

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



**Operation and Maintenance Cost Analysis of Railway
Track Super Structure of Addis Ababa Light Rail
Transit (AALRT)**

**A Thesis in Master of Science in Railway Engineering
(Civil Infrastructure)**

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Science in Railway Engineering Civil Infrastructure

APPROVAL

The undersigned have examined the thesis entitled “**Operation and Maintenance Cost Analysis of Railway Track Super Structure of Addis Ababa Light Rail Transit (AALRT)**” presented by **John Chrysostom Niwamanya**, a candidate for the degree of **Master of Science in Railway Engineering (Civil Infrastructure)** and hereby certify that it is worthy of acceptance.

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UNDERTAKING

I certify that research work titled entitled “**Operation and Maintenance Cost Analysis of Railway Track Super Structure of Addis Ababa Light Rail Transit (AALRT)**” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

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ABSTRACT

Operation and Maintenance Cost Analysis is an engineering economics technique that can be utilized to better formulate maintenance strategy and minimize the O&M cost of projects. It also helps in foreseeing the cost implications of maintenance actions over the service life a product. Addis Ababa Light Rail Transit (AALRT) is constructed using a loan (475M) USD as per ERC report that must be paid in 23 years. The Ethiopian Railways Corporation (ERC) should determine the income, operation and maintenance cost (O&M) of AALRT line in order to pay the loan on time. Thus, by investigating and analysing O&M Costs and optimization of the maintenance strategy the investment can minimize the O&M cost of the Light Rail Transit. The main objective of this research is to develop a decision support tool to AALRT Management for maintenance program and strategic plan through operation and maintenance Cost Analysis. The developed models for O&M cost analysis of railway track infrastructure can be used by managers to make necessary maintenance and renewal decisions. Probabilistic and Analytical methods have been used to predict failure time of the railway track components and analyse the O&M costs of the super structure of the track components. This research determines the total O&M cost of the railway track super structure components in the operation and maintenance phase. It also identifies optimal maintenance and renewal (M&R) strategies for track super structure components. From the analysis, the total cost value for 25 years is 207,572,671Birr. It is observed from the analysis that as more load is applied in MGT, the more M&R costs will be expected.

Keywords: Railway track, Cost Analysis, Operation and Maintenance, Addis Ababa Light Rail Transit (AALRT).

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ABBREVIATIONS/ ACRONYMS

AALRT:	Addis Ababa Light Rail Transit
CSA:	Central Statistical Agency
DSS:	Decision Support System
ERA:	Ethiopian Roads Authority
ERC:	The Ethiopian Railway Corporation
ETB:	Ethiopian Birr
GTK:	Gross Ton Kilometer
LCC:	Life Cycle Cost
LCCA:	Life Cycle Analysis
LRT:	Light Rail Transit
M&R:	Maintenance and Renewal
MGT:	Million Gross Tons
Mo FED:	Ministry of finance and Economic Development
MTTF:	Mean Time to Fail
MTTR:	Mean Time to Repair
NBA:	National Bank of Ethiopia
NPV:	Net present value
O&M:	Operation and Maintenance
PVU:	Passenger Vehicle Unit
RAMS:	Reliability Availability Maintainability and Safety
TPVC:	Total Present value Cost

SYMBOLS

C_b	Cost of ballast in ETB/km
C_{eb}	Equipment cost for ballast cleaning in ETB/hr
C_{ebr}	Equipment cost for ballast renewal in ETB/hr
C_{efr}	Equipment cost for fastener renewal in ETB/hr
C_{eg}	Equipment cost for grinding in ETB/hr
C_{er}	Equipment cost to repair rail breaks in ETB/hr
C_{err}	Equipment cost for rail renewal in ETB/hr
C_{esr}	Equipment cost for sleeper renewal in ETB/hr
C_{et}	Equipment cost for track inspection in ETB/hr
C_{eta}	Equipment cost for tamping the ballast in ETB /hr
C_f	Cost of fasteners in ETB/km
C_L	Average labour cost in ETB (Ethiopian Birr)/hr
C_{lu}	Cost of lubrication material for each lubricator per year in ETB
C_r	Cost of rail in ETB/Km
C_s	Cost of sleeper in ETB/km
L	Total length of track section in km
m	m –year in MGT
M	Life period of track in MGT (Million Gross Tons)
m_{bi}	Interval for ballast cleaning in MGT
$M_{br,i}$	Interval for ballast renewal in MGT
m_{fri}	Interval for fastener renewal in MGT
m_{gi}	Interval for grinding in MGT
m_{rri}	Interval for rail renewal in MGT
M_{sri}	Interval for sleeper renewal in MGT
m_t	Interval for track inspection in MGT
m_{tai}	Interval for ballast tamping in MGT
N	Life period of track (equivalent to M) in years
n_{gi}	Number of grinding passes on track
n_{li}	Number of way side lubricators in lubrication areas
r	Discount rate
T_{bi}	Mean time to clean ballast for in hr/Km

T_{bri}	Mean time for ballast renewal in hr./km
T_{fri}	Mean time for fastener renewal in hr/Km
T_{gi}	Mean time to grind in hr/km
T_{lu}	Mean time to refill lubrication material for each lubricator in hr
T_{rbi}	Mean time to repair rail break in hr
T_{rri}	Mean time for rail renewal in hr./km
T_{sri}	Mean time for sleeper renewal in hr/Km
T_{t}	Mean time to inspect track in hr/Km
T_{tai}	Mean time to tamp the ballast for in hr/km

CHAPTER 1: INTRODUCTION

1.1 Background

Railway transport is vital for a nation's economic and social development. A country can use railway transport for both freight and passengers. A light rail system ("Light rail" or "Light Rail Transit" LRT) as a particular class of urban public passenger railway is an integral part of a public transport system. According to [1], Light Rail Transit (LRT) is a light capacity transit mode utilizing predominantly semi-exclusive right-of-way and electrically propelled rail vehicles capable of multiple unit operation.

Ethiopia has provided its citizens LRT system for passengers in the capital city called AALRT. The transit system was built mainly to provide an alternative means of public transport to the city's road-based system, minimise passenger journey times and to provide a more environmentally-friendly transport option considering its rapid population increase. In addition, it is designed to improve mass transit of passengers in a reliable, available and safe network with in the central business district of Addis Ababa.

The total length of both lines (EW and NS) is 31.05 kilometers with 39 stations. Trains are expected to be able to reach maximum speeds of 70 km/h. The railway was contracted by China Railway Group Limited. ERC began construction of the double track electrified light rail transit project in December 2011 after securing funds from the Export-Import Bank of China.

Addis Ababa light rail Transit like any other project it has to undergo project Operation and maintenance as a phase in project management, this operation and maintenance is done by the Chinese company (Shenzhen Metro Group) which is tasked with training the Ethiopian members of staff and providing knowledge transfer.

The management of AALRT is in charge of achieving operation and maintenance requirement in its system of life cycle. To fulfil this requirement in an effective manner, it is important to know the O&M costs for planning purposes and proper decision making.

The performance of the infrastructure depends largely on the operation and maintenance decisions taken during its life cycle. Solutions that are more affordable in the short term may yield to maintenance and renewal processes which are unfavorable or less sustainable in the long term [2]. According to [3], O&M cost analysis serves as a tool to help decision makers in prioritizing projects systematically.

The main goal of this thesis is to analyze the operation and maintenance cost of AALRT track super structure and determine the maintenance and renewal strategies. At present decision support tools for railway track components that optimize these works are increasingly gaining importance [4]. Given the substantial cost of railway infrastructure operation and maintenance works and the complexity of scheduling these activities, interest has grown in developing and implementing optimal strategies that will reduce O&M costs. At the same time, a good infrastructure performance requires investigation of economic effectiveness of the track maintenance based on performance indicators and/or parameters.

According to [5], Railway infrastructure condition-monitoring and analysis as a basis for maintenance management, the average annual operation and maintenance expenditures per Km of tracks of advanced railway networks revolve around EUR (€) 50,000.

According to [6], the estimated saving made when modern condition-based decision-making approach, embedded in a suitable decision-support information system, are reported to range from modest 15 % up to the optimistic 55 %. In addition, a simple O&M cost model is basically an accounting structure that contains mathematical expressions to estimate the cost associated with each of the cost elements.

It is also noted by [4], optimization model to schedule railway track renewal operations, that the O&M cost analysis approach proved to be effective in scheduling railway track renewal works and thus, offers railway infrastructure managers a useful tool to help decide on an optimal maintenance schedule for railway track components

1.2 Statement of the problem

The Addis Ababa Light Rail Transit (AALRT) is a modern transportation system designed to improve mass transit options and reduce congestion in Ethiopia's capital. The project was launched by the Ministry of Transportation in 2008 and received 85 percent of its funding from the Export-Import Bank of China as a loan, while 15% was funded by the Ethiopian government. AALRT was constructed at an initial capital of 475M USD as per [7]. The loan rate was Libor 6 months (0.507%) plus 2.6 % with a 3-year grace period and 23-years maturity as per the Ethiopian Railways Corporation (ERC). Since the loan must be paid in a specified time, ERC must determine the income, O&M of AALRT line, however, ERC does not have the total operation and maintenance costs of the project for throughout its design life. Thus, by investigating and analysing the O&M cost, and optimisation of the maintenance strategy the Corporation can minimise the life cycle cost (LCC) of the rail track. It is ideal and necessary to determine the effective maintenance in order to have reduced maintenance costs and predict inspection interval, grinding interval, tamping interval, and renewal intervals for maintenance and procurement.

1.3 Objective

The main objective of this research is to develop a decision support tool to AALRT Management for maintenance program and strategic plan through operation and maintenance cost analysis

Specific objectives

1. Develop a model(s) suitable for the analysis of the Operation and Maintenance Cost of AALRT track super structure components.
2. Analyse the operation and maintenance cost of AALRT track super structure components.
3. Determine the optimal maintenance and renewal (M&R) strategies for track super structure components.

1.4 Scope and Limitations

The research is limited to operation and maintenance cost analysis of Rail Track super structure components (Rail and its fastening system, the sleeper and Ballast).

The models used will consider the failure of each component separately not as a whole.

1.5 Structure of the thesis report

This thesis contains five chapters. Chapter one is the introduction which presents the background of the research area, problem statement, objectives of the study, scope and limitations of the research and the report structure. Chapter two is the literature review of previous works that focus on operation and Maintenance cost analysis, Inspection, Maintenance and Renewal works and Track Degradation. Chapter three discusses the adopted methodology for the research in order to achieve the stated objectives. Chapter four shows the mathematical models, data analysis of the track super structure components, discussion of the results and their validation in relation to prior researches. Chapter five shows conclusions and recommendations drawn from the study and recommended areas for further research.

CHAPTER 2: LITERATURE REVIEW

Under this chapter, a review of what has been researched on was done, with a focus on the track, operation and maintenance cost analysis, Inspection, Maintenance and Renewal works, track degradation of the rail, sleeper, fastenings and ballast.

2.1 The railway track structure

Railway track is defined as an assembly of rails, ties and fastenings over which cars, locomotives and trains are moved. Ballast may or may not be a part of the track, depending on the type of the track in question [8]. According to [9], railroad track is the structure that contains parallel lines of steel rails, fastening systems, sleepers, ballast and sub ballast to avail the path for the movement of locomotives, cars or wagons for transportation of freight and passengers.

It is noted by [10] that a railway track is where the vehicle moves along two parallel rails. In addition, these rails support the wheels of the vehicles, which are usually trams or trains. The structure of a rail track is divided into two components that is superstructure (top of the track) and Substructure (below the track). The track superstructure consists of the rails, the fastening system, rail pads and the sleepers, while the substructure consists of the ballast, sub-ballast and the subgrade as shown in Figure.1

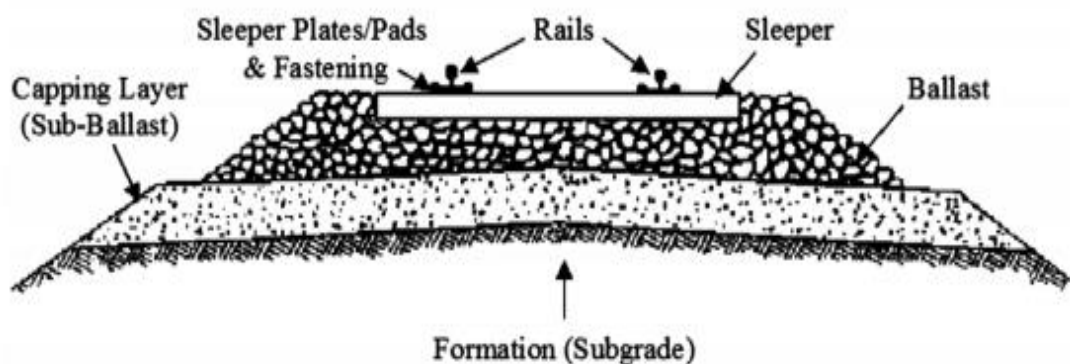


Figure 1: Typical cross section of a railway track [10]

2.1.1 Rails

Rails are made of steel which are constructed longitudinally for the first element in contact with the vehicle wheels. Their main function is for the transmission of the imposed loads that come from the wheel. This load that comes from the wheel is transmitted to the sleeper with the help of the rail. The rail transmits not only the vertical load but also distributes the horizontal force to the sleeper. The other function of the rail is that, it is a guidance of the vehicle wheel [11],

2.1.2 Fastening system

As per [9] fastening system is the structural connection of the three components of rail, rail pads and sleepers. The main purpose of the fastening system is to provide elastic transmission of the imposed loads that come from rail and rail pads to sleeper. In addition, the fastening system provides electrical insulation for concrete sleepers and it withstands various movement of rail.

In the railway track structure, rails and sleepers need to be fixed to each other to protect the rail from longitudinal, lateral and vertical movement. For this purpose, the important components are the fastening system. In addition, fastening systems is important for protecting rails from overturning and it is used as a tool for gauge restraint, reduction of wheel load impact and increasing track elasticity [12]

2.1.3 Sleepers

The sleepers play an important role in railway track system. It is one of the components of railway track that is used to transfer the vertical and horizontal wheel load that comes from rails and fastening system to ballast and used as function of controlling the movement of rails. It is also used as ties and maintain the line, level and the gauge of the rails and resist action of those forces tending to alter the line and level of the rails [11] and [13] cited in [14].

Sleepers is one of the basic elements in the railway track component and has a function of transferring the vertical, lateral and longitudinal rail seat loads to the ballast, sub ballast and subgrade layers. Sleepers may be wooden or pre-stressed / reinforced concrete. They also serve to maintain the track gauge and alignment by providing a stable support for the rail fasteners [15] and [12]

2.1.4 Ballast

In the railway track structure, the ballast layer is often made of angular, crushed, hard stones and rocks of ballasted railway track. It is placed on the upper layer of substructure and to the sides, in the middle of sleepers, outside the rail to form the shoulders and ends down to form a ballast layer. Its fundamental function is to withstand longitudinal force, keep stability and elasticity of the track, limit sleeper movement by resisting vertical, transverse and longitudinal forces from the trains, to distribute the load from the sleepers to protect the subgrade from high stresses, thereby limiting permanent settlement of the track. It also provides necessary resilience to absorb shock from dynamic loading, to facilitate maintenance surfacing and lining operations, to provide immediate water drainage from the track structure, to help alleviate frost problems, and to retard the growth of vegetation and resist the effects of fouling from surface-deposited materials [15] and [16].

