RTA and ERC)

The modal choice of train and truck along the section of Addis Ababa – Adama, Adama – Awase and Awash – Port of Djibouti are:

Modes	**A/A - Adama**	**Adama-Awash**	**Awash –Djibouti**
Train	**62.5 %**	**72.9 %**	**97.6 %**
Truck	**37.5 %**	**27.1 %**	**2.4 %**

Table 4-3 Modal split between Train and Truck

The railway Freight transportation share along the section as well as forecast freight volume form 2016 up to 2050 present in table 4.4 and table 4.5.

Railway share (import)

year	A/A -Adama (62.5%)	Adama - Awash (72.9%)	Awash- Dire Dawa (97.6%)	Dire Dawa - Djibouti (97.6%)
2016	3627761	4231421	5665112	6420460
2017	3807734	4441341	5946158	6738979
2018	3987708	4651262	6227205	7057499
2019	4167681	4861183	6508251	7376018
2020	4347655	5071104	6789297	7694537
2021	4527628	5281025	7070344	8013056
2022	4707601	5490946	7351390	8331576
2023	4887575	5700867	7632437	8650095
2024	5067548	5910788	7913483	8968614
2025	5247521	6120709	8194529	9287133
2026	5427495	6330630	8475576	9605653
2027	5607468	6540551	8756622	9924172
2028	5787441	6750472	9037669	10242691
2029	5967415	6960393	9318715	10561210
2030	6147388	7170314	9599761	10879730
2031	6327362	7380234	9880808	11198249
2032	6507335	7590155	10161854	11516768
2033	6687308	7800076	10442901	11835287
2034	6867282	8009997	10723947	12153807
2035	7047255	8219918	11004993	12472326
2036	7227228	8429839	11286040	12790845
2037	7407202	8639760	11567086	13109364
2038	7587175	8849681	11848133	13427884
2039	7767148	9059602	12129179	13746403
2040	7947122	9269523	12410225	14064922
2041	8127095	9479444	12691272	14383441
2042	8307068	9689365	12972318	14701961
2043	8487042	9899286	13253365	15020480
2044	8667015	10109207	13534411	15338999
2045	8846989	10319127	13815457	15657518
2046	9026962	10529048	14096504	15976038
2047	9206935	10738969	14377550	16294557
2048	9386909	10948890	14658597	16613076
2049	9566882	11158811	14939643	16931595
2050	9746855	11368732	15220689	17250115

Table 4-4 Railway Import Freight Transport

Railway Share(Export)

year	A/A -Adama (62.5%)	Adama - Awash (72.9%)	Awash - Dire Dawa (97.6%)	Dire Dawa - Djibouti (97.6%)
2016	755753	881712	1182076	1182076
2017	795784	928415	1244688	1244688
2018	835814	975117	1307299	1307299
2019	875845	1021819	1369911	1369911
2020	915875	1068521	1432523	1432523
2021	955906	1115224	1495135	1495135
2022	995936	1161926	1557747	1557747
2023	1035967	1208628	1620359	1620359
2024	1075997	1255330	1682970	1682970
2025	1116028	1302033	1745582	1745582
2026	1156059	1348735	1808194	1808194
2027	1196089	1395437	1870806	1870806
2028	1236120	1442139	1933418	1933418
2029	1276150	1488842	1996030	1996030
2030	1316181	1535544	2058641	2058641
2031	1356211	1582246	2121253	2121253
2032	1396242	1628949	2183865	2183865
2033	1436272	1675651	2246477	2246477
2034	1476303	1722353	2309089	2309089
2035	1516333	1769055	2371701	2371701
2036	1556364	1815758	2434312	2434312
2037	1596394	1862460	2496924	2496924
2038	1636425	1909162	2559536	2559536
2039	1676455	1955864	2622148	2622148
2040	1716486	2002567	2684760	2684760
2041	1756516	2049269	2747372	2747372
2042	1796547	2095971	2809983	2809983
2043	1836577	2142674	2872595	2872595
2044	1876608	2189376	2935207	2935207
2045	1916638	2236078	2997819	2997819
2046	1956669	2282780	3060431	3060431
2047	1996699	2329483	3123043	3123043
2048	2036730	2376185	3185655	3185655
2049	2076760	2422887	3248266	3248266
2050	2116791	2469589	3310878	3310878

Table 4-5 Railway Export Freight Transport

4.5.2 Passenger Forecast

Forecast of passenger is difficult due to lack of past data on the line. Therefore, to predict passenger trip it needs analysis from road transportation. The road transportation on the line of Addis to Djibouti line is by cars, mini bus and bus. The passengers mostly use min bus for small distance trip and larger bus for large distance trips. The best method to predict passenger flow is by considering the movement of people in each bus station of the region and project using population growth rate since trip flow is directly proportional to population and income growth. The main bus station on the Addis Ababa **-** Djibouti route is Kaliti Bus station, Adama bus station and Dire Dawa Bus station. Table 4.6 Passenger trip Data collected from bus stations in 2014.

	Destination							
Origin	**A/A**	**Bishoftu**	**Mojo**	**Adama**	**Dire Dawa**	**Harar**	**Dewale**	**sum**
A/A	-	4459	1081	5535	282	231	-	**11588**
Bishoftu	4459	-	-	1488	15	-	-	**5962**
Mojo	1081	-	-	2520	-	-	-	**3601**
Adama	6935	1488	2520	-	360	240	-	**11543**
Dire Dawa	247	15	-	49	-	-	718	**1029**
Harar	282	-	-	360	-	-	-	**642**
Dewale	-	-	-	-	718	-	-	**718**
sum	**13004**	**5962**	**3601**	**9952**	**1375**	**471**	**718**	**35083**

Table 4-6 Passenger trip Data collected from bus stations in 2014

Population growth rate are based on the urban growth rates of Oromia, Addis Ababa, Dire Dawa and Harar areas as predicted by the Central

Statistical Agency. The four states are used because the railway line cross this regions as well as the passengers originate from these regions.

Since the growth rates of passenger number is directly proportional to the population growth, so the growth factor is as follows:

$$f_{j+1} = \frac{(pop_{j+1} - pop_j)}{pop_j} * 100 \ldots\ldots 4.9$$

Where

f_{j+1} = growth factor

pop_{j+1} = population at j + 1 year

pop_j = population at j year

By using the population data which was collect from *Central statistical Agency* (CSA) calculate the growth factor at 2020, 2025, 2030, 2035 and 2037. Table 4.7 show the population number of the region and growth factor.

	Region							
year	Oromia (10^3)	% of growth	A/A (10^3)	% of growth	D/D (10^3)	% of growth	Harar (10^3)	% of growth
2015	33692	-	3272	-	440	-	232	-
2020	38170	13.3	3689	12.7	507	15.2	264	13.8
2025	42690	11.8	4114	11.5	581	14.6	296	12.1
2030	47139	10.4	4530	10.1	660	13.6	328	10.8
2035	51460	9.2	4953	9.3	739	12.0	359	9.5
2037	53121	3.2	5132	3.6	772	4.5	371	3.3

Table 4-7 Growth Factor of the regions (Source Central Statistical Agency of Ethiopia)

Table 4.8 shows the future passenger number at 2016, 2020, 2025, 2030, 2035 and 2037 will calculate by the following equation

$$T_{j+1} = f_{j+1} * T_j \ldots\ldots 4.10$$

Where

T_{j+1} = passenger Number at year j + 1 year

f_{j+1} = growth factor

T_j = passenger Number at year j Year

When the Passenger train start working it will compete with car and bus which flows on the same direction. The main passenger station is Labu (located at Addis Ababa), Adama and Dire Dawa on the Ethiopian Side so the modal split is done by dividing the route in to three sections Addis Ababa – Adama, Adama-Dire Dawa and Dire Dawa – Djibouti.

Table 4-8 Forecast Passenger number

		2016	2020	2025	2030	2035	2037
Addis Ababa - Adama	UP	11075	12486	13925	15333	16765	17371
	down	16483	18674	20845	23017	25127	25938
Adama - Dire Dewa	UP	1128	1275	1415	1560	1704	1762
	down	953	1089	1230	1374	1516	1572
Dire Dewa - Djibouti	UP	718	827	948	1077	1206	1260
	down	718	827	948	1077	1206	1260

Based on the logit equation the modal split between Passenger train, car and bus is presented in table 4.9. The calculation is presented in Appendix-B.

Modes	Addis- Ababa to Adama	Adama – Dire Dawa	Dire Dawa – Djibouti
Train	53.7 %	90.52%	92.14%
Bus	30.1 %	9.45%	7.75%
Car	16.2 %	0.03%	0.11%

Table 4-9 Modal Split B/n Train, Bus and Car

The railway share the passenger flow along the section Addis Ababa - Adama, Adama – Dire Dawa and Dire Dawa – Djibouti from 2016 up to 2050 is presented in table 4.10.

Passenger flow per Day

year	Addis Ababa - Adama		Adama - Dire Dawa		Dire Dawa - Djibouti	
	Up	Down	Up	Down	Up	Down
2016	5946	8850	1030	870	662	662
2017	6172	9216	1070	906	687	687
2018	6330	9454	1097	933	711	711
2019	6488	9693	1125	959	734	734
2020	6704	10026	1164	994	762	762
2021	6805	10170	1179	1013	781	781
2022	6963	10408	1206	1039	805	805
2023	7121	10647	1233	1066	829	829
2024	7280	10885	1260	1093	852	852
2025	7476	11191	1292	1123	876	876
2026	7596	11362	1314	1146	899	899
2027	7755	11600	1342	1173	923	923
2028	7913	11839	1369	1199	947	947
2029	8071	12077	1396	1226	970	970
2030	8232	12358	1425	992	992	992
2031	8388	12554	1450	1279	1017	1017
2032	8546	12793	1477	1306	1041	1041
2033	8704	13031	1504	1332	1065	1065
2034	8863	13270	1531	1359	1088	1088
2035	9001	13490	1556	1111	1111	1111
2036	9179	13746	1586	1412	1135	1135
2037	9326	13926	1609	1161	1161	1161
2038	9496	14223	1640	1466	1183	1183
2039	9654	14462	1667	1492	1206	1206
2040	9812	14700	1694	1519	1230	1230
2041	9971	14939	1721	1546	1253	1253
2042	10129	15177	1748	1572	1277	1277
2043	10287	15416	1775	1599	1301	1301
2044	10445	15654	1803	1625	1324	1324
2045	10604	15893	1830	1652	1348	1348
2046	10762	16131	1857	1679	1371	1371
2047	10920	16370	1884	1705	1395	1395
2048	11079	16608	1911	1732	1419	1419
2049	11237	16846	1938	1759	1442	1442
2050	11395	17085	1965	1785	1466	1466

Table 4-10 Forecast Passenger flow per day using Railway

4.5.3 Determine the Traffic Load

Various kinds of rail vehicles are running on the track: passenger vehicle, freight vehicle, main line locomotive, shunting engines etc. the algebraic sum of the vehicle loads cannot give an accurate quantification of the running load, because it does not take into account the way in which the load applied, the running speed etc. Therefore, a parameter giving an accurate estimate of the passing traffic load is necessary. Railway management and Engineering (V.A.Profillidis) uses the analogues of the passenger vehicle unit (PVU) of traffic engineering. In order to determine the traffic load (tonnage) on the track, the loads of the various trains are first converted into equivalent passenger train load and then speeds are also taken into account.

For this purpose, a composite traffic Volume shall be calculated taking into account both effects of speed and relative wear provoked by axle loads. Line classification has been standardized by the UIC and is determined on the basis of theoretical traffic load T_{th} given by the following formula.

$$T_{th} = S_p.\left(T_p + K_t.T_{pt}\right) + S_{fr}.\left(K_{fr}.T_{fr} + K_t.T_{tf}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots 4.11$$

Where

$T_p =$ The mean daily passenger tonnage hauled (in gross tons)

$T_{fr} =$ The mean daily freight tonnage hauled (in gross tons)

$T_{pt} =$ The mean daily tonnage of tractive units used in passenger traffic (in tons)

T_{tf} = The mean daily tonnage of tractive units used in freight traffic (in tons)

K_{fr} = A coefficient taking into account effects of both the load and wear provoked by freight bogies and is given

- Normally the value $K_{fr} =$ 1.15
- However, for tracks handling heavy loads, coefficient K_{fr} is given the following greater Values
- K_{fr} = 1.30 for traffic based principally on 20t axle loads (more than 50% of traffic) or for a significant proportion of traffic with 22.5t axle loads (more than 25% of traffic

- K_{fr} = 1.45 for traffic based principally on 22.5t axle loads (more than 50% of traffic) or for traffic largely consisting of 20t or heavier axle loads (more than 75% of traffic)

K_t = a coeffecent which allows to take into account track wear resulting from traction vehicles. The coefficient K_t is usually given the value $K_t = 1.4$

S_p and S_{fr} : are coefficients related to the running speed of the train. More particularly, S_p relates to the speed of the fastest passenger trains and S_{fr} relates to the speed of ordinary freight trains. These coefficient are assigned the following values

Speed	s_p / s_{fr}
V < 60Km/hr	1.00
60Km/hr < V < 80km/hr	1.05
80Km/hr < V < 100Km/hr	1.15
100Km/hr < V < 130Km/hr	1.25
130km/hr < V < 160Km/hr	1.35
160Km/hr < V < 200Km/hr	1.4
200km/hr < V < 250Km/hr	1.45
V> 250Km/hr	1.5

Table 4-11: Coefficient of Sp and S_{fr} (Source V.A.Profillidis)

The transportation organization pattern is the line for both passenger traffic and freight traffic. The passenger trains operating in Labu～ Adama, Dire Dawa has the nature and function of intercity passenger transportation. It's suggested using locomotive-traction, small-scaled marshalling trains. Ten carriages marshaled for one train. Based on passenger amount, the operation frequency can be increased as appropriate. The trains operating in Labu~Nagada (Djibouti) are international long-distance trains. It is suggested using locomotive-traction, 16 carriage passenger trains, with dining car and berth cars to enhance service for passenger. The average weights of standard coaches, Dining and Berth car is 61.14, 83.11 and 82.45 tons respectively.

The cargo flow to down-direction is 100% loaded wagon direction and the up-direction is 20.8% loaded wagon. Electric-power dual locomotive traction shall be adopted for freight trains, with a traction mass of 3500t. Pairs of trains in study years are as shown in Table 4.12

The locomotive use:-		
	For Passenger Train	For Freight Train
Model	HX$_D$3C	HX$_D$3B
UIS classification	Co'Co'	Co'Co'
Locomotive Weight	132 tones	160 tones
Axle load	21 tones	23 tones
Type of traction	Electric power (DC)	Electric power (DC)
the weight of railway cars	600tons	750tons
length of arrival - departure track	850m (880 for dual-Locomotive)	850m (880 for dual-Locomotive)
length of locomotive	20.846m	22.781m
Target speed	120km/hr	70km/hr
S_p	1.25	-
S_{fr}	-	1.05
K_{fr}	-	1.3
K_t	-	1.4

Table 4-12 Parameter of locomotive use in Ethio – Djibouti Railway

According to the passenger flow and freight flow on the line, the number of pair train move in a day is presented in Appendix-B

To calculate the traffic load, first determine the mean daily passenger tonnage, mean daily freight tonnage, mean daily passenger and freight tractive tonnage. The mean daily passenger tonnage is determined by multiplying the passenger flow by average weight of a person which is 80kg. The mean daily freight tonnage is determined by dividing the cargo flow in each year by 365days. The mean daily passenger and freight tractive tonnage is determine by multiplying the number of trains per day by their weight. Then using equation (4.11).the determined theoretical load of the line is present in appendix-B. Table 4.13 Show the annual traffic load and Figure 4.6 show the Million gross tons for 35 years that the railroad carry on the section Addis Ababa-Adama, Adama-Dire Dewa, and Dire Dawa – Djibouti.

