ADDIS ABABA INSTITUTE OF TECHNOLOGY (AAiT)

SCHOOL OF CIVIL AND ENVIROMENTAL ENGINEERING

DEVELOPMENT OF MAINTENANCE MODEL AND STRATEGY FOR ADDIS ABABA LIGHT RAILWAY TRANSPORT (AALRT) RAILWAY TRACK LINE

BY: MELESE TESHOME

A thesis submitted to the school of Graduate Studies of Addis Ababa University in Partial fulfillment of the degree of Master of Science in Civil Engineering.

Advisor:

Abdulsetar Siraj (MSc.)

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ABSTRACT

There is a need among transportation maintenance decision makers for a better understanding of the long-term behavior of railroad tracks. The use of accurate techniques (maintenance model and strategy) to predict track conditions increases track safety and maintenance effectiveness as well as reduce maintenance costs through improve planning.

This paper describes the track maintenance model and strategyrelevant for Addis Ababa Light Rail Transit.By using reliability model with weibull distribution, the expected number of critical and degraded failures are determined. Then three failure mechanisms are determined and the rate of critical and degraded failures is determined for each failure mechanism. Finally the governing value of critical and degraded failure are chosen to determine reliability parameters such as mean time to failure(MTTF),mean time to detect(MTTD),mean time before failure(MTBF),mean time to repair(MTTR) and preventive maintenance index(Ipm).

The analysis result shows that, the Frequency of critical failure is reduced by **56%**by conducting **three inspection per year**. And also the Mean time until any failure is detected by conducting inspection at every four months of interval for AALRT Railway track line (MTBF) is obtained as **2.55 years**.

Then after, **four maintenance strategies** are developed for AALRT. These are: Repair as soon as the component is identified to be in a state where repair is necessary, repair when the component is identified in the state where a major repair is required, repair when the component is identified as being in the state where renewal is needed and no repair, component is allowed to deteriorate without any intervention.

Key Words: Maintenance model or strategy, Degraded failure, Critical failure, mean time to failure, mean time before failure, repair.

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Notation	**Definition**
y	*Track settlement*
x	*Tonnage*
α	*Vertical acceleration*
β	*Coefficient proportional to sleeper pressure*
Υ	*Constant depend on initial packing of ballast*
S	*settlement just after maintenance action*
ΔN	*Pre loading period comprising first passing axles*
P	*Ballast pressure*
Q	*Track quality index*
λ_c	*Critical failure rate*
λ_d	*Degraded failure rate*
λ_{dc}	*Mixed degraded and critical failure rate*
T	*Exposure time*
C	*Critical failure*
D	*Degraded failure*
τ	*Inspection/ test interval*
N_c	*Number of critical failures*
N_d	*Number of degraded failures*
P_d	*Probability of detecting degraded failures*
P_c	*Probability of detecting critical failures*
P_o	*Probability of surveying one test interval without failure*
I_{pM}	*Preventive maintenance index*
CSU	*Critical safety unavailability*
$R^{II}(\tau)$	*Survival function*
A	*Availability of component*
υ	*Repair rate*

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INTRODUCTION

1.1 BACKGROUND OF THE RESEARCH

In the past, transport organizations generally focused on construction and expansion of networks. Traditional maintenance plans mainly based on the knowledge and experience of expertise, with the major goal of providing a high level of safety to the infrastructures without so much concern over economical issues. In recent years, the emphasis has increasingly shifted from developing new infrastructure to intelligently maintaining the existing ones. Therefore, efforts are being made to develop a unified framework for maintenance decision making process and the underlying idea is to reduce the operation and maintenance expenditure while still assuring high safety standards.

For mechanical equipment, deterioration can be very quick, and so the economic importance of failure is clear. In case of transportation infrastructures such railway tracks, although most of the time deterioration process is very slow, but it might lead to massive failures with an enormous financial lose. As a result it is very important to decide when and how to perform maintenance operations for such systems and how to allocate the resources (manpower, materials, machines and funds) to the parts of the system with highest need. For railway track networks some maintenance decision support systems have been developed during recent decades to compare different maintenance and renewal policies, reduce costs and improve reliability decades. While for railway track for different geometrical degradation modes and component deterioration the relation with the track load, time, speed of vehicles and other affecting parameters has been studied, the knowledge on degradation analysis and modeling of AALRT tracks has been rudimentary. This knowledge on rail track deterioration, results in different decision support models allowing an optimization of maintenance operations, for long, mid and short term planning of AALRT tracks. With the introduction of new track inspection vehicles that run through track and detect a large amount of data from infrastructure condition, developing a framework for maintenance decision making of AALRT network seems to be necessary.

Due to the lack of long term information on the condition development of light rail infrastructures, this study focuses on forecasting AALRT track conditions. Based on the degradation model, maintenance and renewal operations will be optimized with respect to total cost of maintenance. This paper will present the first results from the literature study on this subject and the methodology which will be used to derive models from the data.

This paper is also concerned with the modeling and statistical analysis of the failure mechanisms (Maintenance strategy) of AALRT railway line. A failure model for AALRT railway line is presented, using Markov model, and the transition rate estimation methods are shown for the future estimation.

The critical failures (broken rail) can either be seen as shocks (i.e., with no "warning"), or as a gradual degradation, where the line goes through various degraded states (with cracks) until it gets a critical failure. When a degraded failure occurs, the railway line is still functioning and the crack can only be revealed by inspections of the line. Those inspections are performed at regular intervals by certain inspection method such as Ultrasonic inspection cars (UIC). However, at each inspection there is only a probability 'P' of detecting a degraded failure; where q is roughly estimated to be between 0.4-0.7. A piece of rail which is degraded is more prone to suffer a critical failure than a piece of rail not degraded (i.e., in OK state). When a critical failure occurs, the failure has to be repaired in order to maintain regular traffic.

The model will demonstrate for instance how various reliability parameters depends on the inspection intervals, and will those support identifications of the most cost effective preventive maintenance strategy for the AALRT railway line in question. Other lines may have different questions, and line specific data with a new estimate of parameters will then be required. However, the presented failure/ maintenance model (strategy) and estimated technique is believed to be useful also for other applications involving imperfect inspections and gradual development of failure.