In the railway ballast track structure, the ballast is the top layer of the substructure and it is the vital element in the railway track structure which supports the rail and sleepers. It is designed to guarantee the capacity of spreading and transmitting the loads that come from the upper structure to the bottom supporting structure. Its main significant purposes are to distribute the load from the sleepers, to absorb impact, noise and vibration induced from the wheels, to damp dynamic loads, and to provide lateral resistance, to reduce the stress intensity to the level to be tolerable for subgrade layer, to facilitate track maintenance operations, especially those related to the correction of track geometry defects and to provide adequate drainage for the track structure. It is a preferable choice for substructure material over other alternatives such as concrete slabs or asphalt because ballast provides less stiff support (which is an important factor in case of differential settlement or subgrade failure), is more economical, and produces less noise [17], [12] and [15].

2.2 Track deterioration

2.2.1 Rail deterioration

The interaction between wheel and rail pose surface defects under various operation conditions. Rail deterioration will result in a rougher rail surface and increase in dynamic

forces of high frequencies. The deterioration limits service life of rail and these include; loss of rail profile, rolling Contact Fatigue (RCF), rail breaks and defectives from various sources and as shown in Figure.2



Figure 2: Rolling Contact Fatigue crack growth [18]

2.2.2 Deterioration of Sleepers and Fastenings

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 fasteners become loose [19].

The sleeper and fastening deterioration depend on traffic and operational factors such as axle loads, speeds, accumulative tonnage and maintenance practices. Concrete sleeper deterioration is composed of;

- 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

2.2.3 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. [20] suggests that the majority of fines are from the ballast itself, as a result of abrasion, impact and physical and chemical weathering. In addition, deterioration process is influenced by track loading, particle size distribution, and particle shape and surface characteristics.

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 as in Figure.3

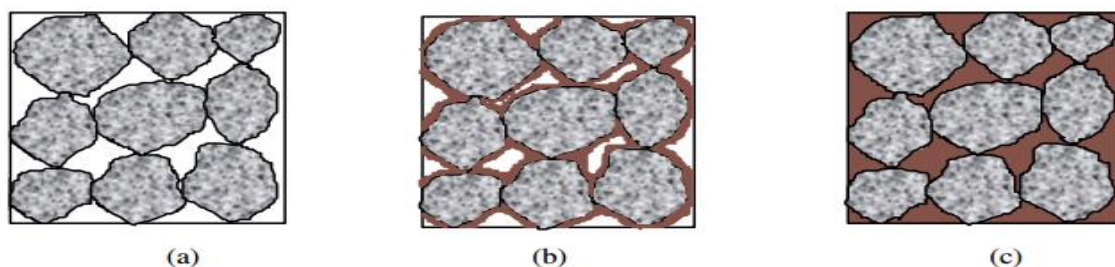


Figure 3: Fouling status (a) fresh ballast, (b) partially fouled ballast and (c) fully fouled ballast [21]

Ageing takes place in the line due to tonnage accumulation on track resulting from traffic movement leading to defects. It is realistic to assume that initiated defects left in the system will continue to grow with increase in cumulative Million Gross Tons (MGT). The number of failures in a statistical sense increases with MGT. That means older track components 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 component failures. As a result, the number of failures till an accumulated MGT is a function of usage MGT and is a random variable and can be modelled using Weibull distribution. Weibull analysis is the most versatile model to forecast the reliability parameters which help as to calculate the expected number of failures during the design period.

2.3 Track Failure Prediction

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 either Normal Distribution, log normal Distribution and Weibull distribution can be used. Most research suggest that Weibull distribution is the best probability distribution used to determine track failure [22], [23], [24] [25] . The Weibull distribution is commonly used to represent the distribution of the time to failure for similar components including most aspects of railroad track [26].

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.1 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 in Equation. 1 is the age of the track in either years or million gross tons [27].

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

Where:

$F(x)$ = cumulative failure distribution

α = Shape factor,

β = Scale factor

x = Age of the track

According to [28] Wear and fatigue in rails are major contributors of rail degradation depending on operational conditions, track characteristics of bogie type, Million Gross Tons (MGT), curvature, traffic type and environmental conditions. In addition, estimation of parameter for failure models (Weibull) is necessary for accurate prediction of expected number of rail defects over a period of time based on MGT of traffic and operating conditions for developing cost effective maintenance.

Weibull analysis has been widely used in the railroad industry for reliability and life data analysis of various track components including rail, ballast, ties (sleepers), turnouts (switches and crossings) and track circuits as well as rolling stock such as locomotives and cars and their components such as wheels and axles [29], [30], [31], [25]. Applications of Weibull analysis in the railroad industry include failure forecasting and prediction, component test design, evaluation of rail manufacturing processes, evaluation of corrective action plans as well as maintenance planning and cost-effective component replacement strategies.

Weibull Analysis has historically been a relatively effective technique in the railroad industry allowing for the short-term, medium-term and long-term analysis of component maintenance strategies. It's been noted by [32] that Weibull analysis has historically been the "go-to" distribution when it comes to analyzing rail defects irrespective of the type, tonnage, size or age.

2.4 Track inspection, maintenance and renewal

2.4.1 Track inspection

Track inspection is done to detect flaws on the track that can lead to failures [33]. Inspection is expected to be done by qualified personnel and it can be done manually or by use of the equipment. Components of a section of track are inspected and their condition recorded on an inspection form, with all deviations or deficiencies recorded on the form. Remedial action for defects must be taken in accordance with the parameters set forth the standard used.

2.4.2 Track maintenance

Maintenance defines the set of activities performed on an item to retain it in or to restore it to a specified state. According [34] maintenance includes all actions necessary for retaining or restoring a system or an item in a state in which it can perform its required function. Maintenance involves servicing, replacement or repair and is necessary when a component or a system is likely to fail or fails to perform its required function [35]. Maintenance can represent a significant portion of the cost in asset intensive organizations, as breakdowns have an impact on the capacity, quality and cost of operation [36]. Maintenance is subdivided into preventive maintenance, carried out at predetermined intervals to reduce wear out failures, and corrective maintenance, carried out after failure recognition and intended to put the item into a state in which it can again perform the required function.

Aim of a preventive maintenance is also to detect and repair hidden failures, that is failures in redundant elements not identified at their occurrence. Corrective maintenance is also known as repair, and can include any or all of the following steps: recognition, isolation (localization & diagnosis), elimination (disassembly, replace and reassembly), checkout. Repair is used hereafter as a synonym for restoration.

2.4.2.1 Maintenance Tasks

A maintenance task consists of a set of maintenance activities performed in a specific order to accomplish maintenance of a component or a system. Maintenance tasks can be divided into three main categories [37];

- Corrective maintenance
- Preventive maintenance
- Predictive maintenance

Corrective or breakdown maintenance tasks include actions performed immediately after failure to restore a system or an item to its required state. It may involve repairs, replacement, or adjustments.

Preventive maintenance tasks include preplanned actions performed to minimize the probability of sudden events. These scheduled actions include adjustments, replacements, renewals and inspection of technical systems or components. Preventive maintenance is advantageous because regular maintenance and refurbishment can make the technical system or components to last longer and reduce the likelihood of such equipment becoming non-operational [38]. Preventive maintenance actions can be triggered based on periodic plans or the actual conditions of the component or system, also known as conditional-based maintenance [39].

Predictive or conditional maintenance tasks are direct monitoring methods used to determine status of items in the system. The objective is to predict sudden failures in the future and aims to achieve the most cost-effectiveness maintenance before failure in system occurs.

The advantages of track maintenance as suggested by [40] are as follows;

- (a) If the track is suitably maintained, the life of the track as well as that of the rolling stock increases since there is lesser wear and tear of their components.
- (b) Regular track maintenance helps in reducing operating costs and fuel consumption.
- (c) Small maintenance jobs done at the appropriate time such as tightening a bolt or key, hammering the dog spike, etc., helps in avoiding loss of the concerned fitting and thus saving on the associated expenditure.

(d) When track maintenance is neglected for a long time, it may render the track beyond repair, calling for heavy track renewals that entail huge expenses.

Typically, main maintenance actions include; Rail Grinding, Rail lubrication, Rail Replacement, Sleeper and Fastening Replacement, Ballast Tamping and Renewal. 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 grinding interval costs of no lubrication is extremely high compared to rail curve with lubrication [41] .

The driving factor causing failures and maintenance is the deterioration of the asset which is normally influenced by the loads on the track. Besides asset deterioration, the factors that also influence the O&M cost are, the amount of preventive maintenance, market prices of labour, 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 [42]. Since the cash flows occur during different operational years, to take these into account all future costs are discounted to present values of cost [43]. According to [44] total present value cost (TPVC) is the sum of all discounted cash flows which is calculated based on the formula presented in Equation.2.

$$TPVC = \sum_{i=0}^N \frac{C_i}{(1+r)^i} \quad (2)$$

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

2.5 The Purposes of O&M cost analysis

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

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

In the O&M cost analysis, the goal is to assess the benefits the system will bring and in order to do so, costs and incomes must be assessed [45]. Incomes are relatively well known in terms of a railway system; the bigger share belongs to faring on passenger tickets or freight services and another part to quantify is costs.

2.6 Operation and Maintenance Cost Process

Operation and Maintenance 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 operation and maintenance costs become the basis for taking decisions on the maintenance and renewal actions of the track.

Figure.4 shows the different steps for estimating the O&M cost of the track infrastructure during the operation and maintenance phase. The input parameters for each step in the process and the corresponding outputs are described in the Figure.4 [43]

The initial step is to understand the technical characteristics of a track section as well as the utilization of the track in terms of tonnage and frequency of trains. For O&M cost calculation, a track section cannot be generalized because of its complexity and utility varies in different places. Track deterioration depends both on various track 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. Track maintenance volume consists of all the corrective and preventive maintenance as well as renewal activities. This

is estimated by means of analysis of the various failure modes. 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. Train derailment probabilities are estimated by track failure modes, maintenance volume and track possession time, finally total present value can be calculated by means of discounting rate.

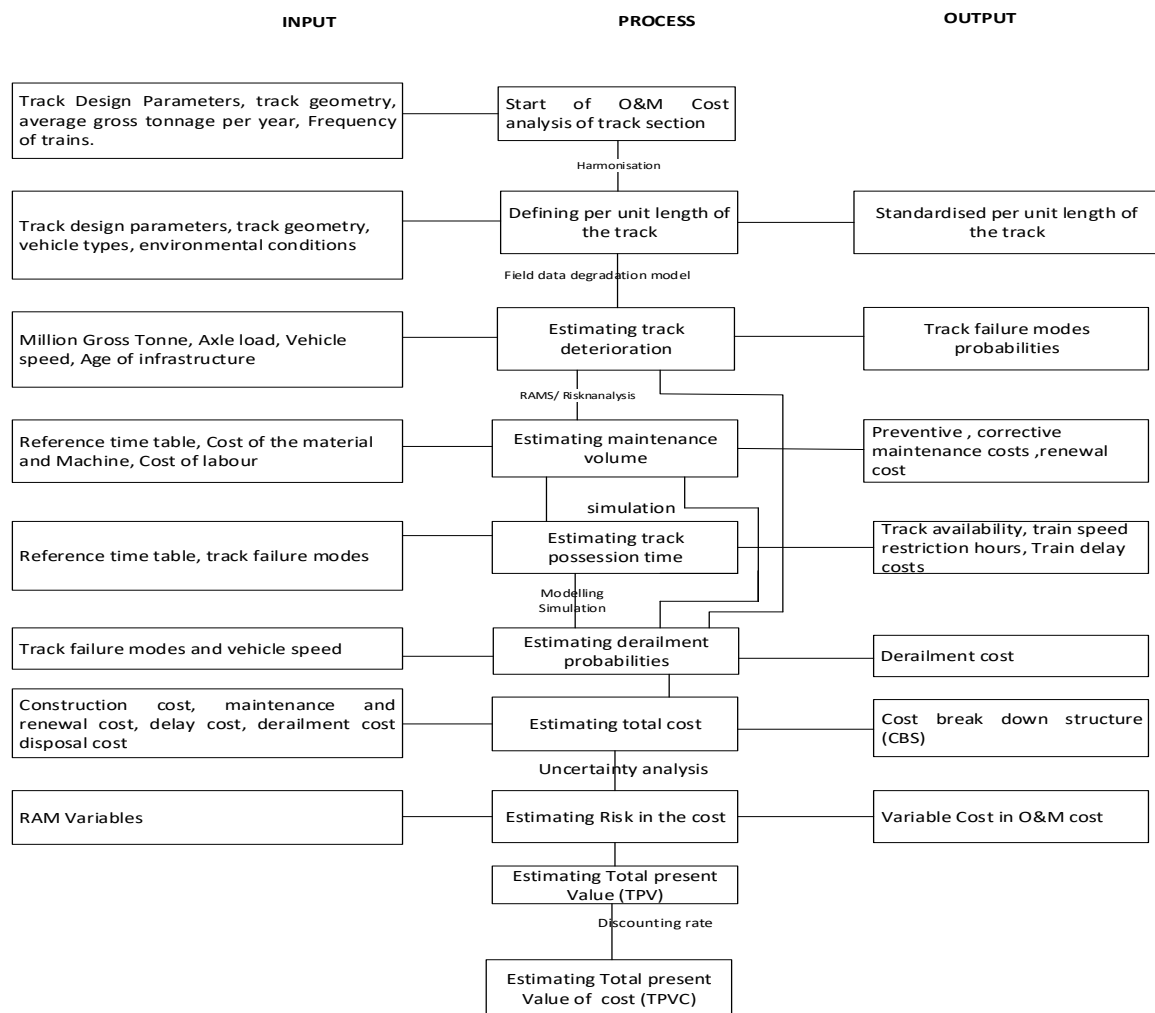


Figure 4: Cost Analysis process in O & M phase [43]

To calculate the results of the analysis at its end, the most suitable method is the Net Present Value (NPV), [46], [47] There are several O&M cost models proposed by different authors with different approaches. As an example, [48] presented the O&M cost model to calculate all the cost related with the rail between two renewals, considering the development of rail defects by a Weibull function. On the other hand, [3] presented a methodology to build Maintenance cost model to railway infrastructure in five steps concerning the loads applied, the maintenance volumes, the cost with M&R activities and unavailability, the infrastructure performance and at last to calculate the O&M cost based on the previous steps.

2.7 Mathematical models for estimation of Railway track O&M costs

According to [42] O&M cost can be presented in three different ways;

- i) Total present value (TPV),
- ii) Internal rate of return (IRR), and
- iii) Annual equivalent or annuity (ANN).