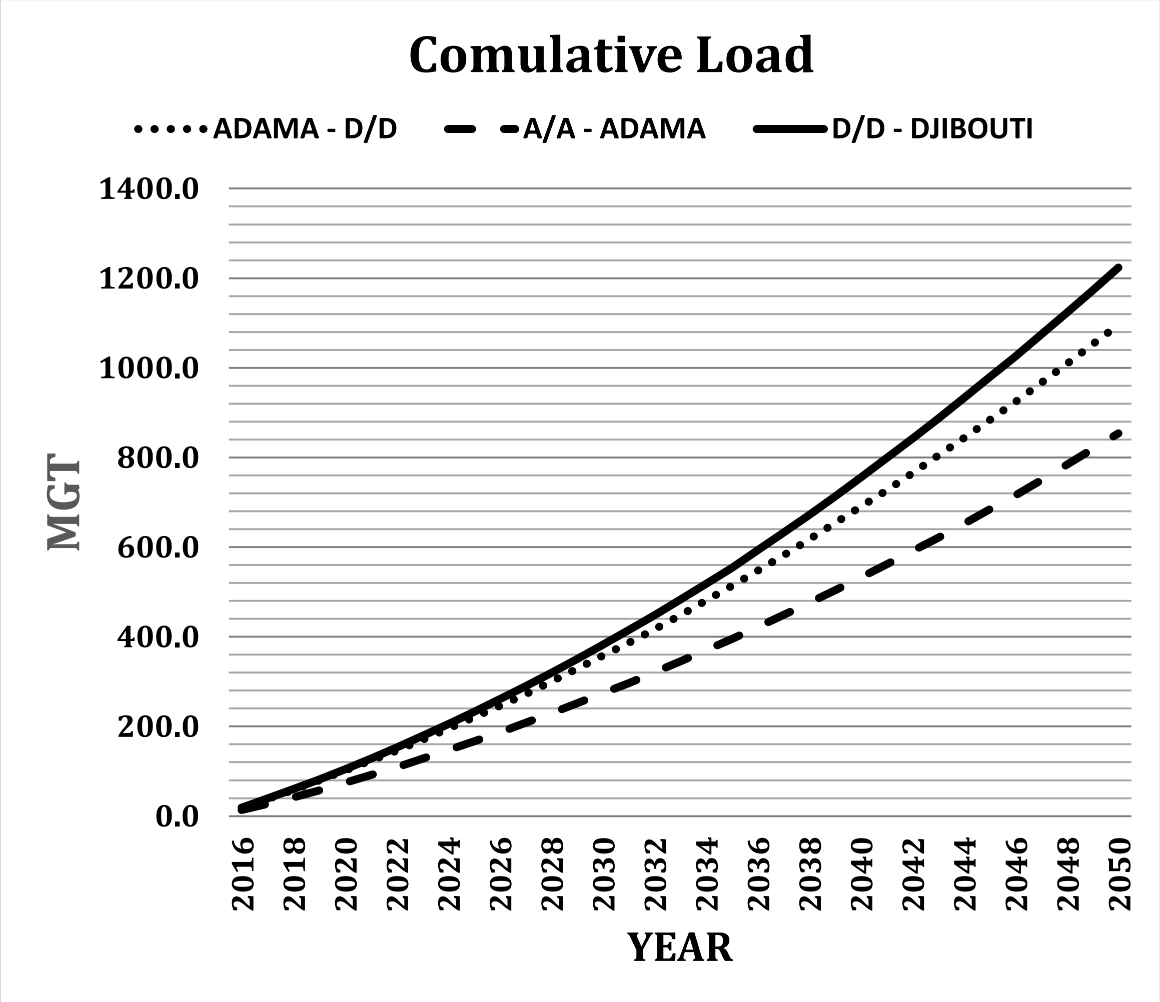


Figure 4.6 Cumulative Million Gross Tons (MGT)

year	**Addis Ababa – Adama (10^6tons)**		**Adama - Dire Dawa (10^6 tons)**		**Dire Dawa – Djibouti(10^6 tons)**	
	up	**down**	**up**	**down**	**up**	**down**
2016	7.3	11.3	5.9	12.0	5.9	13.0
2017	7.4	11.6	6.0	12.4	6.4	13.9
2018	7.9	12.3	6.0	12.8	6.5	14.4
2019	8.5	13.1	6.1	13.1	6.6	14.8
2020	8.5	13.3	7.2	14.5	7.2	15.8
2021	8.6	13.6	7.3	14.9	7.3	16.2
2022	8.6	13.8	7.4	15.3	7.9	17.1
2023	9.2	14.6	8.0	16.2	8.0	17.6
2024	9.7	15.3	8.0	16.5	8.0	18.0
2025	9.8	15.6	8.1	16.9	8.6	18.9
2026	9.9	15.8	8.7	17.8	8.7	19.4
2027	9.9	16.1	8.8	18.2	8.8	19.8
2028	10.9	17.3	8.9	18.6	9.4	20.7
2029	11.0	17.6	9.5	19.5	9.5	21.2
2030	11.1	17.8	9.6	19.8	10.1	22.1
2031	11.1	18.1	9.6	20.2	10.2	22.5
2032	11.2	18.3	10.2	21.1	10.2	23.0
2033	12.2	19.5	10.3	21.5	10.8	23.9
2034	12.5	20.1	10.4	21.9	10.9	24.3
2035	12.6	20.3	11.0	22.8	11.0	24.8
2036	12.7	20.6	11.1	23.1	12.3	26.4
2037	13.2	21.3	11.2	23.5	12.4	26.9
2038	13.8	22.1	11.7	24.4	12.5	27.3
2039	13.8	22.3	11.8	24.8	13.1	28.3
2040	13.9	22.6	11.9	25.2	13.2	28.7
2041	13.9	22.8	12.5	26.1	13.7	29.6
2042	14.5	23.6	12.6	26.5	13.8	30.1
2043	15.0	24.3	12.7	26.8	13.9	30.5
2044	15.1	24.6	13.3	27.7	14.5	31.4
2045	15.2	24.8	13.3	28.1	14.6	31.9
2046	15.2	25.1	13.4	28.5	14.7	32.3
2047	16.2	26.3	14.5	29.9	15.3	33.2
2048	16.3	26.5	14.6	30.2	15.3	33.7
2049	16.4	26.8	14.7	30.6	15.4	34.1
2050	16.4	27.1	14.8	31.0	16.0	35.0

Table 4-13 Annual Million Gross Tons (MGT)

Chapter 5 Analysis the LCC of Ethio-Djibouti Railway Track

5.1 Analysis of Rail Life cycle cost

The aim of this practical chapter is to develop a probabilistic approach to maintenance strategy from a life-cycle cost perspective. Therefore, Addis Ababa/Sebeta – Djibouti track section will be studied, analyzing the costs associated with rail component.

Main technical standard of the project

- Based on china rail way standard (PRC code) the line is class II standard gauge.
- Rail type is 50kg/m and tensile strength is greater than 880 N/mm^2.
- The minimum curve radius is 800m and the maximum slope is 1.85%.
- The total length of the line is 752km the length of each section is:
    - Addis Ababa- Adama = 113.836km
    - Adama – Dire Dawa = 342.75km
    - Dire Dawa – Djibouti = 295.5Km

Effective maintenance strategy reduces the life cycle cost of rail, as the same time it should increase the safety and riding comfort of the rail. The cost components of the life cycle cost of the rail are:

- Inspection cost;
- Rail Grinding cost;
- Rail lubrication;
- Repairing rail break;
- Derailment and damage cost; and
- Rail renewal cost.

5.1.1 Analysis of Inspection Cost

Measuring the system and controlling the quality of the infrastructure through inspections is essential to ensure safety and quality standards. Inspection involves more than just the inevitable measurement of defects for correction in maintenance works, as the measurement of accelerations to guarantee passenger comfort, measurement of forces or even inspection of rolling stock. However, the objective of inspection is not only to assure the non-existence of any faults that might lead to accidents, but also to monitor successive degradation in infrastructure in order to prevent faults and to provide the infrastructure manager with information for short and long term planning of maintenance activities.

Rails are one of the most important track components to ensure safety standards. Commonly, rail inspection consists of ultrasonic rail inspection, focused on detecting internal failures. Ultrasonic trains have replaced manual inspection, though switches and transitions for moveable bridges, junctions and sidings are normally inspected with ultrasonic hand equipment. These ultrasonic trains, like the UST 96, are equipped with a computer-controlled measuring system and an on-board data analysis system, and can be used on all standard gauge lines. Ultrasonic inspection is scheduled once a year for ordinary tracks, but it can be executed twice or even four times a year depending on daily tonnage and specificities of the track (S&C or transitions of moveable bridges).

Inspection interval is influence in detecting of the rail defect and the risk. The benefits of the increased number of rail tests over the long term are: more defects are detected, the service defect rate is controlled and it reduces the risk of derailment. The following equation is used to estimate inspection cost:

$$C_{insp} = \sum_{j=1}^{N} \frac{C_{hr}*\frac{l}{v}*m/m_i}{(1+r)^j} \ldots\ldots 5.1$$

Where

C_{insp}= LCC of rail inspection (USD)
L = track length (miles)
V = average hi-rail vehicle speed (mph)
C_{hr} = inspection cost per hour
m_i = Inspection interval (MGT).

Communication with senior track engineers from a major railroad indicated that the speed of inspection (V) is generally between 15 and 20 mph, although the speed may be lower based on the rail and meteorological conditions. The inspection cost (C_{hr}) including Equipment, Labor and indirect cost is USD 300 per hour per vehicle and the economic cost is 300*0.74= 222USD/hr, (ERC).

5.1.2 Analysis of Preventive Grinding Cost

To determines economic grinding interval and mental removal to make the rail grinding obtain the best cost-benefit ratio considering that when grinding interval is larger, crack propagation is much deeper, and mental removal is large, repeat grinding is needed, which increases the difficulty of actual operation. Low grinding interval lead to unnecessary removal of railhead material that may bring forward the rail replacement. Therefore, grinding interval should be moderately reduced at the original basis, the economical grinding interval is determined by the continuously observing the growth of fatigue cracks and wear condition. The grinding cost is calculated depending on the mental removal per meter and the grinding length. The unit cost of grinding including equipment, labor and indirect cost is 0.58USD/m/hr. and the economic cost is 0.58*0.74=0.43USD/m/h, (ERC). Grinding cost is estimated using the following formula:

$$C_g = \sum_{j=1}^{N} \frac{g_c * l * t_g * m/m_g}{(1+r)^j} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.2$$

Where

C_g = LCC of Grinding (USD)

g_c = Grinding cost per meter (cost/meter/time)

t_g = time needs for grinding

m_g = grinding Interval in MGT

l = grinding length

5.1.3 Analysis of Rail Break Repair and Defect repair

The risk-based test frequency scheduling methodology is used to schedule ultrasonic testing such that a defined level of risk (failure) is held constant, even as rail ages; thus, reducing the level of service failures and risk of derailment to an acceptable level. The methodology evaluates risk as allowable service defects per mile per year. Considering this, there are three primary phenomena that affect the occurrence of a service defect: Defect Initiation, Defect Growth and Detection Reliability.

Defect Initiation

As tonnage accumulates on a stretch of track, defects will form and grow. The number of defects that can be expected to enter the population within a given year or at some time interval after the rail is installed, say between tests can be fairly well predicted using the standard Weibull cumulative probability distribution.

Defect Growth

Once a defect is formed, it will continue to grow in size with passing traffic. The characteristics of this growth are defined by classical fracture mechanics, and represent decades of research. The key in risk based rail testing is to find the defect between the time it grows to detectable size (minimum detection threshold) and the time when actual failure is eminent (maximum allowable defect size). This interval is of the order of 10 to 50 MGT (FRA), depending on a number of factors including curvature, rail section, track modulus, vehicle dynamics, wheel/rail contact, axle load, temperature differential from neutral as well as other residual stress components, and location of the defect.

Detection Reliability

How probable is it that a defect of certain size will be found, Since the ability to reliably detect a defect varies with its size, particularly for small defects, there is a “probability” of finding any given defect based on its size. That means more used rails with higher cumulative MGT passed through the section is expected to have more probability of initiating defects and if undetected then through further passing of traffic can lead to rail failures/breaks. The proposed number of failures for an accumulated MGT, m, as a random variable and modelled using Weibull distribution method.

Ultrasonic inspection is the principal technology used to identify certain types of rail defects before they grow large enough to cause a broken rail. The occurrence and growth of rail flaws is a stochastic process, but the probability of defect formation is positively correlated with the cumulative tonnage passing over a rail. Probabilistic estimation of the formation of rail fatigue defects is generally modeled using a Weibull distribution method, which describes the probability that a rail has a defect at a given time or tonnage Because of technological limitations of current ultrasonic inspection technology, defects of certain types, sizes, and locations may not be detected.

Reliability is obtained from failure rate therefore, recorded failures data is used to predict but Addis Ababa – Djibouti railway line is newly constructed so data from other countries used which has the same track type. Weibull analysis has been used in this thesis to analyze the data and predict the rail failure rate as it has the ability to provide reasonably accurate failure analysis and prediction with extremely small sample size. Another reason is because Weibull distribution is often used to represent the problems related to mechanical component aging, wear and degradation.

Let cumulative MGT of rail, m, be known and $F_n(m)$ and $f_n(m)$ denote the cumulative rail failure distribution and density function respectively, and be modelled as a Weibull distribution given by:

$$F_n(m) = 1 - \exp(-(\frac{N}{\beta})^{\alpha}) \text{ ....5.3}$$

And

$$f_n(m) = \frac{\alpha N^{\alpha-1}}{\beta^{\alpha}} \exp -(\frac{N}{\beta})^{\alpha}) \text{..5.4}$$

Where:

$F_n(m)$= rail failure distribution
α = Weibull shape factor
β = Weibull scale factor
N = rail age (cumulative tonnage on the rail MGT)
$f_n(m)$= density function

Rail track is normally made operational by means of repair or replacement of the failed segment and no action is taken with regards to the remaining length of the whole track. Since the length of failed segment replaced at each failure is very small relative to the whole track, the rectification action can be viewed as having negligible impact on the failure rate of the track as a whole, then the expected number of *failures over period* i *and* $(i + 1)$ *is given by:* (Liu et al, 2014).

$$\frac{S}{D} = \lambda(X - \theta) \text{...5.5}$$

Where

S = rate of broken rails per track-mile between tests
D = rate of detected rail defects per track-mile from the most recent test
X = inspection interval (MGT)
λ = slope of the number of rail breaks per detected rail defect (S/D) versus inspection interval curve
θ = minimum rail defect inspection interval (MGT).

$$(S+D)X = Rf(N)X \text{...} 5.6$$

Where R= rail segment per track- mile

$$SX = \frac{R\,\frac{\alpha N^{\alpha-1}}{\beta^{\alpha}} e^{-(\frac{N}{\beta})^{\alpha}}}{1+\frac{1}{\lambda(X_i-\theta)}} X \text{..} 5.7$$

For the inspection interval($N_{i-1}\ N$), the average rail age is $0.5(N_{i-1}+\ N)$. As such, the expected number of broken rails within the inspection interval is:

$$S_{(i-1,1)} = SX = \frac{R\,\frac{\alpha(0.5N_{i-1}+0.5N_i)^{\alpha-1}}{\beta^{\alpha}} e^{-(\frac{0.5N_{i-1}+0.5N_i}{\beta})^{\alpha}}}{1+\frac{1}{\lambda(X_i-\theta)}} X \text{...} 5.8$$

The parameters in the broken rail risk model (N, R, α, β, λ, and θ) are related to the mechanism of rail defect formation, accuracy of rail defect inspection, and track characteristics. A sensitivity analysis was conducted to understand the marginal effect of these parameters on the rate of broken rails (Liu et al, 2014).

Variable	Value
Initial rail age (N) (MGT)	300
Rail segments per track mile (R)	273
Weibull shape factor (α)	3.1
Weibull scale factor (β)	2150
Slope of the S/D versus inspection interval curve(λ)	0.014
Minimum rail defect inspection interval (θ) (MGT)	10

5.1.3.1 Rail Defect Repair Cost

The AAR developed the following models to estimate the cost for repairing detected defects and broken rails Wells and Gudiness (1981) that were used with updated rail cost information. The detected defect model is shown in Eq 5.9.

$$DDC = \left[\frac{W_{replace}\ x\ L_{replace}(p_{new} - 0.95\ p_{old})}{2000} + C_{drepair}\right] * t \text{........5.9}$$

Where

DDC = total cost for repairing a detected rail defect accounting for rail salvage value, materials, equipment, and labor cost (USD).

$W_{replace}$ = weight of replacement rail, in pound per yard (100.58).

$L_{replace}$ = length of replacement rail, in yard (3).

P_{new} = price of new rail, in dollars per ton (1704.78).