1.2 STATEMENT OF THE PROBLEM

It is obvious that track components will deteriorate over time due to the action of track loading and other factors that might affect the long term performance of the AALRT tracks. A safe, efficient and reliable AALRT railway service cannot be achieved unless a proper maintenance model (strategy) is developed to maintain the desired operational requirements in the future. The AALRT railway transport is the new technology in Ethiopia and no maintenance model (strategy) has been prepared so far. Thus the maintenance model and strategy is required to keep the desired efficiency and extend the service life of the track components.

1.3 OBJECTIVE/AIM OF THE STUDY

1.3.1 General objectives:

- To develop the maintenance Model as well as maintenance strategy for Addis Ababa Light rail Transit (AALRT) railway track line.

1.3.2 Specific objective:

- To model the interrelation between critical and degraded failures of track components.
- To estimation degraded and critical failures rates for the AALRT railway track maintenance model.

1.4 RESEARCH METHODOLOGY

The research methodology for this study involved the following major tasks: literature review is Performed to document the various degradation models their current practices and application to the railway industry. Following literature review, Markov chain analysis method is used to develop maintenance model and strategy for AALRT railway track.

1.5 THESIS STRUCTURE

Chapter 1: In the first chapter, introduction and background of the research about railway track degradation and maintenance model as well as strategy is described.

Chapter 2: In this chapter, Literature review is described for railway track degradation and modeling as well as maintenance strategy.

Chapter 3: In this chapter, the main research is described such as Weibull analysis, identification of severity classes and failure mechanisms of degraded and critical failures, determination of the interaction between degraded and critical failures for AALRT railway line, trial of different failure mechanisms, determination of method for estimation of rates of degraded and critical failures and finally maintenance model and strategy development for AALRT railway line is described.

CHAPTER 2

2.1 LIERATURE REVIEW

2.1.1 RAILWAY TRACK DEGRADATION

It has been observed that the condition of a railway track degrades rapidly over a period of time. Having the knowledge of the degradation process will aid in the estimate of the future state of a track condition and in the mitigation of the problems associated with operational safety. The following section presents the theoretical framework and the current practices related with railway track degradation.

2.1.1.1 GENERAL CONCEPT

Track degradation is a complex process. The mechanism involves many influencing parameters such as axle load, traffic speed, climate, track characteristics and topography (Figure 2.1). Today, research efforts have been carried out not only to address the degradation problems, but also to determine the contribution of each parameter to the entire process.

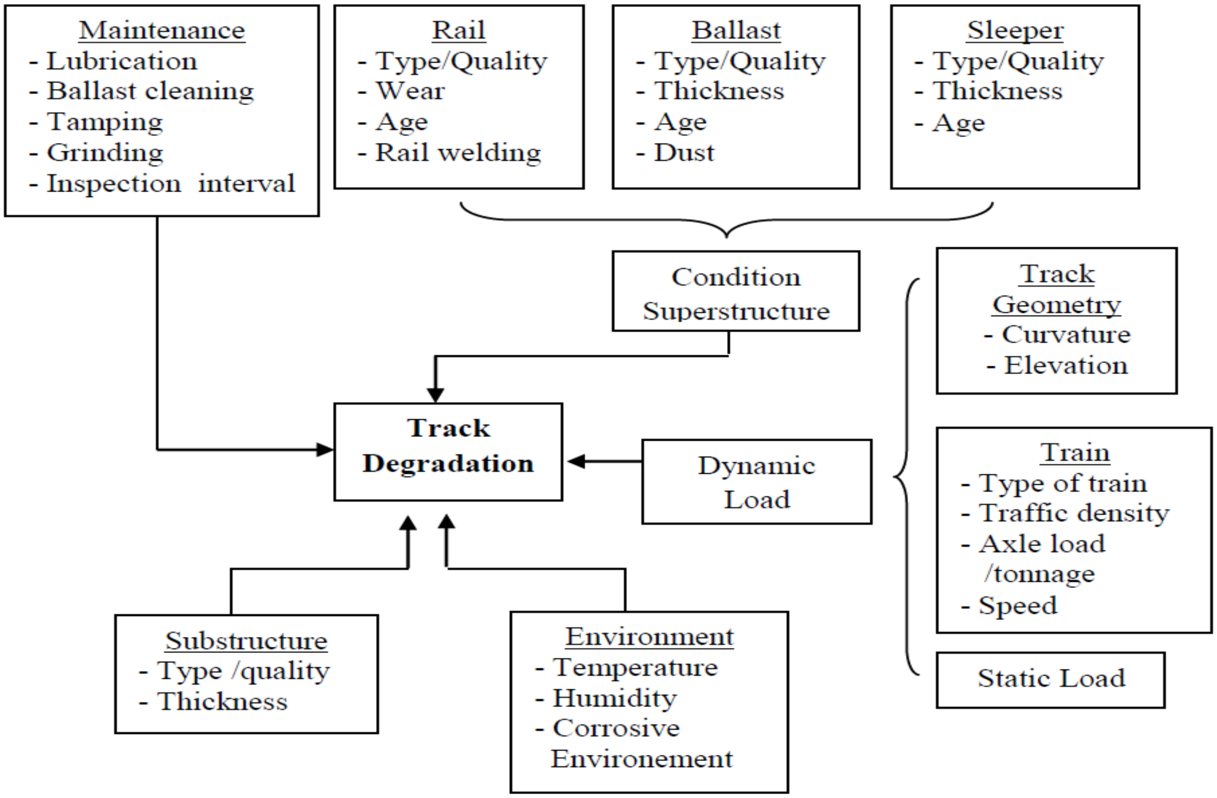


Figure 2.1 – Influencing Parameters to the track degradation [Ferreira & Murray, 1997]

Ferreira & Murray [1997] have investigated the physical factors that may have impact on track deterioration. According to the results, the authors argue that the declination in the track quality is mainly driven by three parameters, i.e. dynamic forces, axle load and train speed. Speed contributes to the deterioration process by increasing the dynamic forces at high speeds and decreasing those at low speeds. Load contributes to increased rail wear and fatigue, wheel wear, and strains in rails and sleepers. As a consequence, cracks in the rail and sleepers will occur, the railhead will be worn out, the rail fastening will be loosen, and the ballast load will thus be redistributed. These situations will lead to reduce travel safety and comfort, and increase track components deterioration and delays.