The following maintenance cost models [43] were developed with respect to the type of maintenance intervention. The O&M costs can be determined according to simplified formulae in the equations.3 to Equation.12 [49] and [50]. According to [51], [52] and [53] models to predict the number of rail defects and the number broken rails to predict cost of repair rail defects and repair broken rails are given in Equation.13 to Equation.18

Rail Grinding Cost

$$= \sum_{i=1}^k \sum_{j=1}^{N-1} \frac{[(T_{gi} * C_L * L_i * n_{gi}) + (C_{eg} * T_{gi} * L_i * n_{gi})] * \frac{m}{m_{gi}}}{(1+r)^j} \quad (3)$$

$$\text{Track Tamping cost} = \sum_{i=1}^k \sum_{j=1}^{N-1} \frac{[(T_{tai} * C_L * L_i) + (C_{eta} * T_{tai} * L_i)] * \frac{m}{m_{tai}}}{(1+r)^j} \quad (4)$$

$$\text{Rail Lubrication Cost} = \sum_{i=1}^k \sum_{j=1}^{N-1} \frac{[(T_{clu} * C_L * n_{li})]}{(1+r)^j} \quad (5)$$

$$\text{Ballast Cleaning Cost} = \sum_{i=1}^k \sum_{j=1}^{N-1} \frac{[(T_{bi} * C_L * L_i) + (C_{eb} * T_{bi} * L_i)] * \frac{m}{m_{bi}}}{(1+r)^j} \quad (6)$$

$$\text{Track Inspection cost} = \sum_{j=1}^{N-1} \frac{[(T_t * C_L * L_i) + (C_{et} * T_t * L_i)] * \frac{m}{m_t}}{(1+r)^j} \quad (7)$$

$$\begin{aligned} &\text{Rail Renewal Cost} \\ &= \sum_{i=1}^k \sum_{j=1}^{N-1} \frac{[(C_r * L_i) + (T_{rri} * C_L * L_i) + (C_{err} * T_{rri} * L_i)] * \frac{m}{m_{rri}}}{(1+r)^j} \end{aligned} \quad (8)$$

$$\begin{aligned} &\text{Ballast Renewal Cost} \\ &= \sum_{i=1}^k \sum_{j=1}^{N-1} \frac{[(C_b * L_i) + (T_{bri} * C_L * L_i) + (C_{ebr} * T_{bri} * L_i)] * \frac{m}{m_{bri}}}{(1+r)^j} \end{aligned} \quad (9)$$

$$\begin{aligned} &\text{Sleeper Renewal Cost} \\ &= \sum_{i=1}^k \sum_{j=1}^{N-1} \frac{[(C_s * L_i) + (T_{sri} * C_L * L_i) + (C_{esr} * T_{sri} * L_i)] * \frac{m}{m_{sri}}}{(1+r)^j} \end{aligned} \quad (10)$$

$$\begin{aligned} &\text{Fastener Renewal Cost} \\ &= \sum_{i=1}^k \sum_{j=1}^{N-1} \frac{[(C_f * L_i) + (T_{fri} * C_L * L_i) + (C_{efr} * T_{fri} * L_i)] * \frac{m}{m_{fri}}}{(1+r)^j} \end{aligned} \quad (11)$$

$$\begin{aligned} &\text{Rail Replacement Cost} \\ &= \sum_{i=1}^k \sum_{j=1}^{N-1} \frac{[(C_r * L_r) + (T_{rbi} * C_L) + (C_{er} * T_{rbi})] * \frac{m}{m_{rbi}}}{(1+r)^j} \end{aligned} \quad (12)$$

The number of broken rails between two successive inspections

$$S(X) = S_{(i-1,i)} = \frac{R \frac{a(0.5N_{i-1} + 0.5N_i)^{a-1}}{b^a} e^{-\frac{(0.5N_{i-1} + 0.5N_i)a}{b}}}{1 + \frac{1}{h(X_i - q)}} x X_i \quad (13)$$

Where:

$S_{(i-1, i)}$ = number of broken rails per track-mile between the $(i-1)^{th}$ and i^{th} inspection

R = rail segments per track-mile, 273 [51]

X_i = interval (MGT) between the $(i-1)^{th}$ and i^{th} inspection 5MGT

a = Weibull shape factor, 3.1 [53]

b = Weibull scale factor, 2,150 [53]

h = slope of the number of rail breaks per detected rail defect (S/D) vs. inspection interval curve, 0.014 [52]

q = minimum rail inspection frequency, in MGT [52]

N_i = rail age (cumulative tonnage on the rail) at the i^{th} inspection, and $N_{i-1} = N_i - X_i$

Rail Defect Repair Cost

$$DDC = \left[\frac{W_{replace} x L_{replace} (p_{new} - 0.95p_{old})}{2000} + C_{d\ repair} \right] (1 - t) \quad (14)$$

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 yards (8).

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

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

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

t = federal and state marginal income tax rate

The number of detected rail defects between successive inspection intervals (N_{def})

$$N_{def} = \frac{S(X)L}{h(Xi - q)} \quad (15)$$

Where

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

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

L = track length in yards

The cost of repairing the rail defect (C_{def})

$$C_{def} = \sum_{j=1}^N \frac{N_{def} * DCC}{(1 + r)^j} \quad (16)$$

Broken Rail Repair Cost

$$SDC = \left[\frac{W_{replace} * L_{replace} * (p_{new} - 0.95p_{old})}{2000} + C_{s\ repair} \right] (1 - t) \quad (17)$$

The cost of repair broken rail (C_{srp})

$$C_{srp} = \sum_{j=1}^N \frac{SDC * N_{def}}{(1 + r)^j} \quad (18)$$

2.8 Prices and costs of O&M in the railways track.

[54], in their 7th Frame work programme to sustainable freight railway; Designing the freight vehicle – track system for higher delivered tonnage with improved availability at reduced cost geared at track design requirements for reduced maintenance, on a project study that took them 48 months cited the average maintenance track costs according to

railway traffic and train speed. This famous study provides some orders of magnitude about the maintenance and renovation costs of some railway infrastructure components.

Table.1 presents the average estimated annual maintenance costs (long term) per track kilometre in terms of railway traffic and train speed.

Table 1: Maintenance track costs according to railway traffic and train speed [54]

Maximum speed (km/h)	10x10 ³ TBK/day	30x10 ³ TBK/day	100x10 ³ TBK/day	300x10 ³ TBK/day
100	7,000 € (5-10k€)	15,000 € (10-20k€)	30,000 € (20-40k€)	60,000 € (40-80k€)
300	20,000 € (10-30k€)	40,000 € (20-60k€)

Also [55] & [56] in Evaluating track structures, average maintenance cost per meter is 150 Euros which is equivalent to 4,800 Birr as shown in the Figure.5

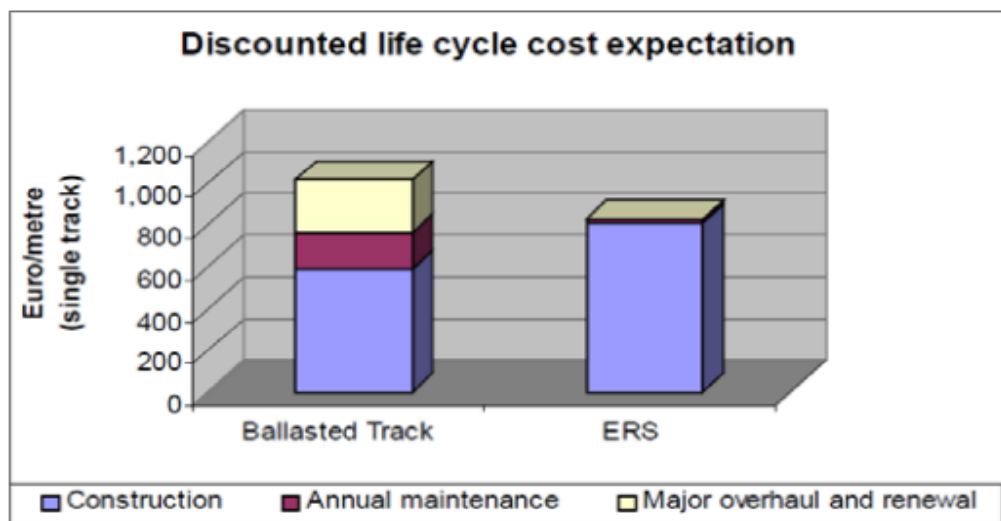


Figure 5: Outcomes of O&M cost analysis of ballasted track [55]

Also [57] in estimation of the life cycle cost of the upper railway track structure as presented in Figure.5. The purpose of the study was to build the O&M cost analysis model for efficiency of a railway track, reliability (failure-free operation, durability) and safety. Different track options were considered and the best option (Track2) selected has similar properties as AALRT.

In the case study, some components are not considered such as sub ballast, subgrade, switches and crossing so it's the reason why the case study cost is 104 Euros versus the whole maintenance cost of the railway track. See the total cost of the current upkeep of 1 km of a seamless track per year. The first and the second track differ in load-intensity by three times. As the first track has a high freight intensity and a short service life, two variants of repairs are considered along this track: according to the classical scheme (option 1) and with the continuous replacement of rails and straightening of the track in the scope of works of an average repair in the middle of the life cycle (option 2) to extend the life cycle. The final results of the O&M cost calculation can be found in Table 2.

As a result of the recalculation of the life cycle duration on the basis of tonnage operating units (million gross tons) per years, it was determined that the service life of the 1 track for the option 1 was 6 years; for the option 2 it was 12 years; and the life cycle of the 2 track is 20 years. As per analysis the average annual cost of the life cycle and its cost for the entire service life is determined taking into consideration discount rate $d = 10\%$.

Table 2: Total cost for maintenance and Repair of 1Km track [57]

Types of Costs	Cost					
	Track1(Option1)		Track1(Option2)		Track2	
	Thousand rubles	Percent	Thousand rubles	percent	Thousand rubles	Percent
Reconstruction	25,000	65.9	25,000	40.2	25,000	63.1
Intermediated repairs and disposal	5,966	15.7	44242	35.7	7466	18.8
Current upkeep	4,520	11.9	10004	16.1	5356	13.5
Continuous replacement and grinding of rails	2,069	5.5	4139	6.7	1176	3
Track failures	392	1	784	1.3	652	1.6
Total	37947	100	62169	100	39650	100

The cost taken is of track2 and it excludes the reconstruction costs. Maintenance cost is $(7,466+5356+1176+562) \times 1000$ Rubles =14,650,000 Rubles per Km=654,018 Birr per Km

CHAPTER 3: METHODOLOGY

3.1 Introduction

Operation and Maintenance cost analysis is an engineering economics technique that can be utilized to focus on maintenance strategy to minimize the life cycle cost and helps in foreseeing the cost implications of maintenance actions over the service life of the track. This chapter describes the utilization of operation and maintenance cost methodologies in track maintenance planning. Proper analysis will help in effective maintenance planning of the track, this answers the question which is the best way to maintain the track

Reliability: When should the track be maintained? Depending on the failure modes of the track.

Availability: How should the 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).

Within O&M cost analysis all payments including future payments will be referred to a reference date using the discount rate, which is a factor that determines the present value of a future cost meaning that all costs in the life of the track will be converted to present time by a discount rate. The discount rate (10.23) [58] of Road/Rail infrastructure has been adopted in this work.

3.2 Maintenance and renewal costs analyzed

Rail grinding cost: Grinding is the maintenance action done on the rail to control rolling contact fatigue defects. Cost due to rail grinding primarily depends on the periodicity of grinding and the number of grinding passes.

Track tamping cost: Tamping is the maintenance action done on the track to correct its alignment. Cost due to track tamping depends on the interval of tamping

Rail lubrication cost: Lubrication is done on the rail to control rail wear. Cost due to lubrication depends on the number of lubricators in the curves and the cost to maintain each lubricator in terms of filling

Ballast cleaning cost: Ballast cleaning is the maintenance action done to eliminate trapped water inside the ballast in order to restore the track quality and stiffness. Cost due to ballast cleaning primarily depends on the periodicity of ballast cleaning

Track inspection cost: Track inspection is done to detect flaws on the track that can lead to failures. The cost due to track inspection primarily depends on the interval of track inspection.

Rail renewal cost: Rail renewal is done when the rail deterioration reaches maintenance or safety limits.

Ballast renewal cost: Ballast renewal is done when ballast deterioration reaches maintenance or safety limits.

Sleeper renewal cost: Sleeper renewal is done when the sleeper deterioration reaches maintenance or safety limits

Fastener renewal cost: Fastener renewal is done when the fastener deterioration reaches maintenance or safety limits.

Rail replacement cost: Rail replacement is done when rail breaks occur on the track. Cost due to rail break primarily depends on the probability of rail breaks

Rail defect repair cost and Rail broken repair costs: These defects are detected while doing inspection and can consequently lead to rail breaks when left un attended to. The cost of repairing the defects depends mainly on the number of defects and for broken rails it depends on the potential defects to cause the rail breaks and the number of broken rails in the track and their frequency of happening.

3.3 Procedure for calculating operation and maintenance costs

The calculation of the O&M costs of the AALRT track takes place in steps described below.

Step 1: Estimating the loads on the infrastructure: Analysis of the transportation forecast were made in order to get annual estimated tonnages on the line and to determine the timetable. It considers axle-loads and train weights, as well as the number of operational hours per day.

Traffic Forecasting: The approach to forecasting AALRT Line demand was based on past trip and travel characteristics that provide the basis for the forecasting the future demands. The traffic forecast takes into consideration Passenger forecast, trip generation, and determination of the traffic load (Annual Million Gross Tonnage) on the Rails.

Passenger Forecast: The best method to predict passenger flow is by considering the movement of people in each train and project using population growth rate since trip flow is directly proportional to population and income growth. Population growth rate is based on the urban growth rates of Addis Ababa city as predicted by the Central Statistical Agency.

Step 2: Determination of Traffic load: In order to determine the traffic load (tonnage) on the track, the loads of the trains will be first converted into equivalent passenger train load and then speeds will also be considered. A composite traffic Volume is calculated considering both effects of speed and relative wear provoked by axle loads.

Step 3: Estimating track deterioration: This depends on various tracks and vehicle characteristics. Estimation of total track failures is done by means of track failure data and degradation models of track and vehicle.

Step 4: Estimating Track maintenance volume: This 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.

Step 5: Estimating Track possession time: The trains time table describes the type of traffic, frequency of trains and 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.

Step 6: Estimating derailment probabilities: Train derailment probabilities will be estimated by track failure modes, maintenance volumes and track possession time

Step 7: Estimating the O&M costs: In the due process the total costs of O&M considering reliability and availability estimates are made. Finally, the economic cost is calculated considering the value of Shadow (estimated monetary Value) price, labour, operation cost, initial cost and discounted cost. The Figure.6 shows the analysis process

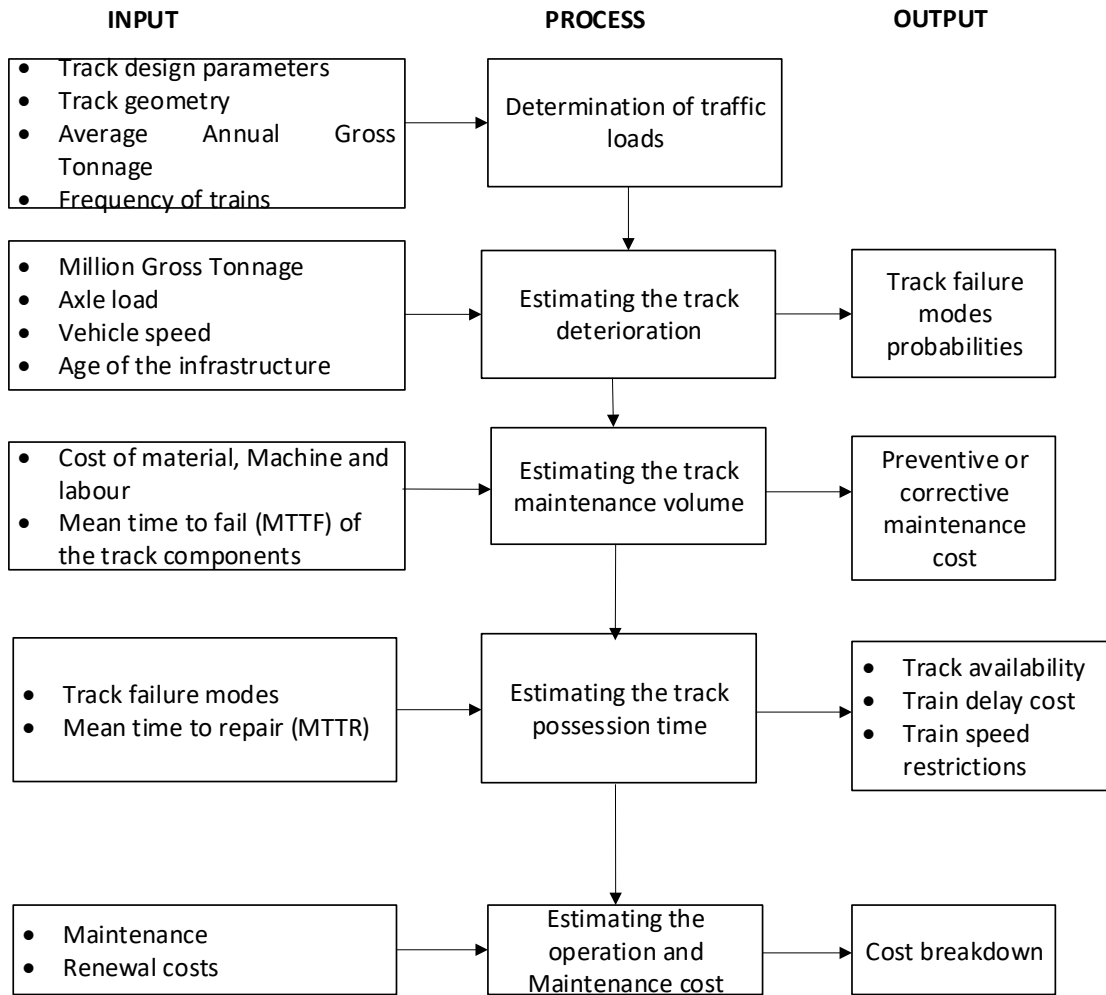


Figure 6:Flow chat of O&M cost analysis process

The output of the model is computed as the Net Present Value (NPV) given by Equation.19.

$$NPV = \sum_{j=1}^N \frac{C_n}{(1+r)^j} \quad (19)$$

Where;

C_n = Sum of all costs incurred in year j

j= Initial year of analysis period

r = Discount rate

N = Last year of the analysis period.