P_{old} = price of Scrap rail, in dollars per ton (238).

$C_{Drepaair}$= expenses for labor, materials, equipment, and thermite welds ($650).

t = Conversion factor from finance to economic cost [0.7] (from MoFED).

Based on the above model, an estimated **$611.11** is needed to repair a rail defect

The costs for repairing rail defects is a multiplication of the number of detected rail defects and the cost of repair. The number of detected rail defects between successive inspection intervals is:

$$N_{def} = \frac{S(X)L}{\lambda(Xi - \theta)} \text{..5.10}$$

Where

N_{def} = the number of detected rail defects.

SX = the number of broken rails per track-mile by rail defect inspection. Frequency using the optimization model.

L = track length in miles.

The LCC of repair rail defect (C_{def}) is

$$C_{def} = \sum_{j=1}^{N} \frac{N_{def} * DDC}{(1+r)^j} \ldots\ldots\ldots\ldots\ldots\ldots 5.11$$

5.1.3.2 Determine Broken Rail Repair Cost

When serious defect is found by flaw detection, the cost of repair a rail defect Taking t time's repair in j years. The present value of the rail repair cost is:

$$SDC = \left[\frac{W_{replace}\, x\, L_{replace}(p_{new} - 0.95\, p_{old})}{2000} + C_{Srepair}\right] * t \ldots\ldots\ldots 5.12$$

Where:

SDC = cost for repairing a broken rail (USD)

$C_{Srepair}$ = direct cost (labor, materials, equipment) for repairing a broken rail ($780).

Based on the model, we estimated an average of **$702.16** for repairing a broken rail. The LCC of repair broken rail (C_{srp}) is:

$$C_{srp} = \sum_{j=1}^{N} \frac{SDC * SX}{(1+r)^j} \ldots\ldots\ldots\ldots\ldots\ldots 5.13$$

5.1.4 Analysis of Derailment Loss Cost

Failure data are analyzed for estimating the probability of detecting defects that have the potential to cause a rail break before the next inspection. Defects developing later in-between inspections or going undetected during inspections can result in rail failures/breaks. Some rail breaks are detected by the signaling system. Some of the previously undetected breaks are detected by visual checks. Undetected rail failures/breaks can result in derailment. The average infrastructure and equipment damage cost is $616,263 per broken-rail-caused train derailment, the cost of which may vary by the type of broken rail. Fortunately, only a small proportion, 0.5 to 1 percent, of rail breaks result in train derailments because most broken rails are identified by either visual inspection or mechanical inspection which will be maintained on time. Therefore, we assume 0.84% of rail breaks may cause train derailments (FRA).

$$C_D = \sum_{j=1}^{N} \frac{d_c * 0.0084 * SX * L}{(1+r)^j} \dots\dots\dots 5.14$$

Where

C_D = Total LCC of derailment cost.

d_c = Average damage cost due to derailment (616,263 USD).

5.1.5 Analysis of Rail Renewal Cost

The service life of rail will vary with traffic (tonnage, axle load, and speed), the amount of curvature, gradient, subgrade and ballast support and the standard of maintenance. Rail life may be determined by wear-abrasion, rail end battle, curve wear. Tangent rail removed primarily because of head wear and rail-end battle for jointed track. Curve rail was usually removed because of side wear.

According to Hay (1982) formulate an approximate value for tangent rail life equation based on wear.

$$L = KxWx\, D^{0.565} \dots\dots\dots 5.15$$

Where

L = Rail Life in millions of gross tons (MGT).

W = Weight of rail in pound per yard.

D = Traffic density in Millions of Gross tons per year.

K= Level of maintenance factor.

The level of maintenance is established by determining how much vertical head wear will be permitted before rail removing from track. The permitted head wear for class II railway is 8mm from China code Hua et al. (2010). To compute rail life over a track segment containing curves of different degrees, an adjusted track mile total for the segment is computed by using an adjusted value for K over each curve segment. Total LCC of Rail renewal is:

$$C_{re} = \frac{re_c * l_{re}}{(1+r)^{T_{rew}/m}} \qquad \text{5.16}$$

Where

C_{re} = Total LCC of Rail Renewal
re_c = Rail Renewal cost USD/Km
T_{rew} = cumulative tonnage when rail renewal (MGT)
l_{re} = rail renewal length (Km)

re_c Rail renewal cost per km include material cost, replacement cost and salvage value. The econometric cost is presented in table 5.

Description	unit	Financial cost	Economical cost
Supply and transport of rail (ERC)	ton	1,704.78	1193.34
Replacement cost (ERC) (equipment, labor and material)	km	44,894.65	33,222.041
Salvage value	ton	238	164.22
Total cost of rail renewal	km	-	168,978.041USD/km

Table 5-1 cost break down of rail renewal

5.1.6 Track Downtime Cost

Downtime on the track occurs due to maintenance actions on the track. Train-free periods are usually used for planning maintenance actions, i.e. the hours between two consecutive trains. However, as the train-free periods are not long enough in most cases, this leads to train cancellations, train speed restrictions etc., which imply penalties imposed on the infrastructure manager by the traffic operators. Preventive maintenance and renewal actions are usually planned well ahead so as not to affect the traffic. However, corrective maintenance on the track generally affects the train operation. In our case we have considered rail breaks for corrective maintenance.

Broken rail replacement and service failures both impose train delay cost, but their magnitude differs due the difference in outage time. Total train delay cost is based on the cost per train-hour, the number of trains delayed, and the length of the delay.

Single-train delay cost includes three components: car cost, locomotive cost, and crew labor cost. Car delay cost refers to the cost of railroad-owned cars that are delayed and therefore are unavailable for use elsewhere. To determine the cost per car, an average car-hire rate was used. Industry experts indicated that a reasonable estimate for this was $0.75 per car-hour. Therefore, the total average car is 30 per train and the delay cost per train was computed to be $22.5 per hour.

The second component of train delay cost is locomotive delay. This cost was estimated available for use elsewhere. The average number of locomotives per train is 2. The average cost of new locomotives, is approximately 547,000.00USD/piece and the depreciation value after 9 years is approximately 231,981USD Assuming a discount rate of 10%. Therefore, the cost per locomotive-hour was 26.48USD per train-hour and the economic cost is 26.48*0.92=24.36USD/train-hour.

The third component of train delay cost accounted for in this analysis is labor expense. Average hourly wages for professional and technical personnel is 3.5USD/hour and 0.8USD/hour for straight time. For overtime professional get 4.375USD/hour and technical person get 1USD/hour. For the calculation of labor cost, only the overtime rate was used based on the assumption that a train delay of more than a few hours will generally result in overtime pay for the train crew. The economic cost for professional is 3.325 and for technical person is 0.76USD/hr. Therefore, based on a train crew (Two profession and Five Labor) the labor cost of delay was 10.45USD per train-hour.

Summing these four components of train-delay cost yields a total of <u>57.31</u> per train-hour. Although this captures most of typical elements of train delay cost it is still only a partial estimate because not all costs could be included due to limitations in data availability.

Cost of Multiple Train Delay

The number of trains delayed and the duration of their delay during a track-outage should also be considered in the calculation of train delay cost. These values can be approximated based on the density of the line and the number of mainline tracks. To determine the number of trains delayed, we assumed that trains will arrive in constant time intervals from both directions. The average train operated on Addis Ababa – Djibouti railroads is 3500 gross tons, including cars and locomotives. Therefore, the average number of trains per year for a particular line is the annual gross tonnage (in millions) (ANMGT) of that line divided by 0.0035 million-tons per train. The interval between trains, t, was then determined by dividing the number of hours per year in three shift work, 5840, by the number of trains per year(n):

$$n = \frac{Annual\ MGT}{Tons\ per\ train\ (million)} = \frac{ANMGT}{0.0035} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.17$$

$$t = hours\ per\ train\ arrival = \frac{hours\ per\ years}{trains\ per\ years} = \frac{5840}{n} = \frac{20.44}{ANMGT} \ldots\ldots 5.18$$

The total cost of train delay can then be calculated by the cost of delay per train-hour and the hours per train arrival of the particular line. The total number of trains delayed is determined by dividing the total delay time by the hours per train arrival. The length of delay for each train is based on the time of their respective arrival. The total cost due to train delay from a service interruption can be calculated using the following formula:

$$C_{DA} = Tx + \sum_{n=1}^{m} (T - nt)x \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.19$$

Where

C_{DA} = total train delay cost for multiple trains
T = total delay time for service interruption
x = cost of delay per train-hour ($57.31)
m = number of following trains delayed = T/t (rounded to the nearest integer)
t = hours per train arrival = 20.44/ANMGT

5.1.6.1 Train Delay Cost Due to Repairing a Detected Defect

The time required to repair a rail defect is dependent on the size, type and location of defect, and various other factors. Estimated train delay time by traffic density and the time to repair a rolling stock service failure using simulation tools. Train delay cost due to repairing a detected rail defect:

$$C_{DDT} = C_o A_D \exp(B_D x) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.20$$

Where:

C_{DDT}= train delay cost due to fixing a detected rail defect (USD)
C_o = train delay cost per hour, ($57.31)
A_D = 1.503 (Schlake et al. 2011)
B_D = 0.0811 (Schlake et al. 2011)
x = number of trains per day (T/0.0035/365) (T: annual traffic density in (MGT)

5.1.6.2 Train Delay Cost due to Repairing a Broken Rail

$$C_{SDT} = C_o A_S \exp(B_S x) \quad\text{.......}5.21$$

Where:

C_{SDT} = train delay cost due to fixing a broken rail (USD)
A_S = 3.559 (Schlake et al. 2011)
B_S = 0.0805 (Schlake et al. 2011)
Other variables are as defined above

Total delay cost is

$$C_{dl} = \sum_{j=1}^{N} \frac{\frac{SX*L*C_{DDT}}{h(Xi-q)} + SX*L*C_{SDT} + 0.0084SX*L*C_{DA}}{(1+r)^j} \quad\text{......}5.22$$

Where:

C_{dl} = Total delay cost; other variable are as defined above

5.1.7 Total Cost of Rail Maintenance and Renewal

The total cost of the line is the sum of Inspection cost, defect repair cost, Replacement cost, rail renewal cost, delay cost and derailment cost.

$$C_T = C_{insp} + C_{re} + C_D + C_{def} + C_{srp} + C_{dl} \quad\text{.......}5.23$$

The analysis of LCC Addis Ababa/ Sebeta – Djibouti railway line is done in this thesis into Three section Addis Ababa – Adama, Adama– Dire Dawa and Dire Dewa – Djibouti based on the track characteristics and annual million gross tons.

5.1.8 Addis Ababa/Sebeta –Adama Section

The total length is 113.834km which is double track, the characteristics, Model Parameter of the section is present in Appendix-C;

5.1.8.1. LCC of Rail Without using Lubrication and Grinding

Rail life is usually expressed in millions of gross tons (MGT) carried. Total MGT divided by annual traffic density gives life in years. The service life of rail will with traffic (tonnage, axle loads, and speed), the amount of curvature, gradient, subgrade and ballast support and the standard of maintenance. In this thesis the Rail life is determined by wear head wear, rail end Battler and curve wear. U71Mn rail grade head wear is 1.5mm/100MGT and the chines code wear limit for class II railroad is 8mm.

Predict the rail life with out of lubrication

$$L = \frac{8mm}{1.5mm/100MGT}$$

$$= 533.33MGT$$

$$K = \frac{L}{w.D^{0.565}} = \frac{533.33}{100.59*19.5^{0.565}} = 1$$

The adjusted K value by the degree of curve is

Tangent track = $61.62\ x\ 1x\ 1 = 61.62$

1.5° – 2.5° = $5.634x1x0.74 = 4.17$

2.5° – 3.5° = $5.056x1x0.61 = 3.08$

3.5° – 4.5° = $13.789x1x0.49 = 6.75$

4.5° – 5.5° = $0.98x1x0.38 = 0.3724$

5.5° –6.5° = $0.66x1x0.30 = 0.198$

6.5° –7.5° = $25.963x1x0.22 = 5.71$

Total Adjusted mile Km =81.96km

The Average adjusted value of $k = \frac{81.96}{113.89} = 0.71$

$$L = 0.71x100.59x19.5^{0.565}$$

$$= 384.028MGT$$

The cumulated tonnage of Sebeta – Adama section for 35 years is 682.5MGT. Therefore, the number of rail renewal and the cost is present in Table 5.2:

Rail Renewal	Average Life(MGT)	Average life in year	No of renewal in the life time	Length (km)	Total cost for the renewal of the rail (USD)
Tangent Line	533.33	27	1	61.63	1,588,729.41
Curve section	384.028	19	1	52.26	2,887,810.25
Total Amount	**4,476,539.663 (USD)**				

Table 5-2 Total Renewal Cost of the Addis Ababa – Adama section

Based on the above Equations and Model the rail life cost is analyzed at different inspection intervals in MGT. The result showed that as inspection interval decrease, the inspection cost as well as rail defect repair will increase but the rail broken repair, risk and derailment and train delay cost will also decrease. Therefore, the minimum total cost is derived by iteration at different inspection interval value which show on the Figure 5.1.

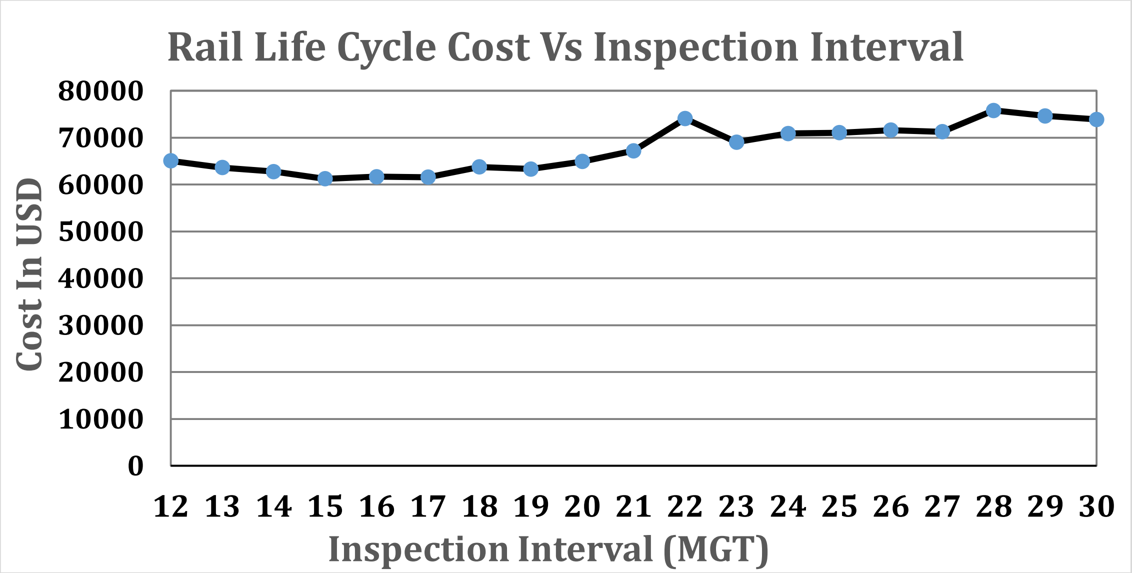


Figure 5.1 LCC of rail Vs inspection interval

Figure-5.1 shows that 15 MGT inspection interval is least total cost compare with other interval. The cost of Inspection, repair defect and broken rail, Risk and Derailment and Train delay based on 15 MGT is present at Appendix-C

Note that when the accommodate tonnage reach 513.85 MGT the straight line is change therefore maintenance volume is reduce because the rail is new.

Total life cycle cost of rail to the present value for 35 years in the section Addis Ababa – Adama is summarized in in the table 5.3.