Later work reported by Larson [2004] has found that wear and fatigue damage are considerably affected by the existence of curvature. The shape and radius of curvature can determine the rail defect with the following relationship:

- Narrow curves implies wear (ahead of fatigue)
- Tangent track implies fatigue (ahead of wear)

Using the Swedish railway data, Larson then attempted to correlate various ranges of curvature with the state of track condition:

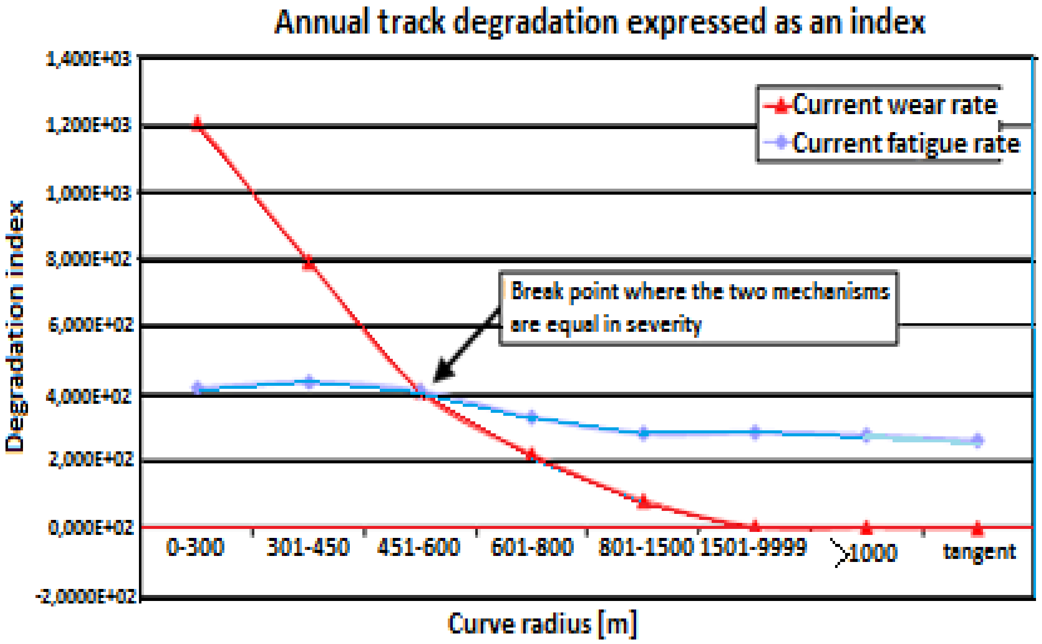


Figure 2.2– Wear and Fatigue mechanisms as a function of Curve Radii [Larson, 2004]

As indicated in the figure, the narrow curve has caused a higher degradation index compared to the plain track. Higher index means shorter service life of the rails. Wear, in this case, governs the rail degradation with short life span, while fatigue drives the rail degradation with long life span [Zarembski, 1991].

Pita *et al.* [2004] and Berggren [2005] later investigated the influence of track stiffness to the track degradation. Based on their experimental study, the authors found that an increase in vertical stiffness produces a negative effect, especially in vertical stresses exerted by the vehicles on the rail. However, having a very flexible track may enhance the energy dissipated from vehicles running at high speed. Considering this duality, an attempt was made to define the optimum value for the vertical stiffness, which minimizes the maintenance cost on the one hand, and the cost due to the dissipated energy on the other. The equilibrium of these two costs is achieved when the vertical stiffness of the track stands at about 70-80 kN/mm for lines on which trains run at high speed.

Similarly, the application of maintenance (consisting of tamping, grinding, lubrication, etc.) could improve the quality of railway track. When the tamping action is performed, the ballast under the ties is re-compacted and the area of contact increases. The larger the areas of contact, the better the ties distribute the weight of the rail and rolling stock, which in turn may impede the acceleration of track to face deterioration. Likewise, the application of preventive grinding also leads to a significant increase in the rail service life, since it slows down the rail corrugation growth and decreases traffic noise. From the experience gained in practice, the combination of maintenance methods, such as rail grinding and lubrication, may extend the life span and the limit of rail components from 50% to 300% [Judge, 2002].

Some other factors contributing to track deterioration have also been examined by many researchers. Lichberger [2001] discussed the effect of initial track quality to preserve the track from rapid degradation. Johansson *et al*. [2008], Witt [2008] and Lundvist [2005] argued that the selection of under sleeper pad could help reduce the ground vibration and minimize track misalignment. The preferences in choosing the material quality are also essential to attenuate the distortion on the track performance. Poor materials can cause more track degradation, while good materials will enhance the resistance of the track to failure [Zwanenburg, 2006].