3.4 Data Collection

The data required for transport demand forecasting was mainly secondary (Historical) data on particularly the economy, trade and transport sectors. Major sources of data were public sectors such as ministry of finance and Economic Development (MoFED), Central Statistical Agency (CSA), National Bank of Ethiopia, Ethiopian Roads Authority (ERA) and The Ethiopian Railway Corporation (ERC) or Addis Ababa Light Rail Transit (AALRT) for data normally regarding the material and vehicle characteristics and some from the related literature and publications.

3.5 Data analysis

In reliability prediction and analysis, failure data are usually based on the assumption of being independent and identically distributed in the time domain. To predict MTTF and MTTR from the data collected, the data was analyzed using probability distribution (Weibull distribution). A probabilistic and analytical approach towards a maintenance strategy was used to analyse O&M cost of AALRT associated with the rail track super structure.

Maintenance costs associated with AALRT track super structure components was estimated separately independent of the other. Some costs like lubrication have been analyzed on curves that are lubricated but due to data inefficiency and unavailability others have been analyzed generally as tangents due to data unavailability. Maintenance cost models have been developed and used to determine the costs with respect to the type of maintenance intervention used at the AALRT. It should be noted that lubrication is done in only curves of radii less or equal to 200m twice a day

CHAPTER 4: MATHEMATICAL MODELS, DATA ANALYSIS AND DISCUSSION OF RESULTS

4.1 Failure Modelling for the track Components

4.1.1 Track Deterioration.

Deterioration is the reduction of the original quality of the component due to various influencing factors and the most contributing factor to deterioration is the Traffic load which is directly related to the axle load and track geometry deterioration. The factors that lead to track deterioration can be grouped into;

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

The life of such components can be divided into three distinctive parts as shown in Figure.7.

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 degradation

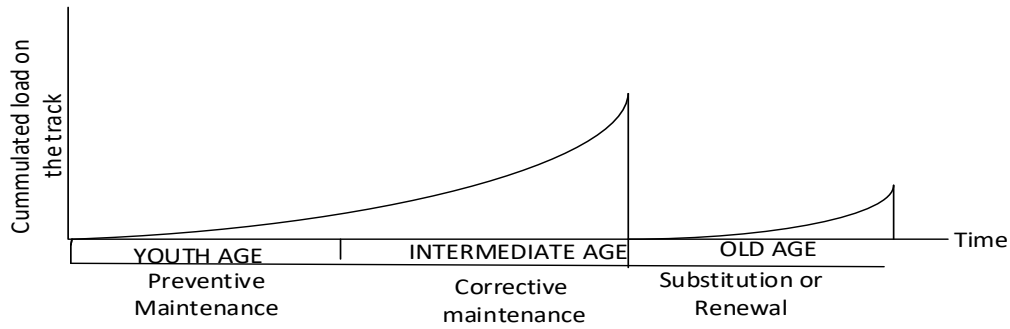


Figure 7:Track degradation Curve [29]

It is also noted that if a part has multiple failure modes, the time to first failure is best modeled by the Weibull distribution.

4.1.2 Steps to forecast reliability parameters using Weibull

Step-1. The failure data (samples) are entered into excel Randomly in a column form

Step-2. The number of failures is ranked in ascending order and assigned failure order number starting form 1,2,3,4,5,6,7,8

Step-3. The proportion of the population that will fail by the number of failures is estimated. This is accomplished using several different methods, however the most common of which is median ranks and thus has been adopted in this study. The formula for Medium Rank is given by,

$$Medium Rank = \frac{(Rank-0.3)}{(Highest Rank+0.4)} \quad [59] \quad (20)$$

Step-4. The data is used to perform the simple linear regression. Using the general linear regression $Y = mX + b$. Here it is expected the graph of Transformed median ranks against $\ln(\text{failures})$ to plot as a straight line.

Step-5. Estimation of Weibull parameters

The Weibull cumulative distribution function can be transformed so that it can appear in the familiar form of a straight-line.

$$Y = mX + b. \quad (21)$$

$$F(x) = 1 - e^{-\left[\frac{x}{\alpha}\right]^\beta} \quad (22)$$

$$1 - F(x) = e^{-\left[\frac{x}{\alpha}\right]^\beta}$$

$$\text{Ln}(1 - F(x)) = -\left[\frac{x}{\alpha}\right]^\beta$$

$$\text{Ln}\left(\frac{1}{\text{Ln}(1 - F(x))}\right) = \left[\frac{x}{\alpha}\right]^\beta$$

$$\text{Ln}\left[\text{Ln}\left(\frac{1}{\text{Ln}(1 - F(x))}\right)\right] = \beta \text{Ln}\left[\frac{x}{\alpha}\right]$$

$$\text{Ln}\left[\text{Ln}\left(\frac{1}{\text{Ln}(1 - F(x))}\right)\right] = \beta \text{Ln}x - \beta \text{Ln}\alpha \quad (23)$$

Comparing this Equation. (23) with the simple equation for a line, we see that the left side corresponds to Y, Ln x corresponds to m and $-\beta \text{Ln}\alpha$ corresponds to b.

The estimate of the Beta (β) or shape parameter comes directly from the slope of the line and the estimate of the Alpha α , or characteristic life parameter is calculated from

$$\alpha = e^{-\left[\frac{b}{\beta}\right]} \quad (24)$$

Interpretation of the results of Weibull parameters

The Weibull shape parameter, called, β indicates whether the failure rate is increasing, constant or decreasing. A $\beta < 1.0$ indicates that the product has a decreasing failure rate. Indicates that the product is failing during its "burn-in" period. A $\beta = 1.0$ indicates a constant failure rate. Frequently, components that have survived burn-in will subsequently exhibit a constant failure rate. A $\beta > 1.0$ indicates an increasing failure rate. This is typical of products that are wearing out. Such is the case with the spring housings-both designs A and B have β values much higher than 1.0. The housings fail due to fatigue, i.e., they wear

out. The Weibull characteristic life, called, α is a measure of the scale, or spread, in the distribution of data. It so happens that equals the number of cycles at which 63.2 percent of the product has failed. In other words, for a Weibull distribution R ($\alpha=0.368$, regardless of the value of β).

Step-6. Calculate Weibull failure rate

$$\text{Weibull failure rate } \lambda(x) = \left(\frac{\beta}{\alpha}\right)\left(\frac{x}{\alpha}\right)^{\beta-1} \quad (25)$$

Step-7. Expected number of failures, $E(N(\Delta t))$

$$E(N(\Delta t)) = \int_{t_1}^{t_2} \lambda(x) dt = \lambda t_2^\beta - \lambda t_1^\beta \quad (26)$$

where $t_2 = 100, t_1=0$

Step-8. Distribute expected number of failures to degraded failure and critical using reliability function Reliability,

$$R(t) = \int_t^\infty f(x) dx = \exp\left[-\left(\frac{x}{\alpha}\right)^\beta\right] \quad (27)$$

Thus, Number of degraded failures, $N_d = R(t) * E(N(\Delta t))$

Number of critical failures

$$N_c = [1-R(t)] * E(N(\Delta t)) \quad (28)$$

Mean Time to Fail (MTTF)=Shape parameter* Gamma $\left(1 + \frac{1}{\text{Shape parameter}}\right)$

$$MTTF = \beta \Gamma\left[1 + \frac{1}{\beta}\right] \quad (29)$$

4.2 Traffic forecast

The traffic forecast will take into consideration Passenger forecast, trip generation, and determination of the traffic load (Annual Million Gross Tonnage) on the Rails.

4.2.1 Passenger forecast

The East-West Line and North-South Line of the light rail in Ethiopia were predicted in the year of 2015. According to China urban rail transit construction standard, the forecast years of the two lines are Initial stage (2018), Short term (2025) and long term (2040).

The main economic figures of 2007 census include; Gross domestic product (GDP) of 20 billion dollars, Growth rate of GDP: 11.1%, Per capita GDP: 180 dollars, Inflation rate:17.2%.

According to the 2007 Notice of Central Statistical Agency (CSA) of Ethiopia, the estimated total population of Addis Ababa is 3,384,569 (census 2007) however these figures are expected to have changed now and the next Addis Ababa — Ethiopia was expected to conduct population and housing census for the 4th time from April, 7-28, 2019, according to the Central Statistics Agency (CSA) but rather this was extended further.

The best method to predict passenger flow is by considering the movement of people in each train station of the lines and project using population growth rate since trip flow is directly proportional to population and income growth. The forecast of the passengers is based on the 39 main train stations of the AALRT. Population growth rate will be based on the urban growth rates of Addis Ababa city as predicted by the Central Statistical Agency (3.8%).

Due to inefficiency in the population figures owing to the continuous postponement of the census in Ethiopia, the population forecast on the EW and NS line of AALRT the passenger forecast figures have been estimated using the past three years passengers boarding the AALRT trains and Table.3 shows a summary of passengers per month, per year and average daily passengers that used the trains on both NS and EW line.

Table 3: Passenger flow on EW And NS lines (Data adapted from AALRT data base)

Year	Month	Passengers flow of both lines		
		EW	NS	Total
2016	2016-1	2,027,740	1,679,591	3,707,331
	2016-2	1,950,794	1,657,523	3,608,317
	2016-3	1,956,100	1,609,638	3,565,738
	2016-4	1,792,578	1,479,101	3,271,679
	2016-5	1,701,699	1,458,086	3,159,785
	2016-6	1,698,189	1,488,319	3,186,508
	2016-7	1,707,863	1,544,128	3,251,991
	2016-8	1,606,785	1,427,046	3,033,831
	2016-9	1,600,883	1,486,946	3,087,829
	2016-10	1,646,700	1,537,174	3,183,874
	2016-11	1,607,173	1,444,085	3,051,258
	2016-12	1,424,559	1,316,366	2,740,925
	Total	20,721,063	18,128,003	38,849,066
2017	2017-1	1,418,026	1,404,190	2,822,216
	2017-2	1,275,724	1,182,490	2,458,214
	2017-3	1,378,963	1,329,257	2,708,220
	2017-4	1,528,808	1,412,637	2,941,445
	2017-5	1,784,002	1,638,650	3,422,652
	2017-6	1,840,888	1,562,504	3,403,392
	2017-7	2,030,656	1,704,634	3,735,290
	2017-8	642,398	1,370,078	2,012,476
	2017-9	1,842,752	1,395,716	3,238,468
	2017-10	2,039,085	1,281,234	3,320,319
	2017-11	1,923,662	1,261,184	3,184,846
	2017-12	1,870,038	1,304,624	3,174,662
	Total	19,575,002	16,847,198	36,422,200
2018	2018-01	1,826,929	1,390,143	3,217,072
	2018-02	1,648,200	1,235,976	2,884,176
	2018-03	1,833,963	1,335,480	3,169,443
	2018-04	1,792,578	1,479,101	3,271,679
	2018-05	1,872,914	1,335,928	3,208,842
	2018-06	1,661,271	1,207,639	2,868,910
	2018-07	1,717,060	1,202,365	2,919,425
	2018-08	1,904,985	1,364,859	3,269,844
	2018-09	1,539,797	1,059,438	2,599,235
	2018-10	2,122,092	1,445,753	3,567,845
	2018-11	1,889,908	1,410,566	3,300,474
	2018-12	2,015,484	1,462,932	3,478,416
	Total	21,825,181	15,930,180	37,755,361
Sum for 3 years		62,121,246	50,905,381	113,026,627
Average per day		56,731.73	46,488.93	103,220.66

4.2.2 Trip generation and Trip forecasting

The approach to forecasting AALRT Line demand was based on past trip and travel characteristics that provide the basis for the trip generation. The trips generated in the past three years of operation are presented in Table.4 and the same trips and passenger forecasted in the long term are used to determine the forecasted trip.

Table 4:Trips generated on AALRT for the last 3 years

Year	Month	Trips on both lines					
		plan - EW	Actual- EW	Plan- NS	Actual- NS	plan total	Actual- total
2016	Jan	3,782	3,711	3,782	3,708	7,564	7,419
	Feb	3,538	3,504	3,538	3,534	7,076	7,038
	Mar	3,782	3,774	3,782	3,775	7,564	7,549
	Apr	3,660	3,650	3,660	3,656	7,320	7,306
	May	3,782	3,770	3,782	3,676	7,564	7,446
	Jun	3,660	3,637	3,660	3,660	7,320	7,297
	Jul	3,782	3,751	3,782	3,763	7,564	7,514
	Aug	3,782	3,774	3,782	3,777	7,564	7,551
	Sep	3,660	3,649	3,660	3,600	7,320	7,249
	Oct	3,782	3,766	3,782	3,772	7,564	7,538
	Nov	3,660	3,526	3,660	3,535	7,320	7,061
	Dec	3,782	3,702	3,782	3,708	7,564	7,410
	Total	44,652	44,214	44,652	44,164	89,304	88,378
2017	Jan	3,844	3,844	3,813	3,816	7,657	7,660
	Feb	3,472	3,455	3,444	3,151	6,916	6,606
	Mar	3,844	3,813	3,813	3,762	7,657	7,575
	Apr	3,720	3,677	3,690	3,630	7,410	7,307
	May	3,844	3,796	3,813	3,787	7,657	7,583

Year	Month	Trips on both lines					
		plan - EW	Actual- EW	Plan- NS	Actual- NS	plan total	Actual-total
	Jun	3,720	3,706	3,690	3,367	7,410	7,073
	Jul	3,844	3,822	3,813	3,603	7,657	7,425
	Aug	3,844	3,754	3,813	2,890	7,657	6,644
	Sep	3,720	3,666	3,690	3,468	7,410	7,134
	Oct	3,844	3,815	3,813	2,941	7,657	6,756
	Nov	3,720	3,686	3,690	3,594	7,410	7,280
	Dec	3,844	3,708	3,813	3,778	7,657	7,486
	Total	45,260	44,742	44,895	41,787	90,155	86,529
2018	Jan	3,844	3,796	3,813	3,756	7,657	7,552
	Feb	3,472	3,465	3,444	3,410	6,916	6,875
	Mar	3,844	3,788	3,813	3,776	7,657	7,564
	Apr	3,720	3,710	3,690	3,684	7,410	7,394
	May	3,844	3,781	3,813	3,752	7,657	7,533
	Jun	3,472	3,234	3,444	3,309	6,916	6,543
	Jul	3,844	3,381	3,813	3,538	7,657	6,919
	Aug	3,844	3,817	3,813	3,758	7,657	7,575
	Sep	3,720	3,387	3,690	3,288	7,410	6,675
	Oct	3,844	3,736	3,813	3,782	7,657	7,518
	Nov	3,720	3,085	3,690	3,652	7,410	6,737
	Dec	4,340	4,021	3,925	3,714	8,265	7,735
	Total	45,508	43,201	44,761	43,419	90,269	86,620
Sum for 3 years		135,420	132,157	134,308	129,370	269,728	261,527
Average per day		123.67	120.69	122.66	118.15	246.33	238.84

4.2.3 Traffic Load

The algebraic sum of all the vehicles, passenger loads cannot give the exact and accurate value of the running load, because it does not put into account the way in which the load is applied, running speed, sway, yawing among others.