Cost due to	Amount (USD)
Inspection cost	26,079
Rail defect repairing cost	43,854
Rail Broken Repairing cost	3,527
Cost of Risk and Derailment	25,163
Train Delay cost	23,841
Rain Renewal	4,476,540
Total Amount	**4,599,003**

Table 5-3 Total life cycle cost of Addis Ababa – Adama Rail

5.1.8.2 Life Cycle Cost of Rail with Lubrication and Rail Grinding

Lubrication at wheel flange and rails on sharp curves is considered as an effective solution for reducing wear loss of material from effective cross-section of rail and wheels. This section presents a model and analysis for lubrication strategy and rail-grinding interval to reduce wear and rolling contact fatigue (RCF). The curve from 2.5° - 7.5° use lubrication then the life of rail is;

The adjusted K value by the degree of curve is

$$\text{Tangent track} = 61.62\ x\ 1x\ 1 = 61.62$$

$$1.5° - 2.5° = 5.634x1x0.74 = 3.97$$

$$2.5° - 3.5° = 5.056x1x0.79 = 3.809$$

$$3.5° - 4.5° = 13.789x1x0.7 = 9.206$$

$$4.5° - 5.5° = 0.98x1x0.62 = 0.579$$

$$5.5° - 6.5° = 0.66x0.9538x0.55 = 0.346$$

$$6.5° - 7.5° = 25.963x0.9538x0.48 = 11.88$$

Total Adjusted mile Km =91.41km

The Average adjusted value of $k = \frac{91.41}{113.89} = 0.8$

$$L = 0.8x100.58x19.5^{0.565}$$

$$= 430.996\ MGT$$

Rail Renewal	Average Life(MGT)	Average life in year	No of renewal in the life time	Length (km)	Total amount to renewal the rail (USD)
Tangent Line	533.33	27	1	61.63	1,588,729
Curve section	430.996	22	1	52.26	2,169,655
Total Amount					**3,758,383.99 (USD)**

Table 5-4 Total Renewal Cost with use Lubrication

Lubrication cost Annual Lubricant cost per meter is 0.083 USD/meter/year and the economic cost is 0.049 USD/m/year (ERC). The total length that will be lubricant in the section is 38875m so the annual cost of lubricant is 3809.95 USD per annual for double track. Total present cost of lubricant for 35years is 37090.123 USD.

Grinding interval and cost Introduced preventive rail grinding to grind away a thin layer of material from rail surface before surface cracks can propagate. The depth of the cut is determined by the depth at which surface cracks appear. It is found that the costs of any grinding program are simply too high and there is a need of better understanding of rail surface cracks and develop economical grinding to minimize the costs and improve the grinding efficiency. RCF is the amount of growth that occur between successive grinding cycles to try to optimize the frequency of grinding. Equations 5.24, 5.25 and 5.26 give the crack depth growth rates (CDGR) in mm/100MGT for grades U71Mn rail type as a function of radius (R) in meters

$CDGR = 0.002\mathrm{R} - 0.587 \quad for\ 200 < R \le 1000$……………………………….5.24

$CDGR = -0.72\ln(R) + 6.15 \quad for\ 1000 < R < 5000$…………………………5.25

$CDGR = 0 \quad for\ R > 5000$……………………………………………………….5.26

After grinding, wheel-rail relation is improved, incidence rate of damage is reduced, corresponding maintenance workload decreases (direct performance is the reduced workload of crack), and maintenance cost is also cut down. In the different grinding interval, that the grinding is operated in different degree of rail damage, due to the developing rail damage, the condition of heavy damage or rail breaking is different, so is the workload of corresponding emergency maintenance. Data was collected from field observation and in the calculation Weibull distribution is used with the parameter α=3.6 and β= 2350 to estimate the rail breaks and derailment.

Based on the Addis- Adama Section parameter data determine the rail wear and grinding interval which is balance the development of grinding and crack. Importing the relationship of mental removing and grinding interval to the model can calculate the total rail utilization cost in the condition of different rail service life during the life cycle. Figure 5.2 the total present value cost of rail utilization cost in the condition of different grinding Interval.

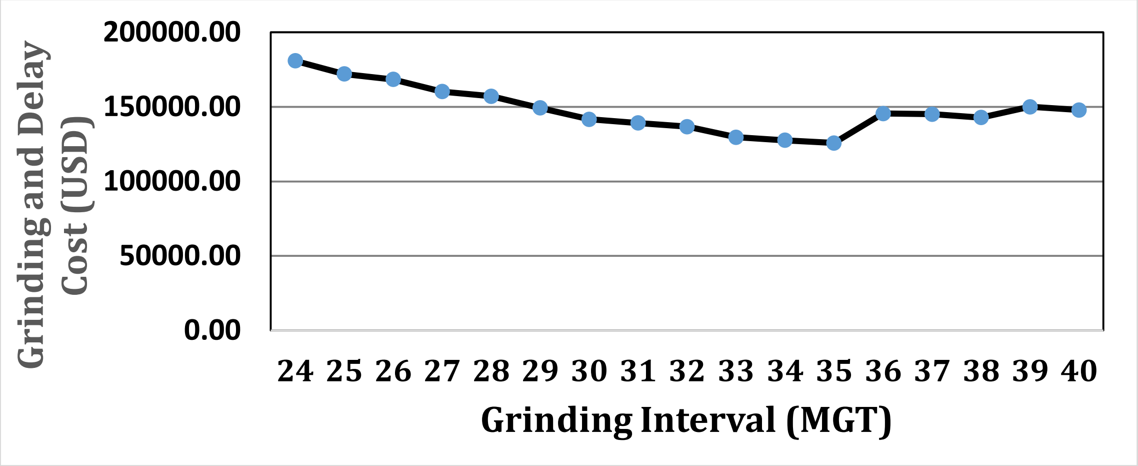


Figure 5.2 Grinding cost Vs grinding interval

From the figure 5.2 show that when grinding interval is larger, crack propagation is much deeper, and mental removal is large, repeat grinding is needed, which increases the difficulty of actual operation. Therefore, the present value cost is increase. On the other hand when grinding interval is reduced the mental removal done early than the crack growth so the rail replace early before life time as same time the grinding cost is increase because too much grinding without necessary. Therefore, total present value of rail utilization cost reaches the minimum when the grinding interval is 35 MGT. The most economical grinding interval for Addis – Adama section is 35 MGT.

Table 5.5 show that the total present cost of inspection cost, Defect repair, broken repair, Derailment and risk cost, train delay cost, train grinding cost and lubrication cost.

Cost due to	Amount (USD)
Inspection cost	26,079
Rail defect repairing cost	14282
Rail Broken Repairing cost	1149
Cost of Risk and Derailment	7812
Train Delay cost	7757
Rain Renewal	3,758,384
Grinding cost	503,126
Lubrication cost	37091
Total Amount	**4,345,678**

Table 5-5 Total Life cycle cost of Rail with lubrication and Grinding

5.1.9 Adama – Dire Dawa and Dire Dawa – Djibouti Section

The rest section of the line are Adama – Dire Dawa and Dire Dawa to Djibouti where the lines are single and the total length are 342.7Km and 295.5Km respectively. The Annual tonnage for those line are 31.8MGT and 34.9MGT.

The calculation of the LCC of rail is same procedure used as Addis Ababa – Adama Section but it change the characteristic of the section and result of life cycle cost of Adama – Dire Dawa rail life is present on table 5.6 and table 5.7.

Section	Adama – Dire Dawa	Dire Dawa – Djibouti
Cost due to	Amount (USD)	Amount (USD)
Inspection cost	109,054	98,642
Rail defect repairing cost	160,806	146,245
Rail Broken Repairing cost	13,110	11,897
Cost of Risk and Derailment	95,393	86,483
Train Delay cost	205,725	186,689
Rain Renewal	15,020,409	13,631,190
Total Amount	**15,604,500**	**14,161,149**

Table 5-6 rail life cycle cost without lubrication and grinding

Section	Adama – Dire Dawa	Dire Dawa – Djibouti
Cost due to	Amount (USD)	Amount (USD)
Inspection cost	171,148	156,418
Rail defect repairing cost	54,247	49,497
Rail Broken Repairing cost	1,752	1552
Cost of Risk and Derailment	12,134	11,071
Train Delay cost	59,204	54,008
Rain Renewal	13,249,231	12,090,248
Grinding cost	412,663	376,323
Lubrication cost	52,662	47,956
Total Amount	**14,013,044**	**12,787,076**

Table 5-7 rail life with lubrication and grinding

5.1.10 Conclusion of this Sub-Chapter

The total rail Life cycle cost of Ethio–Djibouti railway without use of Lubrication and Grinding is **34,364,653.8 USD.** The life cycle cost of rail with using Lubrication and Grinding is **31,145,798.1 USD** Where the LCC reduced by **3,218,855.7 USD**. The cost saving using of lubrication and grinding on the section of Addis Ababa – Adama, Adama – Dire Dawa and D.D- Djibouti are 5.8%, 11.3% and 10.7% respectively.

The optimum inspection interval on the line is **15 MGT**. When ERC use Lubrication as well As Grinding the optimum grinding interval is **35 MGT**. Finally from the result it conclude that using of lubrication and Grinding which reduce the life cycle cost as the same time it increase the life of the rail.

5.2 Analysis of the Life Cycle Cost of Sleeper and Fastening

The main defects for concrete sleepers are cracks, surface defects, and sleeper instability in fastening area and sleeper damage in dry land.

The general state of sleepers may be defined as a present serviceability index (PSI). In this Thesis, the one-parameter exponential CDF was modified and the following equation was used to determine the PSI of the sleepers.

$$\mathrm{PSI(m)} = 1 - \exp\left[K_f\left(\frac{M}{M_L} - 1\right)]\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 5.27$$

Where:

PSI = present serviceability index

k_f = Coefficient (for concrete sleeper the annual MGT greater than 15MGT) is 5.2

M = Cumulative load

M_L = Cumulative load limit ($M_L = S_a * L_a$)

S_a= Age limit of sleeper (35year)

L_a= Annual traffic load (MGT)

The PSI values were also taken into account during the M&R operations for the sleepers. The PSI values were obtained from statistical analyses and expert decisions. The limit values of the PSI are given in Table 5.8, including the required parameters to calculate the PSI (Guler, 2013).

value	**Decision (all type of sleepers)**
$0.6 < PSI \leq 1.0$	Only maintenance
$0.4 < PSI \leq 0.6$	Partial replacement
$0.2 < PSI \leq 0.4$	Planning of renewal
$0.0 \leq PSI \leq 0.2$	Renewal

Table 5-8 PSI Values with Required Parameters

Ethio – Djibouti railway main line is laid with II-type pre stressed concrete sleepers and the sleeper is laid in 1680 Numbers /km. in this thesis the line is divided in to three section according to the annual average tonnage and the characteristics of the line.

Statistical analysis of concrete sleeper replace in each year due to three reason:

- 0.5 % of concrete sleepers are replaced because of the defects each year.
- 0.15 % of concrete sleepers are replaced each year due to concrete sleeper vulnerability to derailment.
- 0.35 % maintenance of concrete sleeper and the fasting in each year.
- Therefore, 1% of concrete sleeper replace in each year in maintenance Action.

Sleeper maintenance cost consist of sleeper production and replacement of defect. Sleeper production for Ethio – Djibouti track is 103.45USD per sleeper (ERC) and the economic cost is 71.38USD/sleeper. The cost of replacement including Equipment, Material and Labor is 44,894.65USD per km and the economic cost is 33,222.041USD/km. Therefore, the total cost per Km is 153,140.441 USD/km.

The life cycle cost of sleeper calculation present at Appendix-c and the three section of LCC of sleeper show on table 5.9:

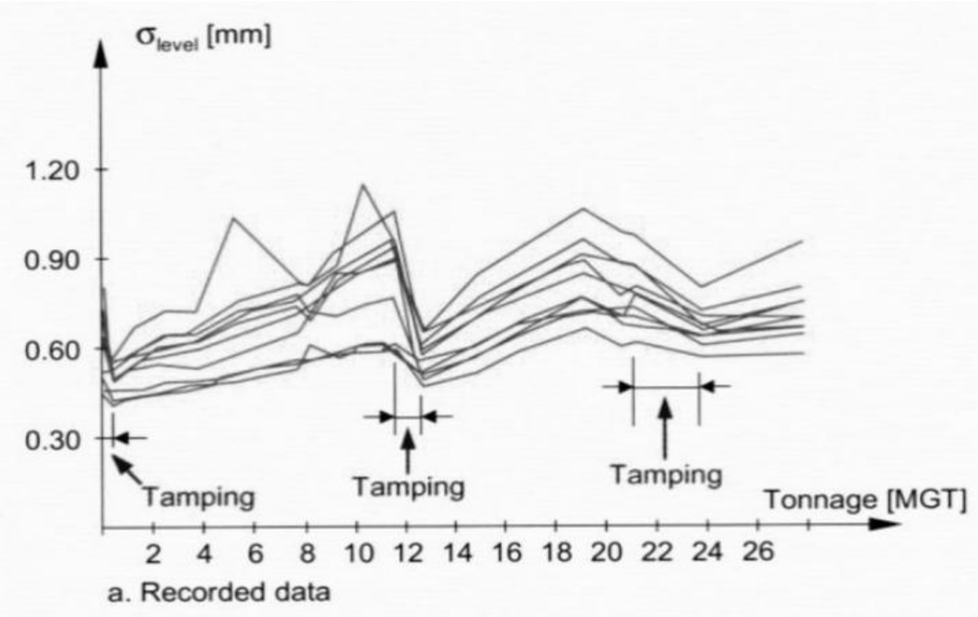
Section	A/A - Adama	Adama - D/D	D/D - Djibouti
maintenance Cost	3,285,728.82	5,146,583.16	4,265,961.63
Renewal cost	1,097,036.10	1,718,336.42	1,424,315.32
Total	4,382,764.92	6,864,919.57	5,690,276.95
Total Sleeper LCC	**16,937,961.45**		

Table 5-9 LCC of Sleeper

5.3 Analysis of the Life Cycle Cost of Ballast

Initial track defect will evolve as a function of traffic load. Knowledge of the way that track defect evolve May help a timely schedule of remedial action by track maintenance teams, before the limits previous mentioned are exceeded. Longitudinal defects are the track defects that reach respective alarm levels earlier after maintenance, and therefore, tamping operations are mainly predicted based on the evolution of the standard deviation of longitudinal defects. To quantify the economic life of ballast, as it is done for the rail, we should assume two types of maintenance operations: tamping and renewal. The tamping machine lifts the track up to the level determined by the measuring system and also positions it laterally; then the ballast under the sleepers is squeezed using so-called tamping tines.

The deterioration rates of quality indices are calculated as a function of traffic in mm/MGT or of time in mm/year. Without including quick settlement and rapid deterioration of track immediately after tamping, the deterioration rate generally displays a linear trend between two maintenance operations as shown in Figure 5.3.



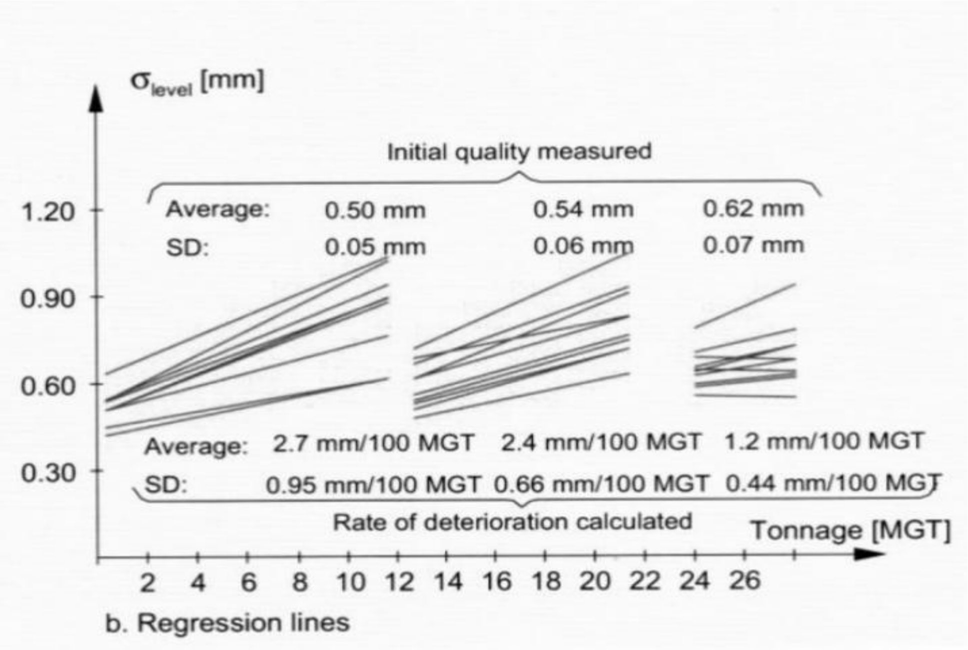


Figure 5.3 a and b Example of track level development on 10 successive sections of 200 m on FS. (Esveld, 2001)

The figure 5.3 illustrates recorded data and respective estimated regression lines for 10 successive maintenance sections of 200 meter each. Tamping operations‟ periods are signaled and statistical measures (average and standard deviation) for the coefficients of regression lines are presented (initial quality measured and calculated rate of deterioration). Regression lines are estimated using the following linear relationship:

$$\sigma = c_1 + c_0 T \text{……………………………………………………}5.28$$

Where:

σ =is the standard deviation of longitudinal defects

c_1 =is the initial quality measured after renewal or tamping operations ($average$=0.50 mm)

$c_{0=}$is the rate of deterioration (2.7 $mm/100\ MGT$).