2.1.1.2 TRACK DEGRADATION CURVE

In order to define where the quality limit is and to decide when the intervention (repair) is required, it is therefore necessary to understand the degradation behavior. Normally, the degradation line will exhibit a "saw tooth" shape, in which the quality deteriorates between two subsequent maintenance activities [Jovanovich, 2004]. This process is schematically shown in the following figure:

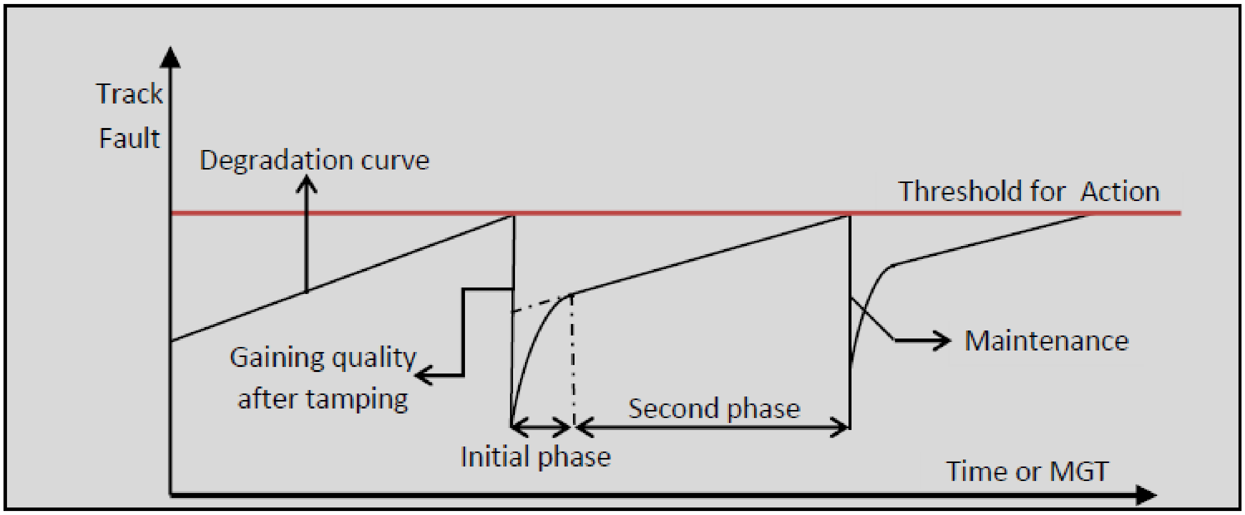


Figure 2.3 – General trend degradation model [Lichtberger, 2001]

The railway track commences with an initial quality from a newly constructed line or previous maintenance action. During the train operation, the track quality starts to degrade as a result of interaction of several effective parameters, such as the cumulative of track loads (MGT), time, speed, etc. When the defect of the track reaches the threshold limit, tamping should be carried out to reduce the amount of standard deviation, leading the track geometry to deterioration in two major phases.

The first phase occurs directly after tamping, around the first 0.5-2 MGT of traffic borne. This period is followed by a rapid exponential track failure, characterized by the breaking off of the points of ballast stone that settle into a more compact position [Lichtberger, 2001]. Once the track has been sufficiently established, the second phase of degradation takes place. The track faults will deteriorate slowly and increase linearly in proportion to the number of load cycles [Lyngby, 2009]. Several mechanisms of ballast and sub-grade behavior are governed during this process. Continuous volume reduction due to particle rearrangement and sub-ballast or sub-grade penetration into ballast voids are examples of such characteristics.

Subsequently, the efficiency of maintenance will decrease in time and the period between two tamping's becomes shorter. When tamping is considered ineffective to repair the geometry faults, line reconstruction should be carried out.

2.1.1.3 TRACK DEGRADATION MODELS

In the past few years, several attempts have been made to build a track degradation model, from the simple one that relies on a single parameter to a comprehensive one which embraces several influencing variables. From the reviews on the available literature, these models can be classified into two different aspects [Sadeghi and Asgarinejad, 2007]:

- Track degradation considered from a structural viewpoint
- Track degradation considered from a geometrical viewpoint

From a structural viewpoint, the model development is based on the progression of defects in the physical structure, such as ballast settlement, wear and corrugation. Shenton [1984], Sato [1997], Chrismer and Selig [1993] and TU Munich [Demharter, 1982] have developed models in this area. From a geometrical viewpoint, the reflection of the actual state of track condition uses geometrical parameters, such as longitudinal profile, alignment, etc. Some of the developers of this model are Bing and Gross [1983] and recently, the practical use of the model has been adopted by many countries. In fact, both viewpoints are correlated. Any deviation in the geometry parameters is known as a result from the track structural problems [Berggren, 2005].

2.1.2 TRACK MAINTENANCE

The maintenance management system is considered one of the aspects standing out as particularly important to guarantee a high level of safety and reliability of the infrastructure system. The concept relies on the combination of all features of technical and administrative actions, including track supervision, intervention and monitoring [Zoetaman & Esveld, 2005].

In this section, a schematic overview on maintenance management will be discussed. The existing methods and technologies used in track maintenance will be briefly presented.

2.1.2.1 LEVEL OF MAINTENANCE

When the track state falls below the acceptable limit value, an appropriate action should be conducted to fix the defect and to ensure that the railway track meets the required safety and quality standards [Esveld, 2001]. Intervention has to be done in a systematic way, i.e. avoiding any potential conflict that can disrupt the operation of train services.

Several levels of maintenance actions have therefore been identified according to the application timing. Such interventions are classified as:

- **Corrective Maintenance**

This type of maintenance can be considered as the oldest intervention activity in the railway systems. It is carried out based on the occurrence of failure or worn out of the structural elements and is, therefore, performed at unpredictable intervals. The corrective maintenance may be twofold: replacement of fault components and repair action. Preferences between these alternatives are based on the cost and benefits resulting from each option.

- **Preventive Maintenance**

Preventive maintenance is contradictory to the previous type of intervention. The activity is performed according to a regular scheduled time which aims to prevent the breakdown and failure of the railway system. When proposing this intervention work, one should consider the economical aspect as the main criteria.

- **Predictive Maintenance**

The predictive maintenance attempts to forecast the "future" condition of the equipment's. By implementing a strategy, maintenance can be performed at a scheduled point in time when the maintenance activity is the most cost-effective or before the performance of the system drops to a threshold limit.

2.1.2.2 TRACK MAINTENANCE ACTIVITIES

According to its purpose, track maintenance can be divided into two distinct categories [Shimatake, 1997]. The first category refers to the repair of defects which occurred in the railway geometry caused by the deformation of supporting materials such as ballast and sleepers. To remove this defect, a particular track intervention known as tamping is applied by using either manual or automatic tamper machine.

In the second category, the maintenance is carried out to repair the mechanical parameters which in most cases could not be restored without parts replacement.