Thus, a parameter giving a more accurate estimate of the passing traffic load is necessary. Railway management and Engineering [60] uses the analogue 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 Equation.31.

$$T_{th} = S_p (T_p + K_t T_{pt}) + S_{fr} (K_{fr} T_{fr} + K_t T_{tf}) \quad [60] \quad (30)$$

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)
- $K_t = A$ coefficient 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 coefficients are assigned the following values as per the Table.5

Table 5: Coefficient of S_p and S_{fr} [60]

Speed	S_p
$V < 60\text{Km/hr}$	1.00
$60\text{Km/hr} < V < 80\text{km/hr}$	1.05
$80\text{Km/hr} < V < 100\text{Km/hr}$	1.15
$100\text{Km/hr} < V < 130\text{Km/hr}$	1.25
$130\text{km/hr} < V < 160\text{Km/hr}$	1.35
$160\text{Km/hr} < V < 200\text{Km/hr}$	1.4
$200\text{km/hr} < V < 250\text{Km/hr}$	1.45
$V > 250\text{Km/hr}$	1.5

The formula has the passenger component and the freight component and since AALRT is purely passenger, only the section for passengers has been adopted for this analysis and computation of then theoretical load in this study. The average weights of standard coaches (without passengers) used on the NS and EW line is 44 tons.

Table 6:Parameters of locomotives used [61]

Parameter	value
Locomotive Weight	44tones
Axle load	11 tones
Type of traction	Electric power (DC)
Length of locomotive	29,700mm
Target highest speed	70km/hr
Sitting capacity	65

According to the passenger flow on the line, the number of pairs of train determine the mean daily passenger tonnage. The mean daily passenger tonnage is calculated from the number of passengers hauled in the years 2016,2017 and 2018 as presented in Table.7

To calculate the traffic load, first determined by multiplying the passenger flow by average weight of a person which is 60kg [61]. The mean daily passenger tractive tonnage is determined by multiplying the number of trains per day by their weight. Then using Equation.31 for the theoretical load, the determined theoretical load of the line is presented herein below in the calculation showing the annual traffic load in Million gross tons for 25 years that the railroad carries on the EW line and NS line.

Table 7:Carrying Capacity of Train as planned

Status / Capacity	Seat	Standing capacity	Total
Seat	65	0	65
Rated capacity standing capacity: 6 persons/m ²)	65	190	255
Overcrowding capacity (standing 8persons/ m ²)	65	286	351

However, the overcrowding number of passengers currently is approximately 480 calculated from average daily passenger so far experienced for the past three years. The Table .8 shows the train weight capacity under the conditions in the status column.

Table 8: Train Weight

Status	Weight of train body (t)	Passenger weight (t)	Total (t)
Train weight	44	0	44
Seat	44	3.90	47.90
Rated capacity standing capacity: 6 persons/m ²	44	15.3	59.3
Overcrowding capacity	44	28.8	72.8

Note: Passenger weight is 60kg [61]

Traffic loading on EW line

$$T_{th} = S_p \cdot (T_p + K_t \cdot T_{pt}) \tag{31}$$

Fore casted passenger up to 2040, using

$$p_n = p_o(1 + r)^n \tag{32}$$

$$p_n = 56,732(1 + 0.038)^{25} = 144,133 \text{ passengers}$$

If the 56,732 generates 121 trips,

Then the 144,133 can ably generate 307.41 trips by ratio and proportion.

$$T_p = 144,133 \times 60 \times 10^{-3} = 8,647.98.5 \text{ tons.}$$

$$T_{pt} = 307.41 \times 44 = 13,526.04 \text{ tons.}$$

$$T_{th} = 1.05(8,647.98 + 1.4 \times 13,526.04) \times 10^{-6} \times 365 = 10.57 \text{ Annual MGT.}$$

The life of the line is 25 years $\times 10.57 = 264.25 \text{ MGT.}$

Forecasted passenger up to 2040, on the NS line using Equation. (32)

$$P_n = 46,489(1 + 0.038)^{25} = 118,109 \text{ passengers}$$

If the 46,489 generates 118.12 trips,

Then the 118,109 can ably generate 300 trips by ratio and proportion.

$$T_p = 118,109 \times 60 \times 10^{-3} = 7,086.54 \text{ tons}$$

$$T_{pt}=300 \times 44=13,200 \text{ tons}$$

$$T_{th} =1.05(7,086.54+1.4 \times 13,200) \times 10^{-6} \times 365=9.80 \text{ Annual MGT}$$

The life of the line is 25years $\times 9.64=245\text{MGT}$.

Table.9 shows the determined some maintenance model parameters that will be used in the next sections of analysis

Table 9:Determined maintenance modal parameters

Parameter	Description	Value estimate	
		EW line	NS line
M	Life period of track in MGT (Million Gross Tons) after 25years	264.25MGT	245MGT
m	Gross tonnage per year in MGT	10.57 MGT	9.80MGT
N	Life period of track (equivalent to M) in years	25 years	25 years
R	Discount rate	10.23%	10.23%
C _L	Average labour cost/hr.	250 ETB	250ETB
L	Total length of track section in km	16.561km	14.739km

Note:

The discount rate adopted is 10.23% [58] that is the discount rate being used in Ethiopia to evaluate infrastructure as per recommended by World Bank.

The Gross tonnage per year in MGT used in this analysis is 10.57 MGT which is the highest and realized on EW line.

4.3 Cost Modelling Mathematical models for the track Components

Maintenance costs are complex cost components of an asset during its life since maintenance is a long continuous process throughout the asset life while the cost of any specified maintenance work on an asset can be comfortably estimated using engineering costing methodologies, estimating maintenance costs throughout the asset life is a much more sophisticated process. This is because the types of maintenance are dependent on many factors, of which the most important are asset deterioration rates, maintenance policy, and budget constraints.

Maintenance schedules, thus, need to be planned to enable the maintenance costs to be estimated. Maintenance costs of track include; Materials, equipment, and labour.

In the following maintenance and renewal cost models have been developed with respect to the type of maintenance intervention. The M&R costs have been determined according to simplified [49], [51], [52], [53]and [62] mathematical models with a few modifications due inefficiencies in data of all curves, so the modifications are to make the track a tangent. The Maintenance and renewal costs are presented Table.10 The cost values and graphs were reached after analyzing using the formulae in the next section.

Table 10: Operation and Maintenance cost per year perspective

Operation and Maintenance cost per year perspective														
Year	j	MGT	Inspection	Rail Grinding	Repair Rail defects	Repair broken Rails	Rail Lubrication	Rail Renewal	Sleeper Renewal	Fastener Renewal	Ballast Tamping	Ballast cleaning	Ballast Renewal	Cost/year
2019	1	10.57	254,642	6,566	71,575	78,730	8,226,095	1,662,310	3,952,708	6,082,354	82,588	19,389	676,569	21,113,527
2020	2	21.14	485,652	12,523	136,507	150,153	15,688,760	3,170,347	7,538,582	11,600,230	157,512	36,978	1,290,349	40,267,593
2021	3	31.71	695,223	17,928	195,413	214,948	22,458,845	4,538,430	10,791,665	16,606,014	225,482	52,935	1,847,166	57,644,048
2022	4	42.28	885,344	22,830	248,852	273,730	28,600,626	5,779,546	13,742,842	21,147,232	287,144	67,411	2,352,307	73,407,865
2023	5	52.85	1,057,821	27,278	297,332	327,056	34,172,413	6,905,480	16,420,133	25,266,997	343,084	80,543	2,810,568	87,708,705
2024	6	63.42	1,214,291	31,313	341,312	375,433	39,227,106	7,926,920	18,848,955	29,004,424	393,832	92,457	3,226,300	100,682,342
2025	7	73.99	1,356,240	34,973	381,211	419,321	43,812,692	8,853,564	21,052,368	32,394,995	439,870	103,265	3,603,449	112,451,949
2026	8	84.56	1,485,015	38,294	417,407	459,135	47,972,709	9,694,210	23,051,292	35,470,901	481,636	113,070	3,945,597	123,129,266
2027	9	95.13	1,601,839	41,306	450,244	495,255	51,746,652	10,456,840	24,864,703	38,261,345	519,526	121,965	4,255,991	132,815,665
2028	10	105.7	1,707,820	44,039	480,033	528,022	55,170,350	11,148,692	26,509,819	40,792,819	553,899	130,035	4,537,579	141,603,108
2029	11	116.27	1,803,967	46,519	507,058	557,749	58,276,308	11,776,337	28,002,258	43,089,357	585,082	137,355	4,793,034	149,575,024
2030	12	126.84	1,891,190	48,768	531,575	584,716	61,094,016	12,345,733	29,356,190	45,172,763	613,371	143,996	5,024,781	156,807,098
2031	13	137.41	1,970,318	50,808	553,816	609,181	63,650,223	12,862,285	30,584,469	47,062,816	639,035	150,021	5,235,020	163,367,994
2032	14	147.98	2,042,103	52,659	573,993	631,375	65,969,199	13,330,898	31,698,757	48,777,461	662,317	155,487	5,425,749	169,319,999
2033	15	158.55	2,107,226	54,339	592,298	651,510	68,072,960	13,756,021	32,709,632	50,332,977	683,438	160,446	5,598,776	174,719,622
2034	16	169.12	2,166,305	55,862	608,904	669,776	69,981,480	14,141,690	33,626,692	51,744,131	702,599	164,944	5,755,745	179,618,129
2035	17	179.69	2,219,901	57,244	623,969	686,347	71,712,877	14,491,567	34,458,643	53,024,323	719,982	169,025	5,898,147	184,062,025
2036	18	190.26	2,268,523	58,498	637,635	701,380	73,283,591	14,808,973	35,213,384	54,185,704	735,752	172,727	6,027,333	188,093,501
2037	19	200.83	2,312,633	59,635	650,033	715,018	74,708,533	15,096,922	35,898,081	55,239,303	750,058	176,085	6,144,530	191,750,831
2038	20	211.4	2,352,649	60,667	661,281	727,390	76,001,232	15,358,147	36,519,234	56,195,121	763,037	179,132	6,250,850	195,068,740
2039	21	221.97	2,388,951	61,603	671,485	738,614	77,173,961	15,595,130	37,082,740	57,062,234	774,810	181,896	6,347,303	198,078,727
2040	22	232.54	2,421,884	62,453	680,742	748,796	78,237,853	15,810,119	37,593,949	57,848,874	785,492	184,404	6,434,805	200,809,370
2041	23	243.11	2,451,761	63,223	689,140	758,033	79,203,010	16,005,155	38,057,715	58,562,508	795,182	186,679	6,514,186	203,286,592
2042	24	253.68	2,478,865	63,922	696,758	766,413	80,078,595	16,182,091	38,478,441	59,209,913	803,972	188,742	6,586,200	205,533,914
2043	25	264.25	2,503,454	64,556	703,669	774,015	80,872,920	16,342,607	38,860,121	59,797,236	811,947	190,615	6,651,530	207,572,671
													Total O&M Cost in ETB	207,572,671
													cost/year/Km in ETB	267,404
													cost/year/Km in USD	9,095
													cost/year/Km in EUROS	8,356

4.4 Analysis of O&M cost for the rail related costs

The rails are a pair of longitudinal steel members with a primary function of guiding the train in the desired direction and to transfer traffic loading to the sleepers. To provide this function the rail should resist wear and rolling contact fatigue (RCF) for the designed axle load and annual tonnage.

4.4.1 Track inspection Cost

Track inspection is done to detect flaws on the track that can lead to failures. The cost due to track inspection primarily depends on the interval of track inspection. The track inspection is done by both visual and automated ultrasonic equipment to detect flaws such that they are attended to as soon as possible.

Measuring the system and controlling the quality of the infrastructure through inspections is essential to ensure safety and quality standards, 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. Ultrasonic inspection is scheduled twice a year at AALRT.

The benefits of the increased number of rail tests over the long term are that more defects are detected and the service defect rate is controlled and it reduces the risk of derailment. Track inspection cost has been analyzed by using the Equation. (33) and the cost of track inspection is 2,503,454 ETB

$$\text{Track Inspection cost} = \sum_{j=1}^N \frac{(C_{et} + C_L) * T_t * L * \frac{m}{m_t}}{(1 + r)^j} \quad (33)$$

The trends of the track inspection costs are shown on the graph in the Figure.8

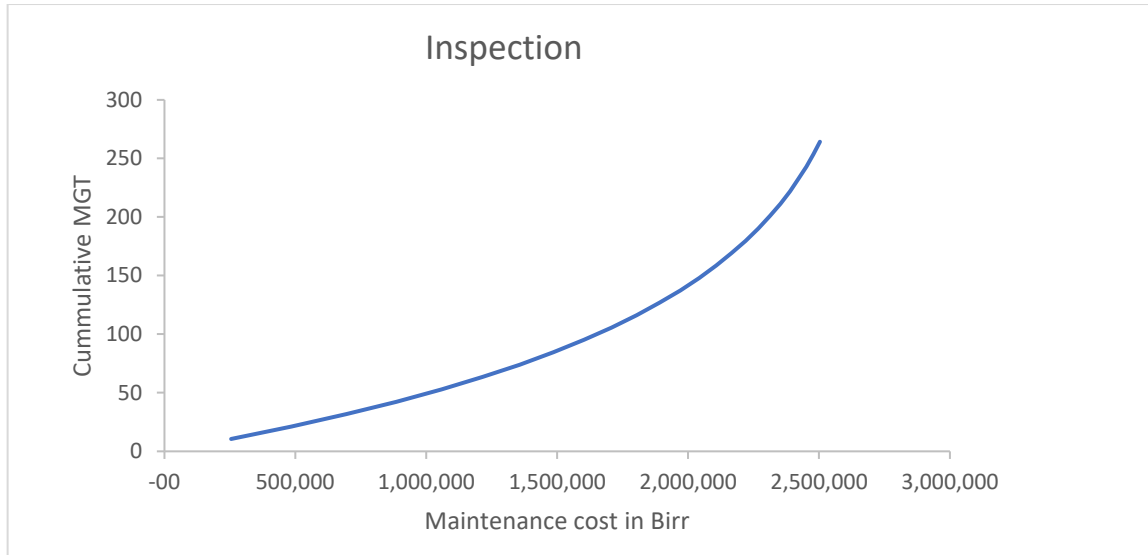


Figure 8: Cumulative MGT Vs. Inspection Maintenance costs

From the Figure.8, the more the load accumulates, the higher is the track inspection maintenance costs if an intervention to maintain is not done.