T= is the accumulated tonnage between tamping operations

Tamping operations are scheduled when the standard deviation of longitudinal defects reach a specified target limit. This limit standard deviation (σlim) for speed 100 -120km/hr. is 1.5mm (UIC). Therefore, a prediction of accumulated tonnage between tamping operations can be calculated based on the following expression:

$$T = \frac{\sigma \lim - c_1}{c_0} \text{……………………………………………………}5.29$$

Despite the improvements offered by this maintenance activity, research has shown that tamping also damage the ballast. Demonstrated that the insertion of tines into the ballast and squeezing them gradually causes ballast breakdown. As a consequence, over time, this tamping process degrades the ballast condition, and, therefore, the track geometry would be expected to deteriorate faster. The reason for this is that ballast breakdown leads to fine particles blocking the voids, this changes the track bed elasticity, leads to poor drainage and, in extreme cases, unusable ballast.

Moreover, in order to include the loss of effectiveness of consecutive tamping operations, Andrade (2008) assume that C_1 will increase at a fixed rate r_1. Concerning the behavior of the deterioration rate C_0 of consecutive tamping operations, we will assume C_0 that will also increase at a fixed rate r_0. Note that both assumptions contribute to diminish the accumulated tonnage between tamping operations over time.

$$T = \frac{\sigma \lim \ -c_{1j}}{c_{0j}} + 2MGT \ldots\ldots 5.30$$

Where:

$C_{1j} = C_1 * (1 + r_1)^{j-1}$

$C_{oj} = C_o * (1 + r_0)^{j-1}$

$r_1 = 0.01$

$r_0 = 0.04$

A series of test and statistical analysis show that a defect present in a track after maintenance, progress rapidly up to a critical traffic load in the order of 2 million tons, beyond which defect progress is much slower. This mean that up to this traffic load the track has not fully stabilized and slow sign of instability, V.A Profillidis.

Total present cost of tamping maintenance up to renewal of ballast calculate by below formula:

$$LCC_{Tamp} = \sum_{j}^{T_{rew}} \frac{C_{tamping}}{(1+r)^{T_{accum}/T_{year}}} \ldots\ldots 5.31$$

Where:

$LCC_{Tamp} =$ Life cycle cost of tamping up to ballast renewal

$C_{tamping} =$ Taming cost per 200m section including Equipment and Labor ($500/section)

T_{accum} = The accumulated tonnage till the i^{th} tamping operation.

$T_{accum} = \sum_{j}^{i} T_i$

T_{rew} = The year when ballast renewal takes place

T_{year} = Is the annual accumulated tonnage (MGT)

Ballast renewal will be necessary when tamping operations become too demanding, meaning that they interfere to a great extent with the availability of the infrastructure, becoming traffic disruptive. Optimal renewal strategy will determine in this thesis by using of the maintenance coefficient K is of considerable assistance in the rational planning of track maintenance works. The number of tamping operations (l) for a given age may differ from the annual average number (l_m) of tamping operations. In this situation, on a particular track section, the track bed maintenance coefficient is defined as Figure 5.4:

$$k = \frac{l}{l_m} \quad \text{...5.32}$$

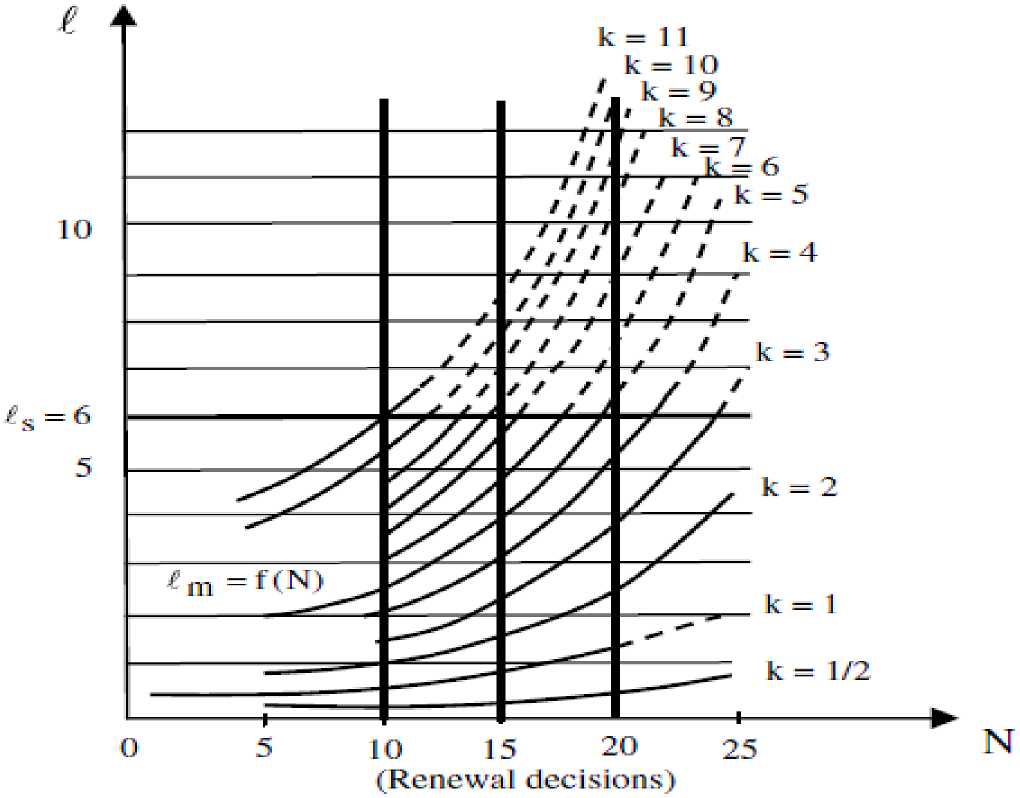


Figure 5.4 Annual number of tamping operations with track bed coefficient

When l exceeds a certain threshold value , track geometry standards can no longer be fully maintained; it will then Ballast renewal be necessary to carry out UIC (2008). Therefore the limit values for k and the decisions are given in Table 5.10 (Guler, 2013).

Limit (K)	Decision
K<1	Correct track bed layer
1 < k < 2.5	Track bed layer slightly under dimensioned
2.5 < K < 5	Under dimensioned track bed layer, sub ballast layers of poor quality and poor functioning of drainage
K > 5	Track bed layers under dimensioned, sub ballast layers of poor quality or nonexistent and poor function of drainage

Table 5-10 Track Bed Maintenance Coefficient

The following expression gives the life-cycle cost of renewal per maintenance section C_{rew}:

$$Lcc_{rew} = \frac{C_{rew}}{(1+r)^N} \quad \text{……………………………………………………………5.33}$$

Where:

LCC_{rew} = Total life cycle cost ballast renewal
C_{rew} = The renewal cost per 200m,
N = Number of year when ballast renewal

The Ballast renewal Cost pre section (C_{rew}) include: the production of ballast 47.56USD/m^3, the salvage value of ballast material is 10.2 USD/m^3 and the laying of ballast (Equipment and Labor) is 19.89 USD/m^3. The quantity of ballast in Ethio –Djibouti rail way track is 3280 m^3/km (ERC), therefore the total renewal cost of ballast per 200m is 37,556 USD/section and the economic cost is 27,791.44 USD/section.

Another life-cycle cost that we will include in the model is the cost of unavailability of the infrastructure due to tamping and geometric inspection cost. As mentioned before, most temporary maintenance operations (tamping operations) are performed during non-operative time (maintenance night shifts), and therefore considered non-disruptive. However, as tamping operations become more demanding they will interfere with the normal operation of infrastructure, causing delays and even train cancellations. Unavailability costs may be quite complex and demand more information on the robustness of the operation schedule. However, in order to quantify total life-cycle cost we will assume a function of unavailability costs with exponential behavior depending on $Trenewal$.

$$LCC_{unavail} = \begin{cases} 0\ , & T_{rew} < T_{Distuptive} \\ 337 * e^{0.02*T_{rew}}, & T_{distuptive} \leq T_{rew} \end{cases} \text{.............}5.34$$

Where:

$LCC_{unavail}$ = The total life-cycle unavailability cost per MGT for 100-km ($)

T_{rew} = The accumulated tonnage till renewal (MGT)

$T_{distuptive}$ = The accumulated tonnage limit above which tamping operations become traffic disruptive. Note that this limit depends on multiple factors, such as: maintenance equipment, human resources teams, IM internal organization, the number of maintenance bases, the extent of track analyzed and of course capacity (number of slots). Nevertheless, we will assume that $T_{distuptive}$=135 MGT (Andrade, 2008).

The following expression quantifies the life-cycle cost of geometric inspection per maintenance section ($LCCgeom.insp$):

$$LCC_{geom.insp} = \sum_{j=1}^{N} \frac{C_{geo.insp} * n}{(1+r)^j} \text{..}5.35$$

Where:

$LCC_{geom.insp}$ = Life-cycle cost of geometric inspection per maintenance section

$C_{geo.insp}$ = The economic cost of geometric inspection (26 USD/section)

$n =$ The number of geometric inspections per year (n=1)

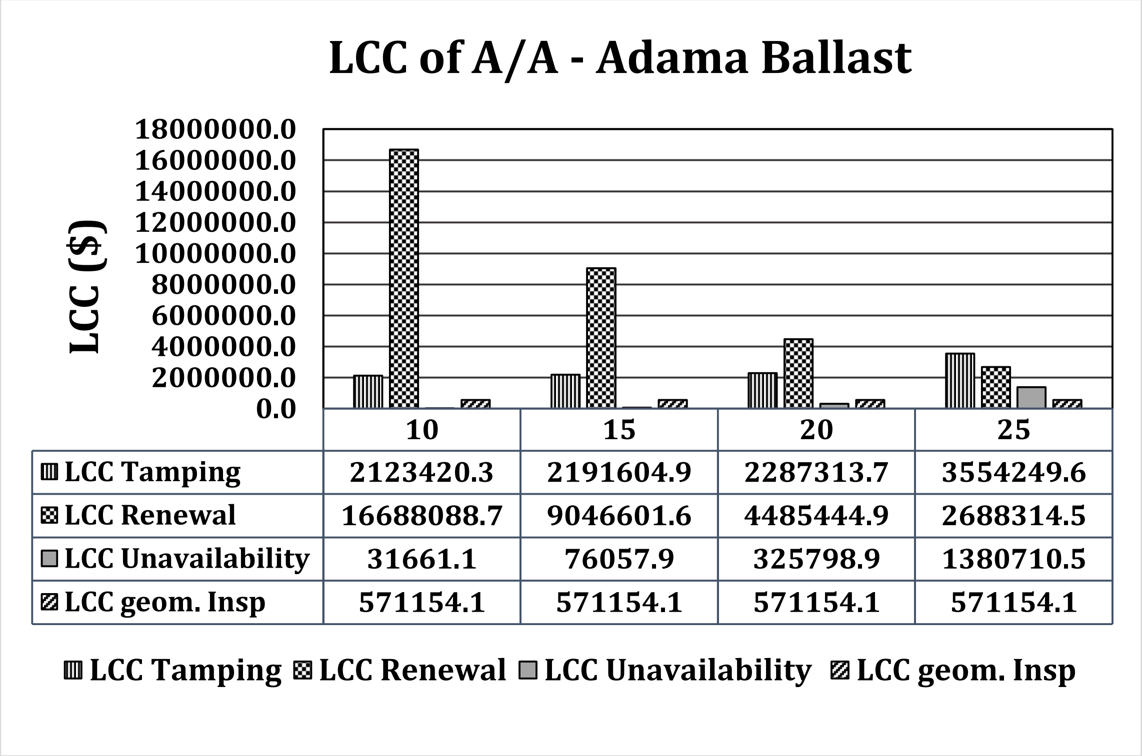
The total presented costs associated with economic life of the ballast $TLCC_{Ballast}$ is:

$$TLCC_{ballast} = LCC_{tamp} + LCC_{rew} + LCC_{unavail} + LCC_{geom.insp} \quad \text{..........5.36}$$

5.3.1 Analysis of the LCC of Ethio – Djibouti Ballast

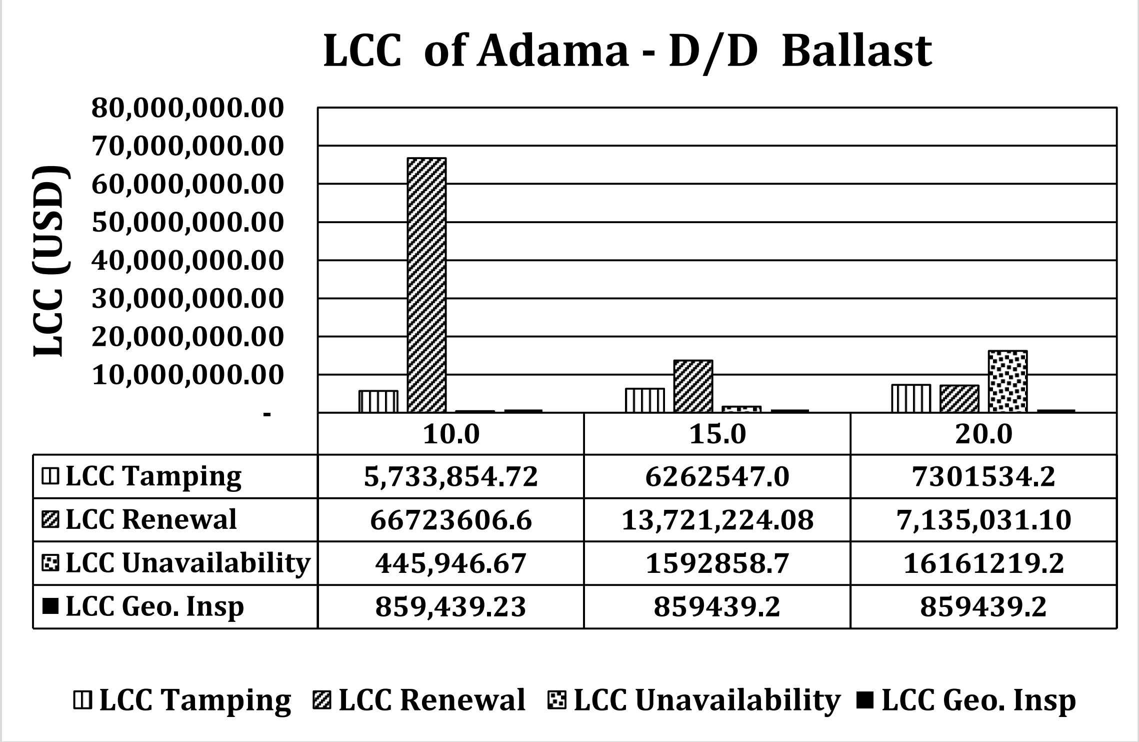
Based on the above equation the LCC of Ethio- Djibouti railway Ballast analysis on three Section Addis Ababa – Adama, Adama – Dire Dawa and Dire Dawa – Djibouti. Addis Ababa – Adama track the optimal ballast renewal carried for 10, 15, 20 and 25 year because the maintenance Coefficient (K =2.5) and the average number of tamping threshold 3 from figure- 5.4. Therefore on this section the ballast renewal can longer up to 25year due to the line is double and the average annual tonnage is 19.5 MGT.

The rest section from Adama – Dire Dawa and Dire Dawa – Djibouti line the track is single which result high Annual Average Tonnage 31.8MGT and 34.9MGT respectively. As a result of this the ballast Particle Deteriorate faster than Addis Ababa – Adama section. Based on the taming threshold the section can longer up to 20 years. Figure -5.5, 5.6 and 5.7. Show the LCC of Ballast for different ballast renewal years.