Various methods of intervention, repair and replacement applied to the track maintenance are briefly described in the following sections. The description includes the procedure and technology used in the current management technique.

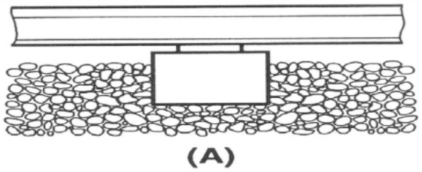
1) Tamping

Tamping is the most common railroad maintenance activity. It is operated by the tamping machine which aims to correct the geometry faults and to compact the ballast beneath the sleepers. The most sophisticated machine, currently available, is capable of adjusting the ballast position simultaneously at a speed of up to 1.6 km per hour, providing the efficiency of 50 manual workers [Lichberger, 2005].

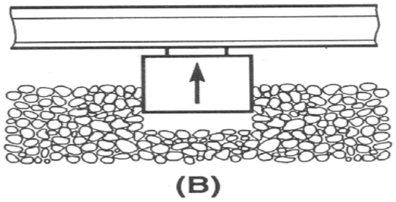
Figure 2.4– Tamping Machine [Plasser and Theurer, 2013]

The principle of operation of such tamping machine comprises several procedures:

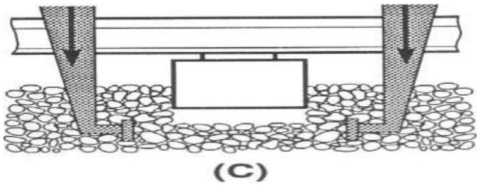
A. The tamping machine takes the position over the sleeper to be tamped.



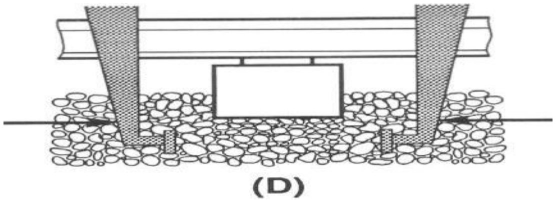
B. The lifting rollers elevate the sleeper and rails to the adjusted level, leaving a void beneath the sleeper.



C. The machine arms bars are pushed down vertically into the ballast in either side of the sleepers.



D. By squeezing and vibrating the arms, the packing is improved.



E. The arms are withdrawn from the ballast and the machine is moved forward to the next sleeper to repeat the cycle operation.

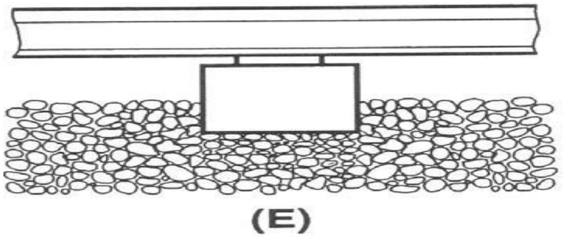


Figure 2.5 – Tamping Process [Selig, 1994]

Some undesired effects may occur during the tamping procedure. The vibration generated by tamping may, for instance, result in completely disturbed and loosened ballast bed. The disturbed ballast thus leads to lateral track instability, putting the track at risk of safety. In order to reduce this drawback, the infrastructure manager usually performs the subsequent activities of re-compaction of the ballast after tamping, using mechanical stabilization.

2) Dynamic Track Stabilization

The lateral track instability commonly occurs due to the loss of compaction of the ballast as a side effect of the vibration induced during the tamping operation. To mitigate this problem, the dynamic track stabilizer is used to consolidate ballast more densely and to provide an optimum homogenous settlement of the track. By imposing the DTS technique, the track will gain a settlement corresponding to 70,000 ton up to 100,000 ton of train loads [Lichtberger, 2005].

Figure 2.6– Dynamic Track Stabilizer [Unitedindustrial, 2013]

The dynamic track stabilizer consists of 4 axle wagon fitted with a diesel engine and pressurized cylinders on the stabilizing unit. When the stabilizing action is carried out, the machine generates a vertical force beneath the track with an approximate load of 356 kN. The vibration that is transmitted to the ballast lies in the natural frequency range and caused the stones to settle closer together within the cavities. This method allows the track to settle more uniformly and systematically, resulting in a 30% extension in the maintenance cycle [Grabe& Maree, 1997].

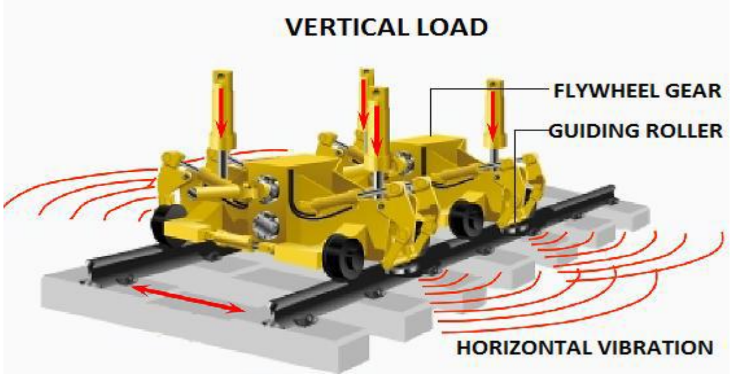


Figure 2.7 – Dynamic track stabilization equipment's [Total Track, 2013]

3) Ballast Cleaning

Ballast becomes degraded due to the repeated passage of trains and to very intense compression during wheel-track interactions. Such ballast crushes into small particles of stones known as fines. When the fines combine with water, the ballast loses its primary function of support to the track bed, as well as its drainage capability.

In order to remove the fines, ballast cleaning can be performed using an automated machine with adjustable excavating chain. The ballast is transferred upwards to the machine frame to be vibrated in order to eliminate the dirt and any other particles smaller than 35 mm. Afterwards; the conveyor arrangement distributes the clean course materials back to the ballast bed.