4.4.2 Rail grinding cost

Grinding is the maintenance action done on the rail to control rolling contact fatigue defects. Cost due to rail grinding primarily depends on the interval for grinding and the number of grinding passes. 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. When grinding interval is larger, crack propagation is much deeper, and metal removal is large, repeated 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. The net present Value of the cost is determined by the Equation. (34).

$$Rail\ Grinding\ Cost = \sum_{j=1}^N \frac{(C_{eg} + C_L) * T_{gi} * n_{gi} * L * \frac{m}{m_{gi}}}{(1 + r)^j} \quad (34)$$

From above mathematical model the estimated the rail grinding cost is 64,556 ETB and trends of the Rail grinding cost are shown by the graph in Figure.9.

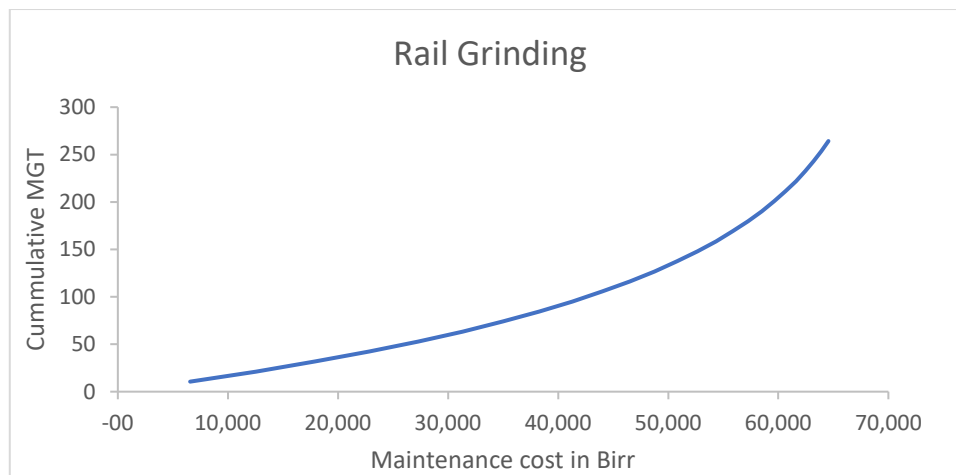


Figure 9: Cumulative GMT Vs. Rail Grinding Maintenance Costs

From the Figure.9, the more the load accumulates, the higher is the rail grinding maintenance costs if an intervention to maintain is not done.

4.4.3 Rail Break Repair and Defect repair costs

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.

4.4.3.1 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 Weibull cumulative probability distribution.

4.4.3.2 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. 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 depends 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.

4.4.3.3 Detection Reliability

This is how possible it is to detect a defect of a certain size since the ability to reliably detect a defect varies with its size. The 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, as a random variable are 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 modelled 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. 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.

4.4.3.4 The number of broken rails between two successive inspections

The defect inspection should be scheduled in a such a way that the occurrence of broken rails defects is minimized. The inspection intervals are generally specified in terms of accumulated traffic carried by rail segment, measured in MGT. The Equation.13 presents the general model to estimate the total number of rail breaks between two successive rail defect inspections assuming no complementary technique is employed.

From Equation.13, the number of broken rails per between two most recent successive inspections is calculated as;

N_i = rail age (cumulative tonnage on the rail) at the i th inspection, $N_i = 4 \times 10.57 = 42.28$ and $N_{i-1} = N_i - X_i = 36.995 \text{MGT}$;

$$S(X) = S_{(i-1,i)} = \frac{273 \frac{3.1(0.5 \times 36.995 + 0.5 \times 42.28)^{3.1-1}}{2150^{3.1}} e^{-\frac{(0.5 \times 36.995 + 0.5 \times 42.28) \times 3.1}{2150}}}{1 + \frac{1}{0.014(5.285 - 5)}} \times 5$$

$S(X) = S_{(i-1,i)} = 3.3683 \times 10^{-7}$ broken rails per track mile between successive inspections

4.4.3.5 Rail Defect Repair Cost

The detected defect model is shown in Eq (14) and from the model,

t = federal and state marginal income tax rate (0.3) [63].

$$DDC = \left[\frac{100.58 \times 8.749(1704.78 - 0.95 \times 238)}{2000} + 650 \right] (1 - 0.3)$$

$$DDC = 910.4 \text{ USD}$$

Based on the above model, an estimated 910.4 USD 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.

From the Equation. (15) The number of detected rail defects between successive inspection intervals is;

$$N_{def} = \frac{3.3683 \times 10^{-7} \times 34,219.16}{0.014(5.285 - 5)} = 2.8887 \text{ detected rail defects}$$

Where L = track length in yards = 34,219.16 yards

The cost of repairing the rail defect (C_{def}) is estimated as per Equation. (16)

$$C_{def} = \sum_{j=1}^N \frac{2.8887 \times 910.4 \times 29.4}{(1+r)^j} = \sum_{j=1}^N \frac{78,896.1744}{(1+r)^j}$$

From the above model, the rail defect repair cost is estimated to be 703,669 ETB.

The trends of the maintenance costs are presented by the curve in Figure. 10

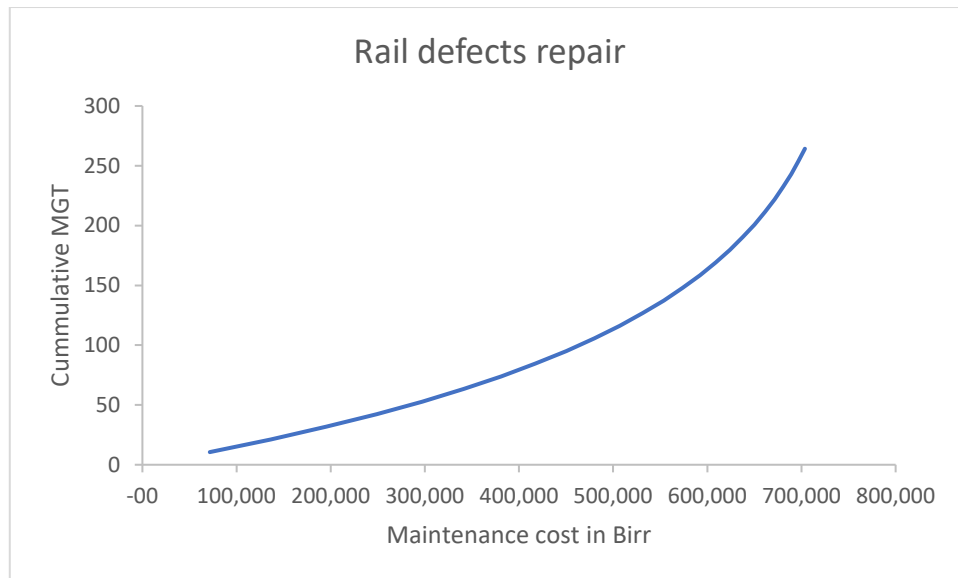


Figure 10: Cumulative GMT Vs. Rail defect Repair costs

From the Figure.10, the more the load accumulates, the higher is rail defect repair cost if an intervention to maintain is not done.

4.4.3.6 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 estimated by the model Equation. (17) where $t = 0.3$ [63]

From the Equation. (17), the rail repair cost SDC is;

$$SDC = \left[\frac{100.58 \times 8.749 (1704.78 - 0.95 \times 238)}{2000} + 780 \right] (1 - 0.3)$$

Based on the model, **1001.42USD** is an estimated value for repairing a broken rail.

The cost of repair broken rail (C_{srp}) is analyzed by the Equation. (18).

$$C_{srp} = \sum_{j=1}^N \frac{1001.42 \times 30 \times 2.8887}{(1+r)^j} = \sum_{j=1}^N \frac{86,784.06}{(1+r)^j}$$

From this model, the cost of repairing the broken rails is 774,015 ETB.

The trends of the costs of repairing the broken rails are shown by the Figure.11 estimation using the Weibull distribution

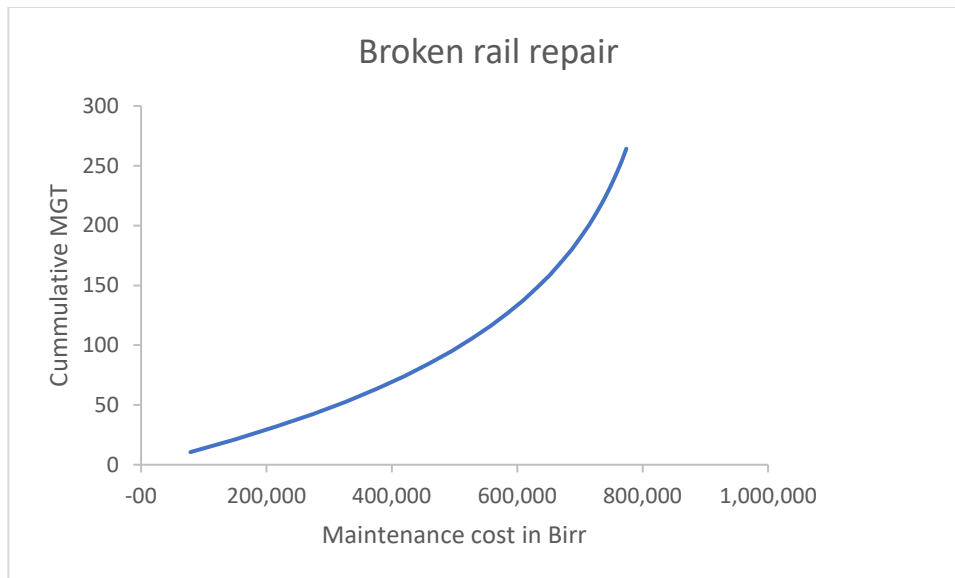


Figure 11: Cumulative MGT Vs. Broken Rail Repair costs

From the Figure.11, the more the load accumulates, the higher is the number of potential rail defects, broken rails and consequently the more will be the maintenance costs for repairing for rectifying the problem.

4.4.3.7 Rail lubrication cost

Rail lubrication is a well-known track maintenance practice. A low coefficient of friction is needed between the rail gauge face and wheel flange. An optimum level of friction is needed on the rail surface to maintain proper traction and reduce bogie hunting in the tangent tracks, in addition to reduced friction in the gauge face contact area [64]. In sharp curves, the wear is more dominant and as a result the lubrication at AALRT is done in curves of radius not exceeding 200m.

These methods used wayside lubrication. The wayside lubrication method is used for both gauge face application and top of rail application. The whole unit consists of a reservoir tank, grease pump unit, controller, connecting hoses, power supply unit, applicator bars, wheel-axle sensor unit or plunger, and sometimes a telemetry or remote condition monitoring system such as RPM (remote performance monitoring).

It consists of a grease tank, grease delivery pump and grease distribution unit. With the passage of each wheel over the plunger, the ramp lever rotates, and this lever is connected

to the pump through the drive shaft. The drive shaft uses the pressure from the wheel impact to pump lubricant to the applicators.

The entire pumping mechanism is housed in the reservoir, and can be removed for servicing. The grease tank can be of different capacities, and applicator bars are also of different sizes. Cost due to lubrication depends on the number of lubricators in the curves and the cost to maintain each lubricator in terms of filling is given by Equation. (35) and the graph showing the trends of lubrication maintenance cost is shown in Figure. 12

$$Rail\ Lubrication\ Cost = \sum_{j=1}^N \frac{[(T_{clu} * C_L * n_{li})]}{(1 + r)^j} \quad (35)$$

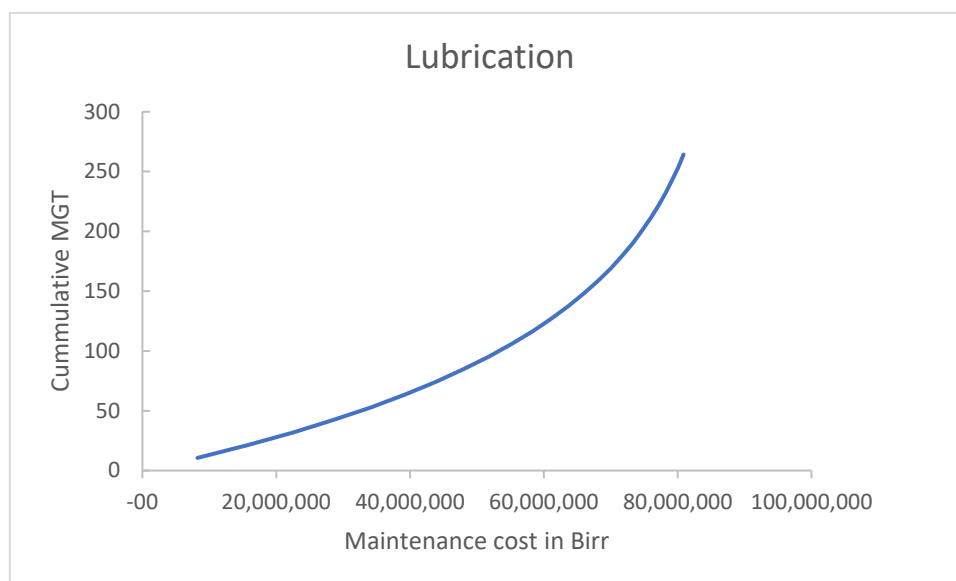


Figure 12: Cumulative MGT Vs. Rail Lubrication costs

From the Figure.12, the more the load accumulates, the higher is the lubrication Maintenance cost of rail lubrication is 80,872,920 ETB. The cost is high because this maintenance activity is done two times per day in curves of less or equal to 200m.

4.4.3.8 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. Rail renewal is done when the rail deterioration reaches maintenance or safety limits. The O&M cost due to rail renewal is given by Equation. (36)

$$\text{Rail renewal Cost} = \sum_{j=1}^N \frac{[C_r + (T_{rri} * C_L) + (C_{err} * T_{rri})] * L * \frac{m}{m_{rri}}}{(1 + r)^j} \quad (36)$$

From the above mathematical model, the average renewal cost is 16, 342,607 ETB. The trends of this cost are shown in Figure. 13

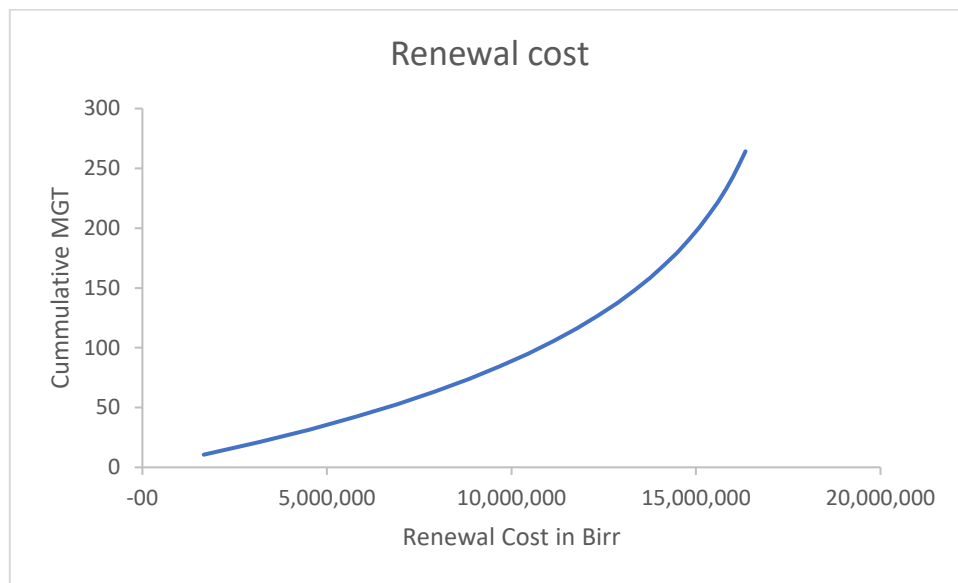


Figure 13: Cumulative MGT Vs. Rail Renewal costs

From the Figure.13, the more the load accumulates, the higher is the rail renewal costs.