	10	15	20	25
▥ LCC Tamping	2123420.3	2191604.9	2287313.7	3554249.6
▩ LCC Renewal	16688088.7	9046601.6	4485444.9	2688314.5
▢ LCC Unavailability	31661.1	76057.9	325798.9	1380710.5
▨ LCC geom. Insp	571154.1	571154.1	571154.1	571154.1

Figure 5.5 The LCC of Ballast Addis Ababa – Adama section at 10, 15, 20 and 25year renewal



	10.0	15.0	20.0
◫ LCC Tamping	5,733,854.72	6262547.0	7301534.2
▨ LCC Renewal	66723606.6	13,721,224.08	7,135,031.10
⊡ LCC Unavailability	445,946.67	1592858.7	16161219.2
■ LCC Geo. Insp	859,439.23	859439.2	859439.2

Figure 5.6 the LCC of Ballast Adama – D/D section at 10, 15 and 20 renewal

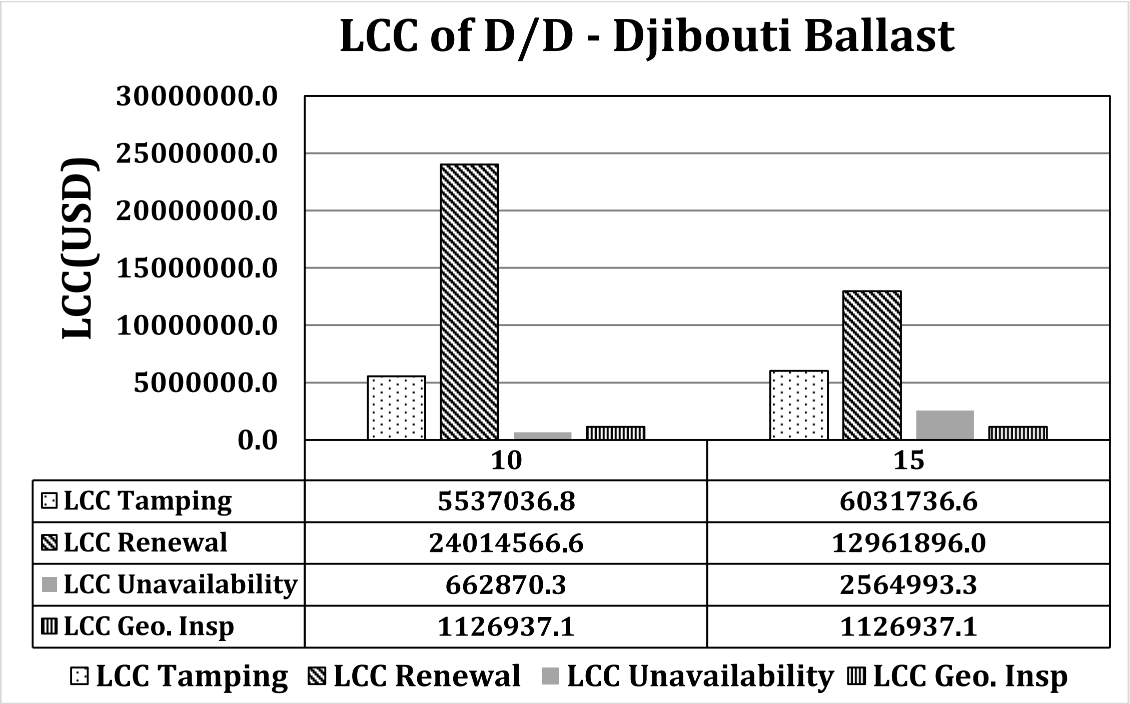


Figure 5.7 the LCC of ballast D/D – Djibouti section at 10 and 15 renewal

From the above graphs The Minimum Ballast LCC get for Addis Ababa – Adama section is 20year ballast renewal but the rest section is 15years renewal. Therefore the total ballast LCC for the three section present on table 5.11.

Section	LCC Tamping	LCC Renewal	LCC Unavailability	LCC Geo. Ins	Total LCC
A/A - Adama	2287313	4485444	325798	571154	7,669,711
Adama - D/D	6262547	13721224	1592858	859439	22,436,068
D/D - Djibouti	6031737	12961895	2564993	1126937	22,685,563
	Total				**52,791,344**

Table 5-11 Ethio –Djibouti Ballast LCC

5.4 Total LCC of Ethio- Djibouti Railway Track

The Ethio- Djibouti railway line is the main line which connect the two country in Freight transportation and Passenger transportation. Therefore the two country should manage the railway line properly to satisfy the demand in the future. In order to run this railway the infrastructure Manger of both country know the life cycle cost railway line. In this Thesis tried to calculate the LCC of the Track (Rail, Fastening, Sleeper and Ballast) on above chapters. The summarized LCC of the track for 35years is present at Figure-5.8.

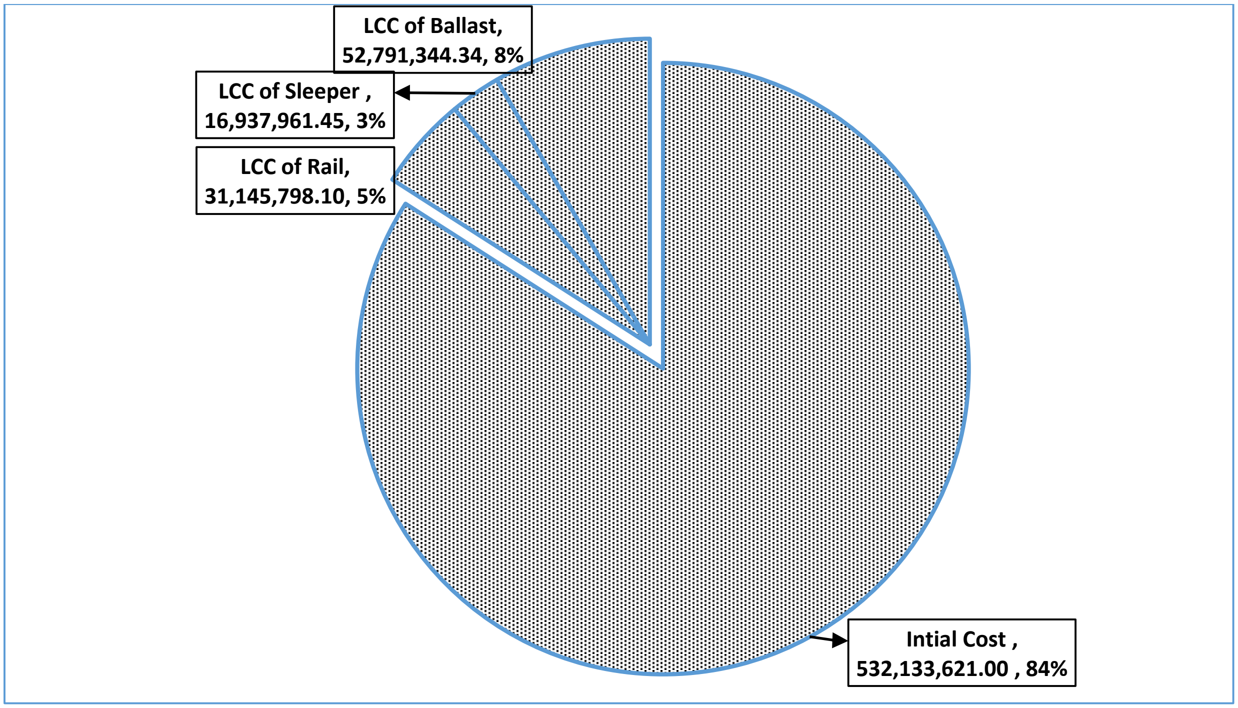


Figure 5.8 Total LCC of Ethio-Djibouti Railway Track

From the above chart we can conclude that the life cycle cost of the Line are:

- Initial construction cost of track is 84% of the Total LCC
- Ballast maintenance and Renewal is 8% of the total LCC
- Rail Maintenance, Inspection, Risk and Renewal is 5% of the Total LCC
- Sleeper Maintenance and renewal is 3% of the total LCC

Chapter 6 Conclusion and Recommendation

6. 1 Conclusion

The aim of this research work was to analyze the life cycle cost of the Ethio-Djibouti Railway Track and develop an approach that could support decision-making on maintenance and renewal action on the Railway infrastructure, especially evaluating optimal rail, sleeper and ballast renewals from a life-cycle cost (LCC) perspective.

Some results obtained from the analysis using state of the art approach enable to draw important conclusions. Therefore, the present research begins with a brief description of the LCC plays a primordial role towards a more conscious and transparent management of Railway infrastructure. Discourse on the track degradation behavior and the maintenance action that should take where evaluated; analysis of LCC was conducted considering track component such as rail, sleeper and ballast.

The rail LCC analysis consist of: inspection cost, rail defect and broken repair cost, derailment cost, Lubrication cost, delay cost and grinding cost. From the results it can be concluded that the use of lubrication and grinding will reduce the LCC rail than otherwise.

The ballast LCC analysis includes four component costs: tamping cost, renewal cost, geometric inspection cost and unavailability cost. The ballast renewal year increase the tamping and unavailability cost increase the cost whereas but the renewal cost is decreased. Therefore, the optimum renewal year is 20 years for Addis Ababa – Adama Section and 15 years for Adama- Djibouti section. Sleeper LCC is less than Rail and Ballast LCC because the sleeper type used in the line is Concrete sleeper which can last as long as 35years or more. Finally, the Total life cycle cost of the Ethio-Djibouti track is **633,008,724.89** USD.

6.2 Recommendation

This thesis study's the life cycle cost of the railway track which is constructed from Addis Ababa to Djibouti. The new railway line is constructed with large amount of capital. Therefore, the two country should manage the infrastructure properly in order to have long term service and run efficiently.

This thesis analyze the life cycle cost of the track specifically rail, sleeper and ballast. The result show that using of lubrication reduce the life cycle cost of the rail also increase the rail life. In addition, it is recommended that rail inspection interval and rail grinding interval should be 15 and 35 MGT respectively.

In addition, the ballast maintenance and renewal should be done based on the MGT. Therefore, the ballast renewal Addis Ababa - Adama section is in 20 years and Adama - Djibouti section is in 15 years. This is due to, the section from Addis Ababa- Adama is double line and the rest is single line. Therefore, it is suggested that Adama-Djibouti section should be double line in order to minimize the LCC and increase ballast renewal period as a result which will decrease the maintenance cost.

Finally, in case of concert sleeper the LCC is lower than the other Track components which shows that concert sleeper is more efficient.

Chapter 7 Future Research

Railway infrastructure is a complex system that consist of the track system, Sub grade, Bridge and tunnel, Power and Communication, Locomotive and so on. In this thesis the analysis done only on the track due to time constrain and the difficulty of analysis all system as the same time. But Ethiopia Railway Corporation should know the LCC of the other System of the Railway in order to manage the infrastructure. So it is recommend to do research on this area.

The limitation of this thesis is that it did not consider the integrated deterioration of the track due to difficulty to analyze and lack of data. So the future researcher can develop a model based on the Ethio-Djibouti railway line data which is collected in the future.

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Appendix - A

Sebeta/Addis Ababa – Djibouti railway Track

Start of LCC analysis of track section Understanding of the technical characteristics of a track section as well as the utilization of the track in terms of tonnage and frequency of trains. The total length of main line is 752.245Km (113.38km Sebeta – Adama), (356.5Km Adama – Dire Dawa) and 295.5 Km Dire Dawa –Nagada). The train speed is 120km/hr for passenger and 70km/hr for freight and the class is Chinese national railway Standard II. The track is jointed ballast track in the whole line

1. Steel rail

The rail adopts 50kg/m hot-rolled new track with a cut-length of 25mU71Mn,

Which has bolt holes.

Rail Chemical composition of Chinese Standard (%)

grade	C	Si	Mn	p	S
U71Mn	0.65-0.76	0.15-0.35	1.1- 1.4	0.04	0.04

Rail Dimension (mm)

type	Head	Height	Bottom	Web	Weight (kg/m)	Length	Tensile Strength (MPa)
P50kg	70	152	132	15.5	51.514	25m	880

2. Sleeper and fastener

The subgrade section of main line is laid with II-type pre stressed concrete sleepers. The sleeper is laid in 1680 No. /km. The turnout area shall be laid with supporting concrete sleepers. The fastening parts of fastener should get anti-corrosion treatment.

3. Ballasted track bed

The material properties of ballast should be consistent with the requirements in Table 1. The gradation of ballast should conform to the requirements in Table 2. The top surface of ballasted track bed should be flush with the top surface of the middle part of sleeper. The parameters of the track bed adopted are shown in Table 3.

Material Property	Parameters	Technical indicators
Abrasion resistance, Impact resistance	Los Angeles abrasion rate LAA%	2 ≤ LAA <32
	Standard aggregate impact toughness IP	10 < IP ≤ 95
	Rock materials wear toughness coefficient K dry grinding	17 < K ≤ 18
Resistance to crushing	Crushing rate of standards aggregate CA (%)	9 < CA < 14
	Crushing rate of ballast aggregate CB (%)	18 ≤ CB < 22
Water Permeability	Permeability coefficient Pm 10-6cm/s	3 < PM ≤ 4.5
	Compressive strength of rock powder test module σ Mpa	0.4 < σ < 0.55
	Rock powder liquid limit LL (%)	20 ≥ LL > 16
	Stone powder plastic limit PL (%)	11 ≥ PL >9
Resistance to atmospheric corrosion Damage	loss rate of soaking in sodium sulfate (%)	< 10
Stability	Density g/cm3	> 20
	Volume weight g/cm3	> 2.5
weak Particle	Saturated uniaxial compressive strenght Mpa	Proportion of soft particle is lesss than 10% (mass ratio)

Table 1 Ballast Material Properties

Side length of square sieve mm	16	25	35.5	45	56	63
Passing sieve mass percentage (%)	0 -5	5 – 15	25 - 40	55 - 75	92 - 97	97 - 100

Table 2 Ballast Gradation

Item			Main line
Top width of single track bed			3.1
Permeable soil and hard rock subgrade	Soil Subgrade	Surface ballast	25cm
		Bottom Ballast	20cm
	Permeable Soil,rock subgrade		30cm
Bridge			>25cm
Side slope of track bed			1;1.75

Table Track bed Parameter

Import And Export data

Year	Import(tons)	Export(tons)
2002	2,595,131.37	561,291.37
2003	5,092,940.56	506,009.15
2004	3,832,543.22	539,495.69
2005	4,413,599.20	748,153.90
2006	4,184,891.78	690,610.14
2007	4,887,537.06	801,230.73
2008	7,443,795.30	809,556.55
2009	8,132,745.75	909,832.78
2010	6,959,264.18	1,130,364.92
2011	7,309,505.90	1,182,913.74
2012	8,464,783.20	1,318,949.74
2013	7,343,061.98	1,339,404.28
2014	10,246,626.01	1,559,664.84

Source Ethiopia Revenue and Costumes Authority (www.erca.gov.et)

Appendix - B

Freight Forecast

Regression calculation for export data

n	x (year)	y (Export)	x*y	x2	y2
1	2002	561,291	1,123,705,327	4008004	315,048,004,281
2	2003	506,009	1,013,536,319	4012009	256,045,255,835
3	2004	539,495	1,081,149,368	4016016	291,055,602,355
4	2005	748,153	1,500,048,566	4020025	559,734,255,691
5	2006	690,610	1,385,363,935	4024036	476,942,361,341
6	2007	801,230	1,608,070,070	4028049	641,970,678,241
7	2008	809,556	1,625,589,559	4032064	655,381,812,910
8	2009	909,832	1,827,854,046	4036081	827,795,679,756
9	2010	1,130,364	2,272,033,496	4040100	1,277,724,860,392
10	2011	1,182,913	2,378,839,527	4044121	1,399,284,911,359
11	2012	1,318,949	2,653,726,880	4048144	1,739,628,420,682
12	2013	1,339,404	2,696,220,817	4052169	1,794,003,827,693
13	2014	1,559,664	3,141,164,987	4056196	2,432,554,411,541
∑	26104	12,097,477	24,307,302,897	52,417,014	12,667,170,082,081

a=	-170824299
b=	85535.2957
r=	0.97194061

n	x (year)	y (Export)	x*y	x^2	y^2
1	2002	561,291.37	1,123,705,327	4008004	315,048,004,281.6
2	2003	506,009.15	1,013,536,319	4012009	256,045,255,835.6
3	2004	539,495.69	1,081,149,368	4016016	291,055,602,355.5
4	2005	748,153.90	1,500,048,566	4020025	559,734,255,691.1
5	2006	690,610.14	1,385,363,935	4024036	476,942,361,341.0
6	2007	801,230.73	1,608,070,070	4028049	641,970,678,241.5
7	2008	809,556.55	1,625,589,559	4032064	655,381,812,910.0
8	2009	909,832.78	1,827,854,046	4036081	827,795,679,756.2
9	2010	1,130,364.92	2,272,033,496	4040100	1,277,724,860,392.2
10	2011	1,182,913.74	2,378,839,527	4044121	1,399,284,911,359.9
11	2012	1,318,949.74	2,653,726,880	4048144	1,739,628,420,682.1
12	2013	1,339,404.28	2,696,220,817	4052169	1,794,003,827,693.2
13	2014	1,559,664.84	3,141,164,987	4056196	2,432,554,411,541.4
∑	26104	12,097,477.83	24,307,302,897.62	52,417,014.00	12,667,170,082,081.3
a=	-170824299				
b=	85535.2957				
r=	0.97194061				