Figure 2.8– Ballast Cleaning Machine [Remtech, 2010]

4) Rail Grinding

Irregularities in the geometry of the rails can cause a very high dynamic load. These irregularities partly occur due to faults in the manufacturing process or as a result of the train operation activities [Magel & Kalousek, 2002]. This special type of track imperfection is the so called rail corrugation, which is a periodic vertical irregularity on the railhead. Although rail corrugations do not pose a risk of immediate derailment, some undesirable problems can occur, such as increase in noise and in the vibrations experienced by passengers, ballast deterioration and higher maintenance cycles [Kumar, 2006].

At present, grinding can be considered the most effective maintenance practice to remove the irregularities and to restore the original rail profile. There are two types of rail grinding strategies. The first one is preventive grinding, which serves to prevent the development of defects growing from the surface or into the subsurface of the rail. In this method, the maintenance operation relies on the application of one pass of a large production grinder or multiple passes of a lighter grinder. The second strategy is the implementation of corrective grinding with the purpose of removing the defects on the surface after they have shown significant presence in the rail [Sroba, 2004]. The operation usually involves multiple passes of a large production grinder.

Typically, the grinding machine consists of a series of vehicles equipped with grinding wheels. As it moves along the track, the equipment performs a grinding operation on the rail surface while it re-profiles the rail [Cope, 1993]. When it is used for grinding operation, several grinding units are blocked in one angle plane while performing the re-profiling operation; the grinding wheels are set at different angles so that a polygonal profile is achieved.

Figure 2.9– Rail Grinding machine [Plasser and Theurer, 2013].

An accurate application of the rail grinding will produce several impacts:

- Overall improvement in rail life
- Reduction in rolling contact fatigue
- Reduction in rail wear
- Reduction in corrugation
- Reduction in energy dissipation
- Reduction in noise

5) Rail Lubrication

Rail lubrication is a technique to reduce the friction and wear that occurs between the flange part of the wheel and the gauge side of curved tracks [Alp *et al*., 1996]. Using lubrication, the wear rate can be reduced about 10 to 15 times in the 300-400 meter curve radius and 2 to 5 times in 600 meter curve radius [Jendel, 1999]. Lubrication may also be made by automatic applicators which are installed in the track or mounted on the motive stock. The selection of the application method will depend on the combination of economic factors, the nature of the railway network and the traffic levels.

6) Replacement

Traditionally, replacement simply consists of replacing the worn-out track components by new ones. As technology steps forwards, the estimate of the service life of a track structure or of a particular component can be easily determined. The replacement strategy is then conducted based on the prediction of the economic life span of the track materials. In this section, some replacement methods commonly used in the track maintenance will be briefly described.

- **Rail Replacement**

Prior to rails replacement, new welded rails are transported to the site using a train vehicle. When these arrive, the rails are brought down and placed beside the defected track for installation. A rail exchanger is then used to take out the old rails from ties and insert the new rails to the sequence.

- **Sleeper Replacement**

Exclusive of rail costs, sleeper replacement represents the most significant maintenance cost for the railways. For efficient maintenance of sleepers, Ethiopian railways corporation needs to plan for a specific amount. For efficient inventory management, firstly it is necessary to predict the demand for sleepers at main location. To forecast future sleeper demand, we need to analyze the trends in demand. In general, the demand for sleepers consists of amounts used with two different activities in maintenance, namely: unplanned and planned maintenance. Unplanned maintenance is done when the failed sleepers are replaced after accidents or at irregular detection. Planned maintenance is undertaken on regular schedule times for replacement. Thus, the planned maintenance interval or strategy affects the demand process of sleepers and is an important factor for inventory management of sleepers.

- **Ballast Replacement**

A ballast replacement machine and its technique are quite similar to ballast cleaning. However, when the ballast replacement is carried out, a number of hopper wagons are normally attached in the sequence of the machine as storage and supplier of the new ballast. When the wagon arrives at the excavated site, the bottom of a bucket is then opened and the ballast falls down to the track.

2.1.3 RAILWAY TRACK LINE MAINTENANCE MODELING APPROACH

Track inspection data provide maintenance decision makers with information on the current condition of the track. This data can be used to develop models that predict future track conditions and provide information for planning of maintenance and rehabilitation interventions.

There are two general approaches for track degradation modeling: mechanistic and statistical models. Mechanistic approach use fundamental theories of infrastructure behavior for modeling, while the statistical approach involves the analysis of many observations of actual track performance and corresponding casual parameters. These two approaches and their contributions in track degradation modeling are outlined in this section.

A. *Mechanistic Approach:*

Several attempts have been made to make mechanistic models based on laboratory studies to explain the track degradation process. Three models explaining mechanistic track degradation approach that are widely used in practical applications around the world are surveyed as follows:

- An empirical track settlement model based on Japanese studies (sato, 1995).
- A series of equations predicting settlement rate from ballast pressure based on experiments at the Technical University of Munich (R. Hummitszch, 2005).
- An Austrian model looking at development of track quality from passenger's point of view (R. Hummitszch, 2005).

In early 1960, studies on track deterioration due to ballast settlement when subject to cyclic loading were initiated in Japan (Y. Satoh, 1959; Y. Satoh, 1961). The following equation is used to estimate the track settlement, *y*, due to their model developed from laboratory studies (sato, 1995).

$$y = \gamma(1 - e^{-\alpha x}) + \beta x \quad \text{......(1)}$$

where *x* is the repeated number of loadings or tonnage carried by the track, α is the vertical acceleration required to initiate slip and can be measured using spring loaded plates of the ballast material on a vibrating table, β is a coefficient proportional to the sleeper pressure and peak acceleration experienced by the ballast particles and is affected by the type and condition of the ballast material and the presence of water, and γ is a constant dependent on the initial packing of the ballast material. As equation (1) represents, the most important variables according to Japanese model are traffic, time, track condition, and humidity. This Choice of variables is supported by German model with some changes. German model do not considers humidity; however it regards vehicle characteristics as an important variable. Experiments under well controlled laboratory conditions at the Technical University of Munich representative of vehicles passing a dipped joint have been used to establish equations to calculate rate of settlement, *S.* The ballast pressure is multiplied by the log of the number of axle passes as follows:

$$s = a \times p \times \ln \Delta N + b \times p^{1.21} \times \ln N \quad \text{......(2)}$$

The first term represents the fast settlement just after a maintenance action. ΔN expresses a pre loading period comprising the first passing axles. ΔN should be <10,000 and N in the second part should express the total number of passing axles. P is ballast pressure could be calculated with the Zimmermann method. The parameters *a*, and *b* are constants suggested to be in the value range; 1.57-2.23 and 3.04-15.2 respectively. TU Graz has examined settlement developments in Austria by a quality index, which represents accelerations in the vehicle caused by track irregularities.