4.5 Cost Analysis of sleeper and Fastenings

The sleeper spacing at AALRT used is 600mm, thus the number of Sleepers per Km are;

$$\text{Number of sleepers per Km} = \frac{(1000 \times 1000)}{600(\text{spacing})} + 1 = 1,668 \text{ sleepers}$$

4.5.1 Sleeper Renewal cost

Sleeper renewal is done when the sleeper deterioration reaches maintenance or safety limits and its given by mathematical model Equation. (37)

$$\text{Sleeper Renewal Cost} = \sum_{j=1}^N \frac{[C_S + (T_{sri} * C_L) + (C_{esr} * T_{sri})] * L * \frac{m}{m_{sri}}}{(1 + r)^j} \quad (37)$$

The cost of a sleeper is averagely 50 USD per piece (<https://www.made-in-china.com/productdirectory> 19/05/2019, 2345 hours), the cost of sleepers per km =50x16668=83,400usd. The O&M cost of the sleeper renewal is 38,860,121 ETB. The graph in Figure.14 shows the trends of sleeper renewal cost

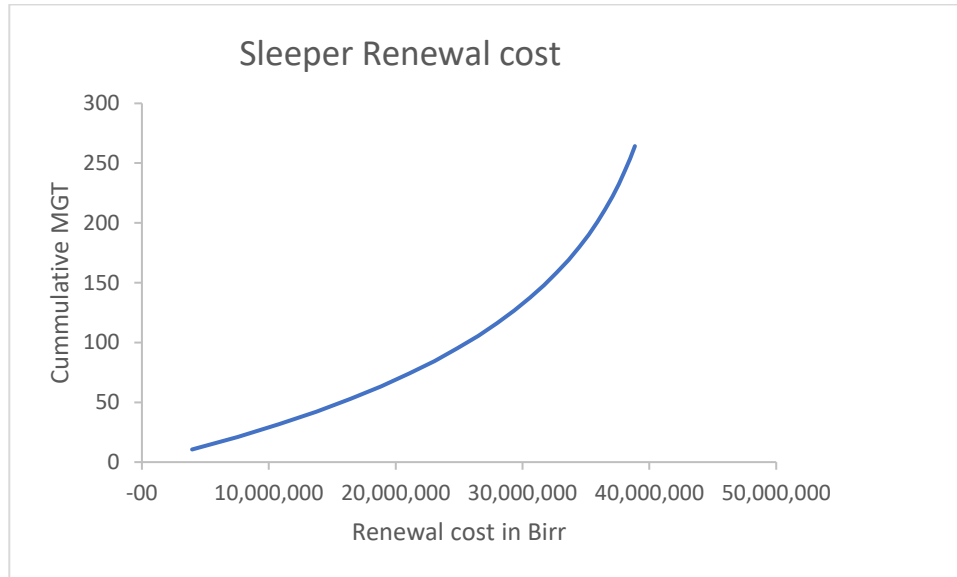


Figure 14: Cummulative MGT Vs. Sleeper Renewal costs

From the Figure.14, the more the load accumulates, the higher is expected deterioration of the sleeper hence higher renewal costs expected.

4.5.2 Fastener renewal cost

Fastening system which attach the rail to the sleeper have a function to properly attenuate and/or transfer loads. The fasteners also retain the rail unto the sleeper and do resist the vertical, longitudinal, lateral and overturning movements of the rail. The fig 15 shows the type of fasteners used at AALT and the respective cost.

The cost of this fastening system in Figure. 15 is 5.5 USD Per seat (https://www.made-in-china.com/products-search/hot-china-products/Rail_Fastening_System.html as at 5/11/2019 11:33:27 PM) this means per kilometer the cost is (5.5x2x1,668)x29.4=539,431.2 ETB



Figure 15: Type II rail fastening system used on AALRT

The cost due to fastener renewal is given by Equation. (38) and from the Equation. (38) the fastener renewal cost is 59,797,236 ETB. The Figure. 16 explains the trend of the sleeper renewal costs.

$$\begin{aligned}
 & \text{Fastener Reenewal cost} \\
 & = \sum_{j=1}^N \frac{[C_f + (T_{fri} * C_L) + (C_{efr} * T_{fri})] * L * \frac{m}{m_{fri}}}{(1 + r)^j} \quad (38)
 \end{aligned}$$

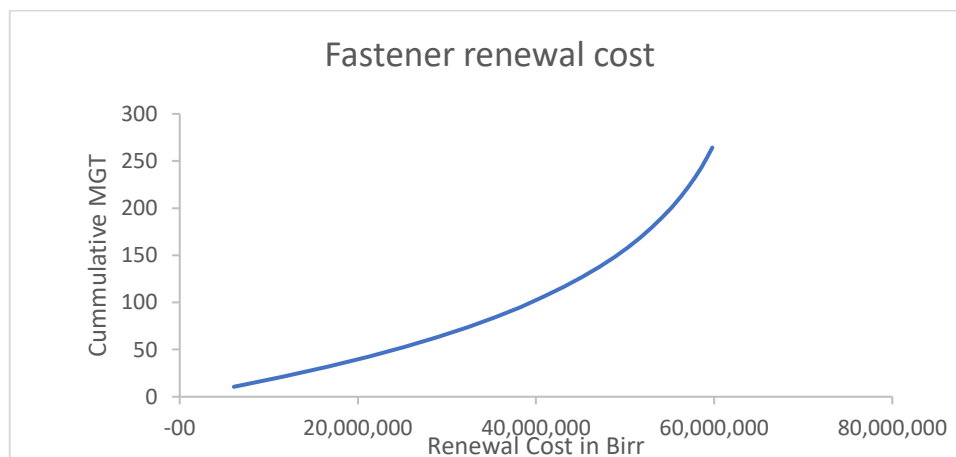


Figure 16: Cumulative GMT Vs. Fastener Renewal costs

From the Figure.16, the more the load accumulates, the higher is expected deterioration of the fastening system hence higher renewal costs expected. Fastener renewal is done when the fastener deterioration reaches maintenance or safety limits.

4.6 Cost analysis of Ballast

To quantify the economic life of ballast, as it is done for the rail, we should assume three types of maintenance operations; tamping, cleaning 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 tamping tines. The Figure. 17 shows the cross section of the track at AALRT but the main interest here is the ballast depth, battered angles to aid in calculating the volume of the ballast per Km and consequently the cost of the ballast per Kilometer.

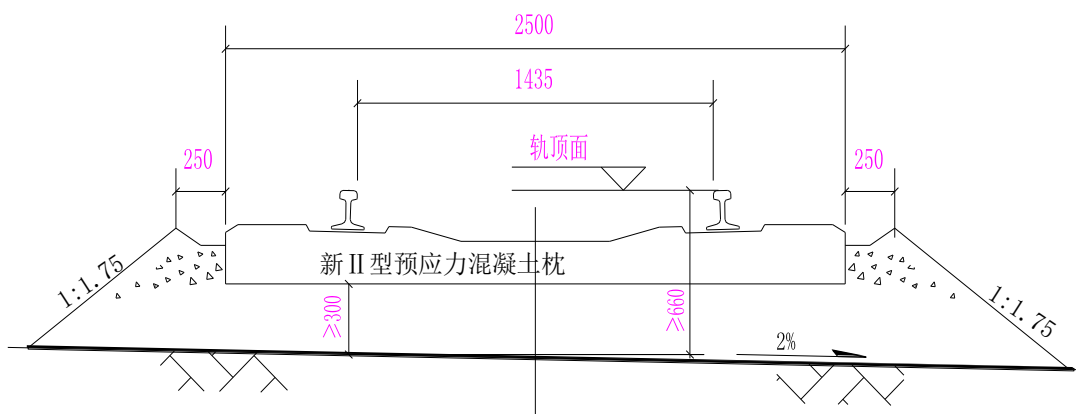


Figure 17: Concrete Sleeper Type Ballasted Track Bed for Ground line [61]

4.6.1 Track tamping cost

Tamping is the maintenance action done on the track to correct its alignment. Cost due to track tamping depends on the interval of tamping and is given by a mathematical model Equation. (39) and from the model equation the O&M cost of tamping is 811,947 ETB.

$$Track\ Tamping\ cost = \sum_{j=1}^N \frac{(C_{eta} + C_L) * T_{tai} * L_i * \frac{m}{m_{tai}}}{(1 + r)^j} \quad (39)$$

The Figure.18 shows the graph showing the trends of tamping cost. The tamping cost is relatively small because the real tamping interval is high.

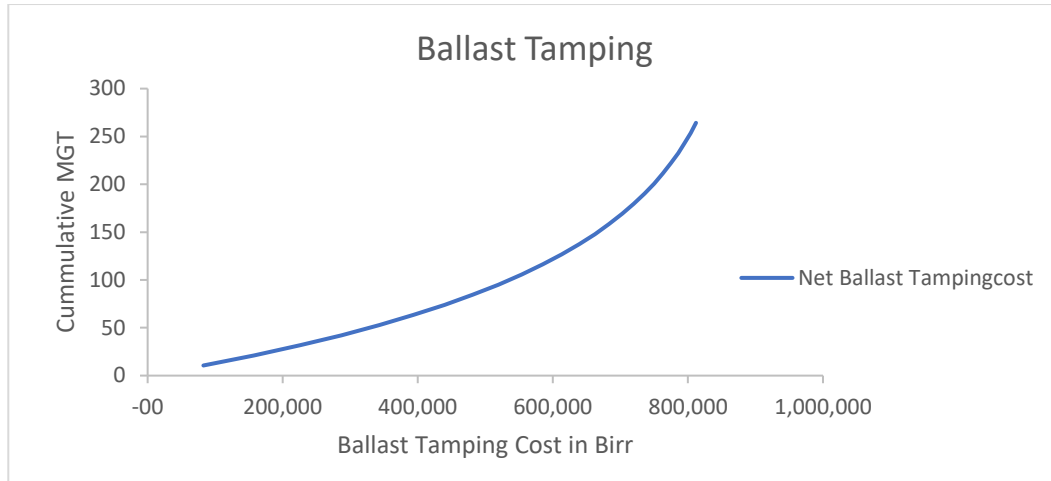


Figure 18: Cumulative MGT Vs. Ballast tamping costs

From the Figure.18, the more the load accumulates, the higher is the expected ballast tamping cost.

4.6.2 Ballast Cleaning Cost

Ballast cleaning is the maintenance action done to eliminate trapped water inside the ballast in order to restore the track quality and stiffness. Cost due to ballast cleaning primarily depends on the periodicity of ballast cleaning and is given by Equation. (40)

$$Ballast\ Cleaning\ Cost = \sum_{j=1}^N \frac{(C_{eb} + C_L) * T_{bi} * L * \frac{m}{m_{bi}}}{(1 + r)^j} \quad (40)$$

From the model Equation. (40), the ballast cleaning is estimated to be 190,615 ETB.

The Figure. 19 shows the trends of ballast cleaning cost in relation to cumulative Million gross tonnage on AALRT track.

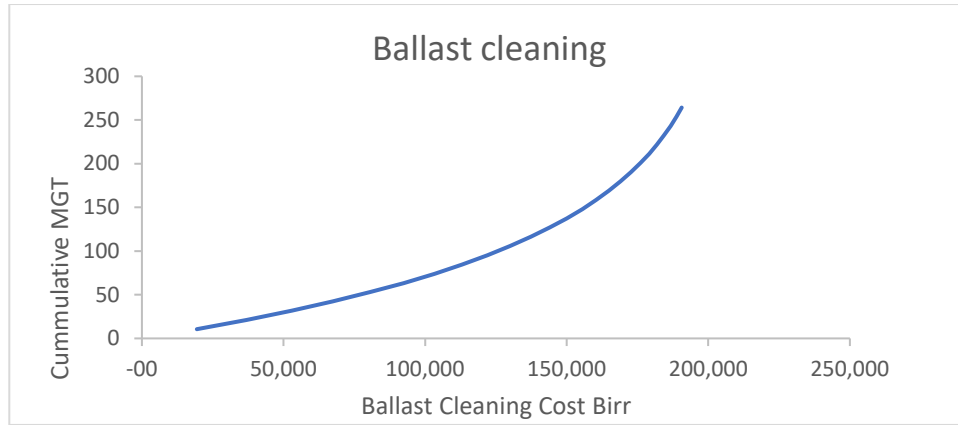


Figure 19: Cumulative GMT Vs. Ballast cleaning costs

From the Figure.19, the more the load accumulates, the higher is the maintenance costs required for ballast cleaning due to ballast deterioration.

4.6.3 Ballast renewal

Life of ballast

In this study it has not been possible to obtain this information from the Infrastructure Managers, however, general data about averages was obtained and used to make some estimates. It is suggested that the ballast renewal takes 10-20 years in high traffic lines and 25-35 years in low traffic lines. In general, it is considered that the renewal of the ballast is appropriate when there are more than 30% of fines, or there are too many particles less than 22mm in size. In this study, 15 years has been taken as the renewal interval for AALRT ballast Renewal.

Ballast renewal is done when ballast deterioration reaches maintenance or safety limits.

The cost due to ballast renewal is given Equation. 42

$$Ballast\ Renewal\ Cost = \sum_{j=1}^N \frac{[C_b + T_{bri} * (C_{ebr} + C_L)] * L * \frac{m}{m_{bri}}}{(1 + r)^j} \quad (41)$$

Figure. 17 has been used for calculation of the volume of the ballast per kilometer taking an average depth of the ballast to be 300mm

The cross-sectional area of the cross section is given in Equation.42, the section is trapezoidal.

$$Area = \frac{1}{2}h(a + b) \quad (42)$$

Where

$$h=300\text{mm}$$

$$a=2500+250 \times 2=3000\text{mm}=3\text{m}$$

$$b=2(3000+300 \times 1.75) + 3000=4050=4.05\text{m}$$

$$Area = \frac{1}{2} \times 0.3 \times (3 + 4.05) = 1.0575\text{m}^2$$

$$\text{Volume of the ballast per km} = 1.0575 \times 1000 = 1,057.5\text{m}^3$$

Cost of ballast per cubic meter is 450 ETB,

Thus, cost of ballast per Km is $450 \times 1,057.5 = 475,875$ ETB

Ballast renewal normally ranges between 10-20 years [65], the average for ballast renewal for AALRT is 15 years which is equivalent to 158.55MGT and the average tamping interval is 1.62 years considering the average of the 10 cases [65] on investigation and benchmarking maintenance and operating costs and for this study the ballast renewal interval is 17.1234MGT.