Regression calculation for Import data

n	x (year)	y (Import tons)	x*y	x^2	y^2
1	2002	2,595,131.37	5,195,453,009	4008004	6,734,706,843,128.9
2	2003	5,092,940.56	10,201,159,932	4012009	25,938,043,496,763.7
3	2004	3,832,543.22	7,680,416,605	4016016	14,688,387,503,580.7
4	2005	4,413,599.20	8,849,266,403	4020025	19,479,857,929,489.1
5	2006	4,184,891.78	8,394,892,906	4024036	17,513,319,188,968.6
6	2007	4,887,537.06	9,809,286,872	4028049	23,888,018,478,074.0
7	2008	7,443,795.30	14,947,140,954	4032064	55,410,088,402,945.3
8	2009	8,132,745.75	16,338,686,212	4036081	66,141,553,433,167.7
9	2010	6,959,264.18	13,988,121,005	4040100	48,431,357,951,526.8
10	2011	7,309,505.90	14,699,416,361	4044121	53,428,876,476,843.4
11	2012	8,464,783.20	17,031,143,791	4048144	71,652,554,557,994.2
12	2013	7,343,061.98	14,781,583,762	4052169	53,920,559,215,246.1
13	2014	10,246,626.01	20,636,704,783	4056196	104,993,344,574,259.0
∑	26104	80,906,425.49	162,553,272,593.91	52,417,014.00	562,220,668,051,987.0
			-		
a=	**-1021720267**				
b=	**511924.22**				
r=	**0.9015**				

Freight distribution along Different part of Ethiopia

Year	Import (Tones)	Djibouti port Share (75%)	East Ethiopia (10%)	Central Ethiopia (75%)
2015	9807040.747	7355280.56	735528.056	5516460.42
2016	10318964.97	7739223.727	773922.3727	5804417.795
2017	10830889.19	8123166.893	812316.6893	6092375.17
2018	11342813.41	8507110.06	850711.006	6380332.545
2019	11854737.64	8891053.227	889105.3227	6668289.92
2020	12366661.86	9274996.393	927499.6393	6956247.295
2021	12878586.08	9658939.56	965893.956	7244204.67
2022	13390510.3	10042882.73	1004288.273	7532162.045
2023	13902434.52	10426825.89	1042682.589	7820119.42
2024	14414358.75	10810769.06	1081076.906	8108076.795
2025	14926282.97	11194712.23	1119471.223	8396034.17
2026	15438207.19	11578655.39	1157865.539	8683991.545
2027	15950131.41	11962598.56	1196259.856	8971948.92
2028	16462055.64	12346541.73	1234654.173	9259906.295
2029	16973979.86	12730484.89	1273048.489	9547863.67
2030	17485904.08	13114428.06	1311442.806	9835821.045
2031	17997828.3	13498371.23	1349837.123	10123778.42
2032	18509752.52	13882314.39	1388231.439	10411735.79
2033	19021676.75	14266257.56	1426625.756	10699693.17
2034	19533600.97	14650200.73	1465020.073	10987650.54
2035	20045525.19	15034143.89	1503414.389	11275607.92
2036	20557449.41	15418087.06	1541808.706	11563565.29
2037	21069373.64	15802030.23	1580203.023	11851522.67
2038	21581297.86	16185973.39	1618597.339	12139480.04
2039	22093222.08	16569916.56	1656991.656	12427437.42
2040	22605146.3	16953859.73	1695385.973	12715394.79
2041	23117070.52	17337802.89	1733780.289	13003352.17
2042	23628994.75	17721746.06	1772174.606	13291309.54
2043	24140918.97	18105689.23	1810568.923	13579266.92
2044	24652843.19	18489632.39	1848963.239	13867224.29
2045	25164767.41	18873575.56	1887357.556	14155181.67
2046	25676691.63	19257518.73	1925751.873	14443139.04
2047	26188615.86	19641461.89	1964146.189	14731096.42
2048	26700540.08	20025405.06	2002540.506	15019053.79
2049	27212464.3	20409348.23	2040934.823	15307011.17
2050	27724388.52	20793291.39	2079329.139	15594968.54

Passenger forecast

Passenger trip at
2020

	Destination							
origin	**A/A**	**Bishoftu**	**Mojo**	**Adama**	**Dire Dawa**	**Harar**	**Dewale**	**sum**
A/A		5027	1219	6240	318	260		13064
Bishoftu	5052			1686	17			6754
Mojo	1225			2855				4079
Adama	7857	1686	2855		408	272		13077
Dire Dawa	285	17		56			827	1185
Harar	321			410				730
Dewale					817			817
sum	14739	6730	4074	11247	1560	532	827	39709

Passenger trip at
2025

	Destination							
origin	**A/A**	**Bishoftu**	**Mojo**	**Adama**	**Dire Dawa**	**Harar**	**Dewale**	**sum**
A/A		5606	1359	6959	355	290		14570
Bishoftu	5650			1885	19			7554
Mojo	1370			3193				4563
Adama	8787	1885	3152		450	300		14576
Dire Dawa	326	20		65			948	1359
Harar	360	0	0	459				819
Dewale					936			936
sum	16493	7512	4512	12562	1760	591	948	**44377**

Passenger trip at
2030

	Destination							
origin	**A/A**	**Bishoftu**	**Mojo**	**Adama**	**Dire Dawa**	**Harar**	**Dewale**	**sum**
A/A		6173	1497	7663	390	320		16043
Bishoftu	6239			2082	21			8342
Mojo	1512			3526				5038
Adama	9703	2082	3481		497	332		16095
Dire Dawa	371	23		74			1077	1544
Harar	399			509				908
Dewale					1038			1037
sum	18223	8278	4978	13853	1946	651	1077	**49006**

Passenger trip at 2035

	Destination							
origin	**A/A**	**Bishoftu**	**Mojo**	**Adama**	**Dire Dawa**	**Harar**	**Dewale**	**sum**
A/A		6750	1636	8379	427	350		17541
Bishoftu	6811			2273	23			9106
Mojo	1651			3526				5177
Adama	10592	2273	3800		543	362		17570
Dire Dawa	415	25		82			1206	1728
Harar	436			557				993
Dewale					1162			1161
sum	19905	9048	5436	14816	2154	712	1206	**53278**

Passenger trip at 2037

	Destination							
origin	**A/A**	**Bishoftu**	**Mojo**	**Adama**	**Dire Dawa**	**Harar**	**Dewale**	**sum**
A/A		6994	1696	8681	442	362		18175
Bishoftu	7030			2346	24			9400
Mojo	1704			3640				5344
Adama	10934	2346	3923		560	374		18137
Dire Dewa	433	26		86			1260	1805
Harar	451			576				1027
Dewale					1214			1213
sum	20553	9366	5618	15329	2240	736	1260	**55102**

Sample Calculation of Modal Split

A/A - Adama Mode and trip characteristics

	Trip distance (km)	Speed km/h	In vehicle travel time (min)	Walk and waiting time	Unit cost $ (cent)/km	Out-of-pocket cost
Car	98	100	59	5	9.70	950.60
Bus	98	75	78	15	1.45	142.10
Train	97.5	120	49	15	2.30	224.25

Logit model parameters

Parameters:	Car	Bus	Train
in vehicle Time-parameter:	-0.0250	-0.0250	-0.0250
out of vehicle Time-parameter	-0.0500	-0.0500	-0.0500
Cost parameter:	-0.0020	-0.0020	-0.0020

Utility functions:

		IVTT	*OVTT*	cost	*sum*
Car:	V(X)=	-1.47	-0.2500	1.8960	-3.616
Bus	V(X)=	-1.96	-0.7500	0.2834	-2.993
Train	V(X)=	-1.22	-0.7500	0.4473	-2.416

Utility calculation

	exp(V(X))	Car-Bus-Train
Car:	0.0269	0.0269
Bus:	0.0501	0.0501
Train:	0.0893	0.0893
Sum	0.1663	0.1663

Mode Choice Distribution:	***Car-Train-Bus***
Car:	**16.2 %**
Bus:	**30.1 %**
Train:	**53.7 %**

Sample calculation of Theoretical load

Dire Dawa - Djibouti								
year	Mean Daily Passenger Traction tonnage	Mean Daily Freight Traction Tonnage	Mean Daily passenger Tonnage		Mean Daily Freight Tonnage		T_{th} (tons per day)	
			up	down	up	down	up	down
2016	1143.6	6510.0	52.9	52.9	3238.6	17590.3	16057.8	35647.9
2017	1143.6	7440.0	55.0	55.0	3410.1	18463.0	17661.6	38208.7
2018	1143.6	7440.0	56.8	56.8	3581.6	19335.6	17898.1	39402.3
2019	1143.6	7440.0	58.7	58.7	3753.2	20208.3	18134.6	40595.8
2020	1143.6	8370.0	61.0	61.0	3924.7	21080.9	19738.7	43156.9
2021	1143.6	8370.0	62.5	62.5	4096.3	21953.6	19974.7	44350.0
2022	1143.6	9300.0	64.4	64.4	4267.8	22826.2	21578.3	46910.6
2023	1143.6	9300.0	66.3	66.3	4439.3	23698.9	21814.9	48104.1
2024	1143.6	9300.0	68.2	68.2	4610.9	24571.5	22051.4	49297.7
2025	1143.6	10230.0	70.1	70.1	4782.4	25444.2	23655.0	51858.3
2026	1143.6	10230.0	72.0	72.0	4954.0	26316.9	23891.5	53051.8
2027	1143.6	10230.0	73.8	73.8	5125.5	27189.5	24128.0	54245.4
2028	1143.6	11160.0	75.7	75.7	5297.0	28062.2	25731.6	56806.0
2029	1143.6	11160.0	77.6	77.6	5468.6	28934.8	25968.1	57999.6
2030	1143.6	12090.0	79.4	79.4	5640.1	29807.5	27571.6	60560.0
2031	1143.6	12090.0	81.4	81.4	5811.7	30680.1	27808.2	61753.7
2032	1143.6	12090.0	83.3	83.3	5983.2	31552.8	28044.8	62947.3
2033	1143.6	13020.0	85.2	85.2	6154.7	32425.4	29648.4	65507.9
2034	1143.6	13020.0	87.1	87.1	6326.3	33298.1	29884.9	66701.4
2035	1143.6	13020.0	88.9	88.9	6497.8	34170.8	30121.3	67894.9
2036	2287.2	13950.0	90.8	90.8	6669.3	35043.4	33726.3	72456.9
2037	2287.2	13950.0	92.9	92.9	6840.9	35916.1	33963.0	73650.6
2038	2287.2	13950.0	94.6	94.6	7012.4	36788.7	34199.3	74844.0
2039	2287.2	14880.0	96.5	96.5	7184.0	37661.4	35802.9	77404.6
2040	2287.2	14880.0	98.4	98.4	7355.5	38534.0	36039.4	78598.1
2041	2287.2	15810.0	100.3	100.3	7527.0	39406.7	37643.1	81158.8
2042	2287.2	15810.0	102.2	102.2	7698.6	40279.3	37879.6	82352.3
2043	2287.2	15810.0	104.1	104.1	7870.1	41152.0	38116.1	83545.8
2044	2287.2	16740.0	105.9	105.9	8041.7	42024.7	39719.7	86106.5
2045	2287.2	16740.0	107.8	107.8	8213.2	42897.3	39956.2	87300.0
2046	2287.2	16740.0	109.7	109.7	8384.7	43770.0	40192.7	88493.5
2047	2287.2	17670.0	111.6	111.6	8556.3	44642.6	41796.3	91054.2
2048	2287.2	17670.0	113.5	113.5	8727.8	45515.3	42032.8	92247.7
2049	2287.2	17670.0	115.4	115.4	8899.4	46387.9	42269.4	93441.3
2050	2287.2	18600.0	117.3	117.3	9070.9	47260.6	43873.0	96001.9

Pairs of trains per Day

	Addis Ababa - Adama		Adama - Awash		Adama - Dire Dawa		Dire Dawa - Djibouti	
year	**Passenger**	**Freight**	**Passenger**	**Freight**	**Passenger**	**Freight**	**Passenger**	**Freight**
2016	8	4	1	5	1	7	1	7
2017	8	4	1	5	1	7	1	8
2018	8	5	1	5	1	7	1	8
2019	9	5	1	6	1	7	1	8
2020	9	5	2	6	2	8	1	9
2021	9	5	2	6	2	8	1	9
2022	9	5	2	6	2	8	1	10
2023	9	6	2	7	2	9	1	10
2024	10	6	2	7	2	9	1	10
2025	10	6	2	7	2	9	1	11
2026	10	6	2	7	2	10	1	11
2027	10	6	2	8	2	10	1	11
2028	11	7	2	8	2	10	1	12
2029	11	7	2	8	2	11	1	12
2030	11	7	2	8	2	11	1	13
2031	11	7	2	8	2	11	1	13
2032	11	7	2	9	2	12	1	13
2033	12	8	2	9	2	12	1	14
2034	12	8	2	9	2	12	1	14
2035	12	8	2	9	2	13	1	14
2036	12	8	2	10	2	13	2	15
2037	12	9	2	10	2	13	2	15
2038	13	9	2	10	2	14	2	15
2039	13	9	2	10	2	14	2	16
2040	13	9	2	11	2	14	2	16
2041	13	9	2	11	2	15	2	17
2042	13	10	2	11	2	15	2	17
2043	14	10	2	11	2	15	2	17
2044	14	10	2	12	2	16	2	18
2045	14	10	2	12	2	16	2	18
2046	14	10	2	12	2	16	2	18
2047	15	11	3	12	3	17	2	19
2048	15	11	3	13	3	17	2	19
2049	15	11	3	13	3	17	2	19
2050	15	11	3	13	3	17	2	20

Appendix - C

Modelling and Analysis of A.A – Adama Rail LCC (sample calculation)

Section Parameters and Characteristics

item	**Scope**	**Sebeta – Adama Section**
1	No. of main line	Double - Track
2	Rail type	50kg/m, U71Mn Tensile Strength is 880Mpa
3	Total Length	113.89km
4	Straight line	61.627km
5	Curve section (degree of Curve)	
	1.5 – 2.5	5.634km
	2.5 – 3.5	5.056km
	3.5 – 4.5	13.789km
	4.5 – 5.5	0.98km
	5.5 – 6.5	0.66km
	6.5 – 7.5	25.962km
6	Mean traffic load per annual (MGT)	19.5 MGT

Cost in USD

Type	**Value**
Annual Tonnage (MGT)	19.5
average cost of repairing a defect rail (USD)	611.11
average cost of repairing a broken rail (USD)	702.16
The average infrastructure and equipment damage cost is per broken-rail-caused train derailment (USD)	616,263
inspection cost per hour (300 USD)	300
train delay cost due to fixing a detected rail defect (USD)	330.31
train delay cost due to fixing a broken rail (USD)	774.76
Train delay cost due to derailments (USD)	12234.16
Rail Renewal (USD/Km)	168,978.041
Unit price of grinding(USD/meter/time)	0.58
Life cycle year	35
Discount Rate	10%