This index comprises of both horizontal and vertical deviations in tracks together with a lack of super elevation and speed (R. Hummitszch, 2005). An exponential development of track quality index over time was found giving the following expression for track quality:

$$Q = Q_o \times e^{-b \times t} \quad \text{……..(3)}$$

Where Q is the track quality index and Q_0 is the initial track quality. The Austrian exponential model says that the rougher the track becomes the more dynamic forces are created when trains pass, which increases the settlement. Although mechanistic approach provides a good engineering understanding of how track responds to vehicle loading, it relies on mechanical properties of track parameters which are difficult to quantify and is very different from place to place. The result is that when mechanistic models are used to predict track degradation, considerable predictive errors are expected. On the other hand, the statistical approach involves the analysis of many observations of actual track condition and the corresponding causal parameters. When actual observations are used for modeling, more realistic prediction of track condition is expected to be given comparing to the mechanistic approach. Thus when a large amount of recorded data is available, it is preferred to use statistical approach for track degradation modeling.

B. Statistical Approach

Aim of statistical based degradation models is to find a general pattern for the statistical distribution of the track geometry using inspected data of track condition. Primary investigations to understand the fundamentals of deterioration mechanism of railroad track were carried out by the Office for Research and Experiments (ORE) of the International Union of Railways (UIC2) in the 1980s (C. Esveld, 2001).The ORE examined data available from a number of administrations and proposed a model that divided into two parts: the first part describes the deterioration directly after tamping,e_0, and the second part describes the deterioration depending on traffic volume T, dynamic axle load 2Q and speed v. The relationship reads:

$$e = e_o + h\,T^{\alpha}(2Q)^{\beta}v^{\gamma} \quad \text{……..(4)}$$

Where h is a constant and the parameters α, β, and γ have to be estimated from experimental data. The ORE model has been analyzed on the data obtained from American and Indian Railways by (J. Corbin, 1975) and (P. Subramanian, 1978), respectively. Zwanenburg conducted statistical analyses on the Swiss Federal Railways network to retrieve the lifetime expectancy of complete railway switch and crossing system and their respective components (W.-J. Zwanenburg, 2009). He conducted single parameters analyses and multi parameters analysis on switch and crossing life expectancy.

From the single parameters analysis, it can be concluded that 4 parameters including; soil quality, switch angle, percentage of freight trains and speed have an effect on the life time distribution of standard turnouts. For multi parameter analysis, it could be derived that the percentage of freight trains and the frog angle have some significant effects. Model results are presented in (F. Peng, 2012).

$y = s + \alpha\, x_1 + \beta\, x_2 + \gamma\, x_3 + \delta\, x_4$……………………………………………………………………..(5)

Where y is life time expectancy of switch and crossing x_1 is percentage of freight trains, x_2 is frog angle, x_3 is a variable related to soil quality of sub grade and x_4 is speed. More recently, several approaches have been proposed to capture the nonlinear characteristics of track quality deterioration (J. Sadeghi, 2010)

2.1.3.1 STOCHASTIC TRACK DEGRADATION APPROACH

It would be helpful to look at the rail track from the stochastic point of view. The track is considered to be reliable when it performs its intended function under operating conditions for a specific period of time. When this is not the case, the track fails. The probability that the track will fail in a small time interval, is called the hazard rate. The concept of the hazard rate is involved in many methods and approaches to maintenance analysis (R. Mishalani, 2002). The hazard rate function can have several behaviors. As far as railroad is concerned, the most likely character is the so-called bathtub curve, as shown in Fig. 11.

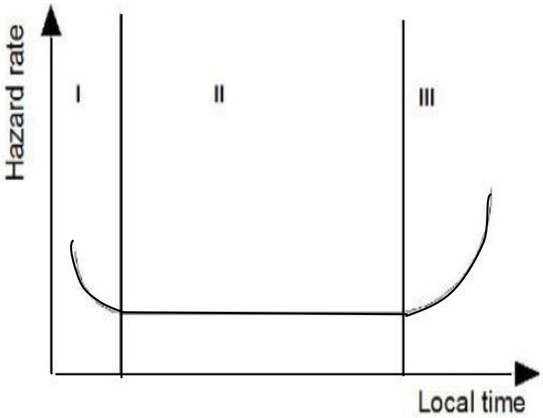


Figure 2.10. Bathtub curve with a local time-dependent hazard rate (R. Ahmad, 2012).

During the early life of an item (I), there are early failures caused by initial weakness or defects in material, poor quality control, inadequate manufacturing methods, human error, initial settlement, etc.