From the Model Equation. (42), the O&M cost for ballast renewal is 6,651,530 ETB

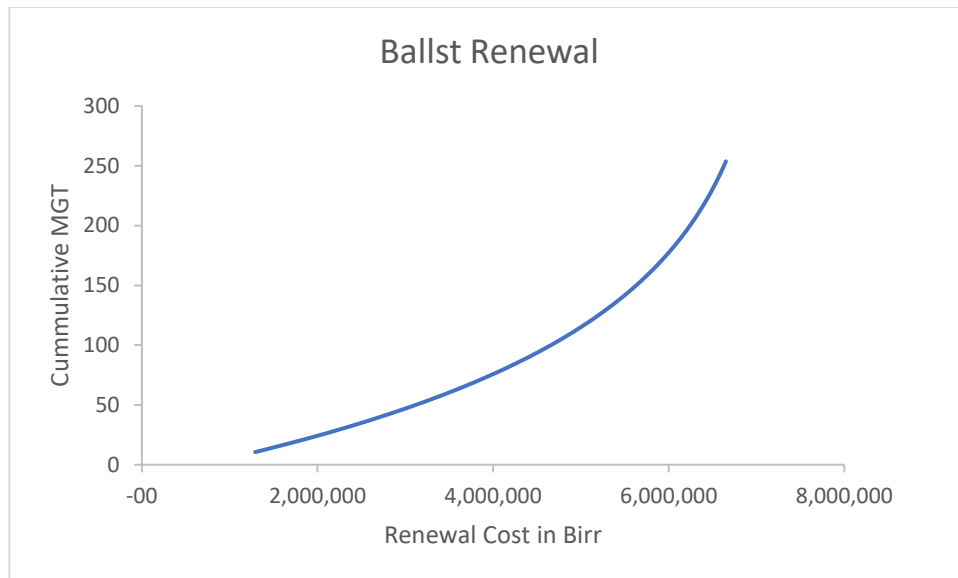


Figure 20: Cummulative MGT Vs. Ballast Renewal costs

From the Figure.20, the more the load accumulates, the higher expected deterioration of the ballast which consequently leads to higher ballast renewal costs.

From the above analysis, it is observed that generally the more load accumulates onto the railway track, the more will be either the maintenance or renewal cost as shown by the general graph in Figure.21.

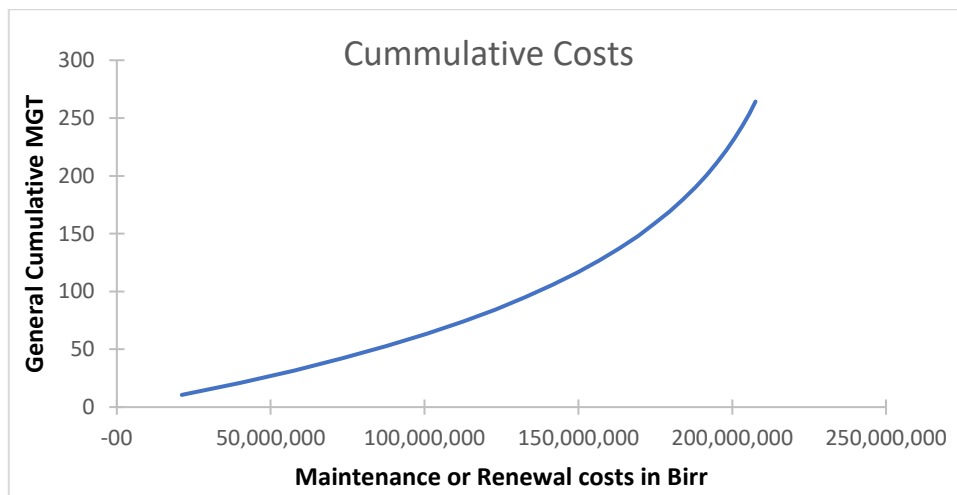


Figure 21: General Cummulative MGT Vs. Maintenance or Renewal costs

4.7 Validation of the result

The results of analysis are validated from previous studies and publications for ensuring that the mathematical models can work as a basis for analysing O&M cost of track super structure. The total O&M cost was reached as 207,572,671 Birr, the cost per year per kilometre as 267,404 ETB equivalent to 9,095 USD/ year/ Km (1USD=29.4ETB) or 8,356 Euros (1 Euro=32ETB) as shown in Table.10

[54], in their 7th Frame work programme to sustainable freight railway; Designing the freight vehicle – track system for higher delivered tonnage with improved availability at reduced cost geared at track design requirements for reduced maintenance, on a project study that took them 48 months cited the average maintenance track costs according to railway traffic and train speed. This famous study provides some orders of magnitude about the maintenance and renovation costs of some railway infrastructure components. Basing on Table.1, AALRT track line has a maximum speed of 70Km/h, and the value (8,103 Euros) lies between 5,000-10,000 Euros per Km.

Also [55] and [56] in evaluating track structures cost analysis as a structured approach in Tokyo came up with the conclusion

From the Figure.5 analysis of a ballasted track average maintenance cost, the cost per meter is 150 Euro equivalent 4800 Birr. Comparing to AALRT case study, whose total cost is 207, 572, 671 ETB.

$$\text{cost per meter in Euros} = \frac{207,572,671}{(31.05 \times 1000 \times 2)} = 3,343 \text{ Birr for single track}$$

In the case study, some components are not considered such as sub ballast, subgrade, switches and crossing so it's the reason why the case study cost is 3,343 Birr per meter versus the whole maintenance cost of the railway track of 4800 Birr per meter

Also [57] and [55] in estimation of the life cycle cost of the upper railway track structure as presented in Table.2, the cost of O&M that excludes reconstruction costs is $(7,466+5356+1176+562) \times 1000$ Rubles = 14,650,000 Rubles per Km = 6,540,179 Birr/ Km

$$\text{AALRT case O\&M cost (in Rubles/Km)} = \frac{207,572,671}{31.05} = 6,685,110 \text{ Birr/Km}$$

Note: The exchange rate of Ethiopian birr to Ruble is 2.24 as of (02/06/2019)

4.8 Optimal Maintenance and renewal strategies for track super structure components.

Maintenance costs of track infrastructure consist of preventive maintenance cost, renewal cost, and corrective maintenance cost. Maintenance and Renewal works should be organized at AALRT with the ultimate goal of reduction of O&M cost while offering the maximum possible reliability, availability and safety of the network. To achieve this objective, the following strategies are proposed that relate to cost, availability and quality. The chart in Figure.22 presents the general maintenance strategy, however, the preferred maintenance line for AALRT is preventive maintenance strategy.

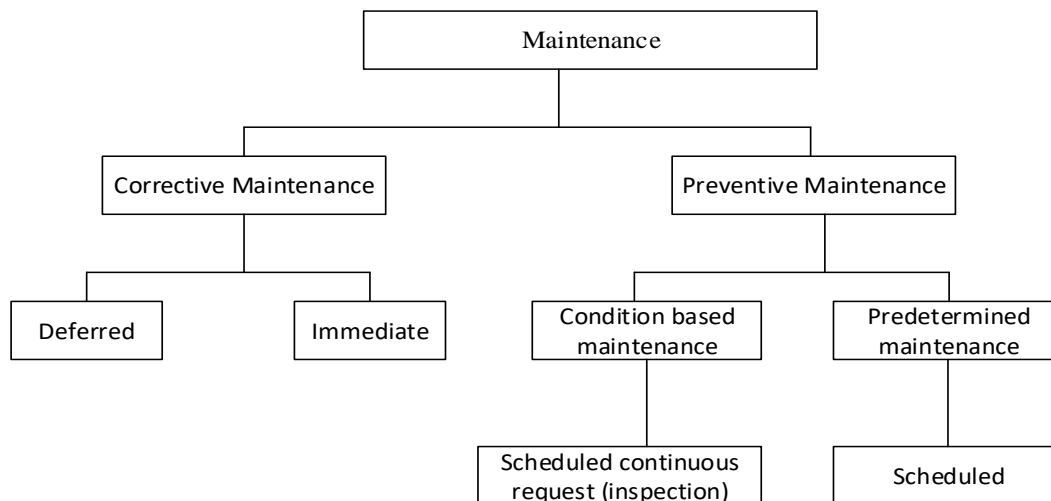


Figure 22: Structure for maintenance Strategy

4.8.1 Railway Track Maintenance at AALRT

The maintenance process at AALRT is divided into corrective and preventive maintenance, where the latter is based on condition or time. The current strategy at AALRT is to minimise corrective maintenance and to change time-based maintenance to condition-based. Table 11 shows the different track maintenance strategies and actions at

AALRT track components which are normally triggered by either time, condition or failure of the component.

Table 11:Track M&R interventions at AALRT

Type of Maintenance	Maintenance action	Maintenance trigger
Preventive maintenance	Track inspection	Time
	Rail lubrication	Time
	Rail grinding	Time
	Ballast Tamping	Condition
	Ballast cleaning	Condition
	Rail renewal	Condition
Renewal (preventive maintenance)	Sleeper renewal	Condition
	Fastener renewal	Condition
	Ballast renewal	Condition
Corrective maintenance	Rail replacement	Failure

Track maintenance and renewal works carried out at the right time are crucial to realizing an efficient and optimized maintenance and renewal work plans, thus increasing the life of the track components, whereas carrying out maintenance and renewal works too late is certainly unsafe and as the railway track gets older, the maintenance and renewal costs increase.

4.8.2 Operation, maintenance and renewal rules

M&R rules are guidelines for tactical planning of the infrastructure M&R. Infrastructure managers may use many rules and it is difficult to encompass all of them. Thus, the approach considers three basic M&R rules:

1. Renewal threshold: this is a certain amount of traffic, expressed in MGT or certain number of years after which a renewal action should be launched.
2. Type of components that must be used at the time of renewal.
3. Quality of infrastructure (quality of the geometry).

The value of these rules, namely values of thresholds and type of components, will be considered as variables and their combined variation may lead to a minimal total of M&R actions over the planning span.

Condition Monitoring which is actually recommended for optimal maintenance means that the status of the railway track condition is monitored, recorded, and reported so that maintenance actions can be conducted before a problem occurs, thus reducing breakdowns which improves the overall track performance and reduces costs

CHAPTER 5: CONCLUSIONS AND RECCOMENDATIONS

5.1 Conclusions

The purpose of this study was to develop a decision support tool to AALRT Management when making decisions of maintenance program and strategic plan through analysis of operation and Maintenance cost. Some results obtained by the analysis from the previous chapters and by the probabilistic and analytical approach in chapter 4 give the evidence needed to come to important conclusions and suggest fruitful ideas for further research.

The research begins with a brief description of the role of AALRT and Railway transportation at large in the country's economy. It describes the vital role of O&M cost towards optimal maintenance and renewal strategy of the railway track super structure of AALRT.

The O&M cost analysis was conducted considering the super structure track components; Rail, sleeper and Ballast. The analysis put into account the inspection cost, rail grinding cost, repair broken rail cost, rail defects repair cost, rail grinding cost, rail lubrication cost, rail renewal cost, sleeper renewal cost, fastener renewal cost, ballast tamping cost, ballast cleaning cost and ballast renewal cost

From the analysis in the chapter.4, the more the load in terms of Cumulative gross tonnage (MGT) is exerted onto the track components the higher will be the deterioration and consequently higher maintenance costs. Thus, a planned optimal maintenance strategy proposed towards a reduced O&M cost has to be adopted. It is also noted that the components with higher or longer maintenance/renewal intervals account for lower O&M cost, take an example of sleeper with the renewal interval of 25 years and above, its cost is low. Finally, the total O&M cost of AALRT for a period of 25 years is 207, 572,671 Ethiopian Birr.

It is noted that conducting such a comprehensive analysis, requires big data sets, however, the major limitation was limited and missing data, even when measurements are conducted regularly on the track sections. It is not known why the information is lost or missing and

some documents where one would find further information or data regarding the track had not yet been handed over by the Chinese.

5.2 Recommendation

This thesis was carried out on AALRT which was constructed by using 85% of its initial capital as a loan from China, thus there is a need to have optimized maintenance and Renewal strategy through O&M cost perspective such that all the revenues from the project are not spent on operation and maintenance rather pay the loan other than the project becoming the burden to Federal Democratic Republic of Ethiopian Government.

There is still more of labour intensive on AALRT in the O&M especially in inspection, lubrication, etc. This increases down time and reduced accuracy in the works done. There is need for more automation in some activities like inspection for the reduced downtime.

There was a challenge with the documentation and data management in this department of O&M, some inspection reports were missing, work procedures and some data sets. Relying on people to have data and information from their brains is good, though its better when the data or information is documented and well managed for future use. A well data management system should be thought of for easy management of O&M works at AALRT.

5.3 Future Research areas

The study was basically on the three major components of the railway track super structure (Rail, Sleeper and the Ballast) of AALRT. There is need to look at how other components such as bridges, switches, crossings, tunnels and others interact with the track super structure components and have integrated O&M cost of the full track other than looking at some structures like the bridges and the tunnels independently.

This research considered failure and cost of the components independently as the failure of one component could not have a direct impact on the other component(s). A further research on how these components affect each other dynamically (integrated deterioration) should be put into account while conducting or analysing the O&M cost of the track

because the deterioration of one component may have a dynamic impact of on the failure of other component(s) in attenuation.

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APPENDICES

Appendix 1: The values of the parameters used in the models as per data collected from different sources.

Parameter	symbol	Value
Life years)	N	25
Life (MGT)	M	265.25
MGT/year	m	10.57
Discount rate	r	0.1023
Average Labour cost in ETB	CL	250
Total Length of the Track	L	31.05
Equipment cost for track inspection ETB/h	Cet	8790
Interval for track Inspection in MGT	mt	5.285
Mean time to grind in h/km	Tgi	0.15
Number of grinding passes	ngi	20
Equipment cost for grinding in ETB/h	ceg	450
Interval for grinding in MGT	mgi	3.52
Million Gross Tons per year (MGT)	m	10.57
Cost of lubricating material per year in ETB	Tclu	36,270.50
Number of way side lubricators	nli	2
Cost of rail in ETB/km	Cr	160200
Mean time for rail renewal in h/km	T _{rri}	400
Equipment cost for rail renewal in ETB/h	C _{err}	1500
Interval for rail renewal in MGT	m _{rri}	158.55
Cost of sleeper in ETB/km	C _s	2,451,960.00
Mean time for sleeper renewal in h/km	T _{sri}	55.60
Equipment cost for sleeper renewal in ETB/h	C _{esr}	1,017.50
Interval for sleeper renewal in MGT (25years)	M _{sri}	264.25
Cost of sleeper in ETB/km	C _f	1,078,862.40
Mean time for fastener renewal in h/km	T _{fri}	1.20
Equipment cost for fastener renewal in ETB/h	C _{efr}	400.00
Interval for fastener renewal in MGT	m _{fri}	52.85
Mean time to tamp ballast in h/km	T _{tai}	4
Equipment cost for tamping in ETB/h	C _{eta}	1000
Interval for tamping in MGT	m _{tai}	17.1234
Mean time to clean ballast in h/km	T _{bi}	2
Equipment cost for ballast cleaning in ETB/h	C _{eb}	5000
Interval for ballast cleaning in MGT	m _{bi}	162.778
Cost of ballast in ETB/Km	C _b	475,875
Mean time for ballast renewal in ETB/km	T _{bri}	2
Equipment cost for ballast renewal in ETB/h	C _{ebr}	2000
Interval for ballast renewal in MGT	m _{bri}	211.4