LCC of rail Without Lubrication and Grinding

N (mgt)	Rail Inspection	Rail Defect Repair	Rail Broken Repair	Risk & Derail	Train delay cost due to defect	Due to broken	Due to derail
0	0	0	0		0	0	
15	954.53	0	0	0	0	0	0
30	887.06	0	0	0	0	0	0
45	824.35	49.05	3.94	0	23.84	2.26	0
60	766.07	91.16	7.33	0	44.31	4.21	0
75	711.92	127.07	10.22	0	61.76	5.87	0
90	661.59	157.45	12.66	0	76.53	7.27	0
105	614.82	224.71	18.07	0	109.22	10.38	0
120	571.36	276.81	22.26	0	134.55	12.78	0
135	530.97	320.42	25.77	318.57	155.75	14.8	6.32
150	493.43	390.04	31.37	296.05	189.58	18.01	5.88
165	458.55	444.31	35.74	275.12	215.96	20.52	5.46
180	426.13	514.32	41.37	255.67	249.99	23.75	5.08
195	396.01	575.57	46.29	237.6	279.76	26.58	4.72
210	368.01	622.46	50.06	441.6	302.56	28.74	8.77
225	342	662.74	53.3	410.38	322.13	30.6	8.15
240	317.82	710.43	57.14	381.37	345.32	32.81	7.57
255	295.35	750.59	60.37	531.62	364.83	34.66	10.55
270	274.47	797.84	64.17	494.04	387.8	36.84	9.81
285	255.07	817.32	65.74	459.11	397.27	37.74	9.11
300	237.04	860.28	69.19	568.87	418.15	39.73	11.29
315	220.28	879.97	70.78	528.66	427.72	40.64	10.5
330	204.71	904.76	72.77	491.29	439.77	41.78	9.75
345	190.24	932.97	75.04	570.69	453.48	43.08	11.33
360	176.79	940.64	75.66	530.35	457.21	43.44	10.53
375	164.29	953.73	76.71	591.43	463.58	44.04	11.74
390	152.68	969.36	77.97	549.62	471.17	44.76	10.91
405	141.89	969.58	77.98	595.9	471.28	44.77	11.83
420	131.86	972.76	78.24	553.77	472.83	44.92	10.99
435	122.53	978.98	78.74	588.14	475.85	45.21	11.68
450	113.87	978.49	78.7	546.56	475.61	45.19	10.85
465	105.82	973.18	78.27	571.42	473.03	44.94	11.34
480	98.34	963.72	77.51	590.02	468.43	44.5	11.71
495	91.39	956.18	76.91	548.31	464.77	44.16	10.89
510	84.93	945.62	76.06	560.51	459.63	43.67	11.13
525	78.92	0	0	0	0	0	0
540	73.35	0	0	0	0	0	0

N (mgt)	Rail Inspection	Rail Defect Repair	Rail Broken Repair	Risk & Derail	Train delay cost		
					due to defect	Due to broken	Due to derail
570	63.34	7.54	0.61	0	3.66	0.35	0
585	58.86	10.51	0.85	0	5.11	0.49	0
600	54.7	13.02	1.05	0	6.33	0.6	0
615	50.84	18.58	1.49	0	9.03	0.86	0
630	47.24	22.89	1.84	0	11.12	1.06	0
645	43.9	26.49	2.13	26.34	12.88	1.22	0.52
660	40.8	32.25	2.59	24.48	15.68	1.49	0.49
675	37.91	36.74	2.95	22.75	17.86	1.7	0.45
690	35.23	42.53	3.42	21.14	20.67	1.96	0.42
Total cost	**26078.84**	**43854.24**	**3527.18**	**25162.76**	**21315.96**	**2025.14**	**499.54**

LCC of Rail With lubrication and Grinding

N (mgt)	Rail Inspection	Rail Defect Repair	Rail Broken Repair	Risk & Derail	Train delay cost		
					due to defect	Due to broken	Due to derail
0	0	0	0		0	0	
15	954.53	0	0	0	0	0	0
30	887.06	0	0	0	0	0	0
45	824.35	7.01	0.56	0	3.41	0.32	0
60	766.07	6.52	0.52	0	3.17	0.3	0
75	711.92	18.17	1.46	0	8.83	0.84	0
90	661.59	39.36	3.17	0	19.13	1.82	0
105	614.82	36.58	2.94	0	17.78	1.69	0
120	571.36	67.99	5.47	0	33.05	3.14	0
135	530.97	63.18	5.08	0	30.71	2.92	0
150	493.43	88.07	7.08	0	42.81	4.07	0
165	458.55	109.13	8.78	0	53.04	5.04	0
180	426.13	130.39	10.49	0	63.38	6.02	0
195	396.01	144.73	11.64	0	70.35	6.68	0
210	368.01	156.4	12.58	0	76.02	7.22	0
225	342	186.04	14.96	205.19	90.43	8.59	4.07
240	317.82	191.8	15.43	190.69	93.22	8.86	3.79
255	295.35	213.38	17.16	177.21	103.72	9.85	3.52
270	274.47	233.29	18.76	164.68	113.4	10.77	3.27
285	255.07	247.15	19.88	153.04	120.13	11.41	3.04
300	237.04	271.99	21.88	142.22	132.2	12.56	2.82

					Train delay cost		
N (mgt)	**Rail Inspection**	**Rail Defect Repair**	**Rail Broken Repair**	**Risk & Derail**	**due to defect**	**Due to broken**	**Due to derail**
330	204.71	297.53	23.93	122.82	144.62	13.74	2.44
345	190.24	310.45	24.97	228.28	150.9	14.34	4.53
360	176.79	321.56	25.86	212.14	156.3	14.85	4.21
375	164.29	337.92	27.18	197.14	164.25	15.61	3.91
390	152.68	341.29	27.45	183.21	165.89	15.76	3.64
405	141.89	352.13	28.32	170.26	171.16	16.26	3.38
420	131.86	358.62	28.84	237.33	174.31	16.56	4.71
435	122.53	370.76	29.82	220.55	180.21	17.12	4.38
450	113.87	371.65	29.89	204.96	180.65	17.16	4.07
465	105.82	377.76	30.38	253.96	183.62	17.44	5.04
480	98.34	387	31.13	236.01	188.11	17.87	4.69
495	91.39	386.82	31.11	219.33	188.02	17.86	4.35
510	84.93	390.52	31.41	254.78	189.82	18.03	5.06
525	78.92	0	0	0	0	0	0
540	73.35	0	0	0	0	0	0
555	68.16	0.58	0.05	0	0.28	0.03	0
570	63.34	0.54	0.04	0	0.26	0.02	0
585	58.86	1.5	0.12	0	0.73	0.07	0
600	54.7	3.25	0.26	0	1.58	0.15	0
615	50.84	3.02	0.24	0	1.47	0.14	0
630	47.24	5.62	0.45	0	2.73	0.26	0
645	43.9	5.22	0.42	0	2.54	0.24	0
660	40.8	7.28	0.59	0	3.54	0.34	0
675	37.91	9.02	0.73	0	4.39	0.42	0
690	35.23	10.78	0.87	0	5.24	0.5	0
Total cost	**26078.84**	**14281.94**	**1148.68**	**7811.92**	**6942**	**659.5**	**155.08**

LCC of Grinding and Delay due to Grinding

Grinding Interval	**Grinding cost**	**Train Delay Cost**
35	18542.57	1897.475099
70	15626.991	1599.12172
105	13169.849	1347.680545
140	11099.061	1135.775238
175	9353.8775	957.1892949
210	7883.1014	806.683678
245	6643.5859	679.8431197
280	5598.968	572.946596
315	4718.6029	482.8581659
350	3976.6637	406.9349744
385	3351.3848	342.9497213
420	2824.423	289.0253203
455	2380.3191	243.5798328
490	2006.0447	205.2800595
525	1690.6202	173.0024294
560	1424.7921	145.8000385
595	1200.762	122.8748712
630	1011.9577	103.5543895
665	852.84046	87.2718032
690	754.74501	77.23362236
Total	114111.16	11677.08052

Modelling and analysis of D/D – Djibouti Sleeper LCC (sample calculation)

Analysis Sleeper LCC

Maintenance action	Cost ($)
sleeper maintenance cost	153140.441
Sleepers renewal cost	153140.441

section	D/D - Djibouti
Total length	295.5
Sa =	35
ML=	34.9
Kf=	5.2
Discount ®	10.00%

year	Cumulative load	PSI	Maintenance Action	Total Cost
1	18.87258519	0.99	only maintenance	411,390.91
2	39.26525292	0.99	only maintenance	373,991.74
3	60.17988756	0.99	only maintenance	339,992.49
4	81.61648909	0.99	only maintenance	309,084.08
5	104.5733699	0.99	only maintenance	280,985.53
6	128.0518882	0.99	only maintenance	255,441.39
7	153.0503564	0.99	only maintenance	232,219.44
8	178.5707916	0.99	only maintenance	211,108.59
9	204.6131936	0.99	only maintenance	191,916.90
10	232.1755455	0.99	only maintenance	174,469.91
11	260.2598644	0.98	only maintenance	158,609.01
12	288.8661501	0.98	only maintenance	144,190.00
13	318.9923857	0.98	only maintenance	131,081.82
14	349.6405883	0.98	only maintenance	119,165.29
15	381.8086335	0.97	only maintenance	108,332.08
16	414.4987528	0.97	only maintenance	98,483.71
17	447.7108391	0.96	only maintenance	89,530.65
18	482.4428752	0.96	only maintenance	81,391.50
19	517.6968782	0.95	only maintenance	73,992.27
20	553.4727971	0.94	only maintenance	67,265.70
21	592.2296659	0.93	only maintenance	61,150.64
22	631.5086266	0.92	only maintenance	55,591.49
23	671.3094293	0.9	only maintenance	50,537.72
24	712.6301818	0.89	only maintenance	45,943.38
25	754.4729012	0.86	only maintenance	41,766.71

year	**Cumulative load**	**PSI**	**Maintenance Action**	**Total Cost**
26	797.8355706	0.84	only maintenance	37,969.73
27	841.7202068	0.8	only maintenance	34,517.94
28	886.12681	0.76	only maintenance	31,379.95
29	932.053363	0.71	only maintenance	28,527.22
30	978.5018829	0.64	only maintenance	25,933.84
31	1025.47237	0.57	Partial of Replacement	235,762.18
32	1073.962807	0.47	Partial of Replacement	214,329.25
33	1122.97521	0.34	renewal	974,223.88
34	1172.509581	0.19	renewal	
35	1223.563901	-0.01	renewal	
			total maintenance	1,424,315.32
			total renewal	4,265,961.63

Modelling and analysis of Adama – Dire Dawa Ballast LCC (sample calculation)

Ballast Analysis Adama – D/D

Type of work	Cost
Ballast Tamping (Tc), ($/200m)	370
Ballast Renewal (Rc), ($/200m)	27,791

Parameters	Value
Section	Adama –D/D
Track Type	1
Total Length	342.75
Annual Tonnage	31.8
Total life year	35
c1	0.5
coj	2.7
ro	0.04
r1	0.01
σ lim	1.5
C1j=	$(1+r1)^{j-1}$
coj	$(1+r0)^{j-1}$

10 year					
No tamping	**Taming interval**	**tamping cost**	**Renewal cost**	**unavailable**	**Inspection cost**
1.0	39.0	564074.4			
2.0	37.4	504207.8			
3.0	35.9	452774.3			
4.0	34.4	408384.9			
5.0	33.0	369907.7			
6.0	31.7	336415.5			
7.0	30.4	307145.3			
8.0	29.1	281466.5			
9.0	27.9	258855.0			
10.0	26.8	238873.8			
			17942287.7	293648.9	
1.0	39.0	212498.4			
2.0	37.4	189945.4			
3.0	35.9	170569.4			
4.0	34.4	153847.0			

No tamping	Taming interval	tamping cost	Renewal cost	unavailable	Inspection cost
5.0	33.0	139351.8			
6.0	31.7	126734.6			
7.0	30.4	115708.0			
8.0	29.1	106034.2			
9.0	27.9	97516.0			
10.0	26.8	89988.7			
			6759228.3	110623.6	
1.0	39.0	80052.5			
2.0	37.4	71556.3			
3.0	35.9	64257.0			
4.0	34.4	57957.3			
5.0	33.0	52496.7			
6.0	31.7	47743.5			
7.0	30.4	43589.6			
8.0	29.1	39945.3			
9.0	27.9	36736.3			
10.0	26.8	33900.6			
			2546340.1	41674.2	
1.0	39.0	30157.4			
2.0	37.4	26956.7			
3.0	35.9	24206.9			
Total		5733854.7	66723606.6	445946.7	859439.2
15 year					
No tamping	**Taming interval**	**tamping cost**	**Renewal cost**	**unavailable**	**Inspection cost**
1.0	39.0	564074.4			
2.0	37.4	504207.8			
3.0	35.9	452774.3			
4.0	34.4	408384.9			
5.0	33.0	369907.7			
6.0	31.7	336415.5			
7.0	30.4	307145.3			
8.0	29.1	281466.5			
9.0	27.9	258855.0			
10.0	26.8	238873.8			
11.0	25.7	221156.8			
12.0	24.7	205396.1			
13.0	23.7	191331.6			
14.0	22.7	178743.0			
15.0	21.8	167442.9			

No tamping	Taming interval	tamping cost	Renewal cost	unavailable	Inspection cost
16.0	20.9	157271.1			
17.0	20.1	148090.5			
			11123372.1	1290594.5	
1.0	39.0	131739.0			
2.0	37.4	117757.2			
3.0	35.9	105745.0			
4.0	34.4	95377.9			
5.0	33.0	86391.6			
6.0	31.7	78569.5			
7.0	30.4	71733.5			
8.0	29.1	65736.2			
9.0	27.9	60455.3			
10.0	26.8	55788.7			
11.0	25.7	51650.9			
12.0	24.7	47970.0			
13.0	23.7	44685.3			
14.0	22.7	41745.3			
15.0	21.8	39106.1			
16.0	20.9	36730.5			
17.0	20.1	34586.4			
			2597852.0	301417.0	
1.0	39.0	30767.5			
2.0	37.4	27502.1			
3.0	35.9	24696.6			
4.0	34.4	22275.4		847.2	
Total		6262547	13721224.1	1592858.7	859439.2
20 year					
No tamping	**Taming interval**	**tamping cost**	**Renewal cost**	**unavailable**	**Inspection cost**
1.0	39.0	564074.4			
2.0	37.4	504207.8			
3.0	35.9	452774.3			
4.0	34.4	408384.9			
5.0	33.0	369907.7			
6.0	31.7	336415.5			
7.0	30.4	307145.3			
8.0	29.1	281466.5			
9.0	27.9	258855.0			
10.0	26.8	238873.8			
11.0	25.7	221156.8			

No tamping	Taming interval	tamping cost	Renewal cost	unavailable	Inspection cost
12.0	24.7	205396.1			
13.0	23.7	191331.6			
14.0	22.7	178743.0			
15.0	21.8	167442.9			
16.0	20.9	157271.1			
17.0	20.1	148090.5			
18.0	19.3	139783.2			
19.0	18.5	132247.7			
20.0	17.8	125396.0			
21.0	17.0	119151.7			
22.0	16.4	194471.1			
23.0	15.7	203993.4			
24.0	15.1	213550.2			
25.0	14.5	223122.2			
26.0	13.9	232690.8			
			7135031.1	16023770.7	
1.0	39.0	84503.3			
2.0	37.4	75534.8			
3.0	35.9	67829.6			
4.0	34.4	61179.7			
5.0	33.0	55415.4			
6.0	31.7	50398.0			
7.0	30.4	46013.1			
8.0	29.1	42166.2			
9.0	27.9	38778.8			
10.0	26.8	35785.4			
11.0	25.7	33131.2			
12.0	24.7	30770.1			
13.0	23.7	28663.2			
14.0	22.7	26777.3			
15.0	21.8	25084.4			
16.0	20.9	23560.6		137448.5	
Total		7301534.	7135031.1	16161219.2	859439.2

Ballast renewal year	LCC Tamping	LCC Renewal	LCC Unavailability	LCC Geo. Insp	LCC
10.0	5733854.7	5733854.7	445946.7	859439.2	74572864.8
15.0	6262547.0	13721224.1	1592858.7	859439.2	22436069.0
20.0	7301534.2	7135031.1	16161219.2	859439.2	31457223.8