Early failures show up early in the life of an item and are characterized by a high failure rate in the beginning, which keeps decreasing as time elapses. During the second part of the bathtub curve (II), the hazard rate is approximately constant. This period of life is known as the useful life during which only random failures occur. After the useful life the wear out period starts (III), when the failure rate increases. The causes for these wear-out failures include wear due to aging, fatigue cracking, corrosion and creep, poor maintenance, wear due to friction, and incorrect overhaul practices. In the degradation models, a limit called critical failure progression is defined. This is a limit saying that degradation passing this limit is assumed to be critical. However, in real life there often exists more than just one level. The failure progress can be specified in various ways. The most common used model for the failure progression is the **Gamma process** which is a continuous time stochastic processes. For further info on systems with gamma deterioration process refer to (C. Meier-Hirmer, *et al*., 2009). A limitation of these processes is that the degradation is assumed to be linear with time. This is some time problematic when, for example rail cracks are modeled, since the failure progression is believed to go faster and faster as the crack size increases. An alternative approach is to base the analysis on Markov models. By using Markov models a wide range of dependencies can be taken into account. Shafahi(Y. Shafahi, 2009) developed a Markov model where the track quality index is calculated in a range of 0-100 based on the track unevenness, twist, alignment and gauge measurements. The 100 unit range was then mapped onto 5 states in the Markov model. Transition probabilities for the transition matrix were then established from changes in the track quality index over time. An alternative 50-state Markov model is proposed by Lyngby (N. Lyngby, 2008) to represent the variation of twist over time. In this treatment each of the states represents the twist on a section of track up to 50mm. Alternative deterioration rates were given for the model depending on whether the track section was straight, curved or a transition section. The model also was used to optimize the frequency between track geometry inspections. Prescott (D. Prescott and J. Andrews, 2013) proposed a model that considers the degradation, inspection and maintenance of a single one eighth of a mile section of UK railway track. A Markov model of such a section is produced. Track degradation data from the UK rail network has been analyzed to produce degradation distributions which are used to define transition rates within the Markov model. The model considers the changing deterioration rate of the track section following maintenance and is used to analyze the effects of changing the level of track geometry degradation at which maintenance is requested for the section. Reliability, Availability, Maintainability and Safety (RAMS) approaches to rail failure modeling are also used by Podofillini et al (L. Podofillini, 2006).

2.1.4. RAILWAY TRACK MAINTENANCE/DEGRADATION MODEL

Victorian public transport corporation defines three limits for track condition to ensure the safe operation of Light rail service (PTC, 1997). A maintenance limit (D) indicates further investigation, an action limit (C) says that maintenance is required, and finally safety limit (F) says operational restriction is required. The first degraded state, denoted "D", is for minor degraded failures. When a "C" fault is found in track a speed restriction will be imposed, the inspections are made more frequently and maintenance intervention is desirable but not mandatory. When a "C" fault is found in a track section, in addition to speed restriction prompt maintenance intervention is required. Finally when an "F" fault is found, that section of track is considered condemned. The critical failure due to degradation can be avoided by preventive maintenance if they are found in inspection intervals. In order to model the maintenance of the degradation failures, the degradation states will be split, according to whether these states are inspected or not.

2.1.4.1 RELIABILITY MODELS

The exponential and Weibull reliability models are generally the most common models used for the reliability analysis of Railway systems. The main assumption in the exponential model is that the times between failures are exponentially distributed or, expressed simply the failure (hazard rate) is independent of time.

The Weibull reliability model is a most versatile model for characterizing the life of railway systems. The failure density function of the two-parameter Weibull distribution is defined as:

$$f(x) = \frac{\beta * t^{\beta-1}}{\eta^{\beta}} exp[-r(\frac{\mathrm{t}}{\beta})^{\beta}] \ldots\ldots\ldots\ldots(6)$$

The parameter η is the *"characteristic life"* parameter. It has the same units as ***t*** and the parameter β is a *"shape"* parameter and is a non-dimensional quantity. The great versatility of the Weibull distribution stems from the possibility of adjusting it to fit the many cases where the hazard rate either increases or decreases, because this distribution has no fixed characteristic shape.

β =1 represents the constant failure rate and the reliability model is converted to:

$$R(t) = \exp(-\lambda \mathrm{t}) , \mathrm{t} \geq 0$$

With the failure rate: $\lambda(\mathrm{t}) = \frac{1}{\eta} = \frac{1}{MTBF}$

This model represents the exponential reliability model. In the model *R(t)* is the reliability of the system, $\lambda(t)$ is the constant failure rate *=1/MTTF*, and ***t*** is the period of operation. The exponential distribution is the most widely used and well-established statistical distribution, and it explains the general failure distribution of a system during its normal operating life period, when the failure occurs at random. The most important factor for the applicability of this model is that the hazard rate must be constant and the age should have no effect on the failure rate of the system.

2.1.4.2 PREDICTING THE NUMBER OF FAILURES

The expected number of failures from time 0 to t is calculated by:

$$E(N(t)) = \int_0^t \lambda(t)dt = \lambda t^{\beta} \quad \text{.....(7)}$$

Therefore, the expected number of failures from time t_1 to t_2 is:

$$E(N(t)) = \int_{t1}^{t2} \lambda(t)dt = \lambda {t_2}^{\beta} - \lambda {t_1}^{\beta}$$

Where $\Delta t = t_2 - t_1$.

And the reliability function is given by:

$$R(t) = \int_t^{\infty} f(x)dx = \exp[-(\frac{t}{\eta})^{\beta}] \quad \text{.....(8)}$$

$$\lambda(t) = (\frac{\beta}{\eta})(\frac{t}{\eta})^{\beta-1}$$

Where: $t>0$, $\beta>0$, $\eta>0$

CHAPTER 3

3.1 MAINTENANCE/DEGRADATION MODEL FOR THE AALRT TRACK

Determining maintenance model during a planning horizon as well as maintenance strategy, while satisfying certain constraints in Ethiopian railway system, is the objective of this study. To reach this objective, a Markov model for track deterioration is chosen and applied to Addis Ababa Light Rail Transit. Using the probabilistic data approach the following calculations are done for AALRT track.

3.1.1 Expected number of failure for AALRT Railway Track

Weibull analysis is the most versatile model to forecast the reliability parameters which help as to calculate the expected number of failure during the design period. Steps to forecast reliability parameter for AALRT is as shown below:

Step-1. Assume six expected number of failure randomly; 25,50,75,100,125,150

Step-2. Rank the number of failure in ascending order and assign failure order number starting form 1,2,…..6

Number of failure	Failure Order
25	1
50	2
75	3
100	4
125	5
150	6

Table 3.1 Failure order

Step-3. Obtain Median rank, MR=(i-0.3)/(N+0.4)

Number of failure	Median rank
25	0.1093
50	0.265
75	0.421
100	0.578
125	0.734
150	0.890

Table 3.2

Step-4. Using rank regression on 'X'

X= a + bY; where a = $\frac{\sum_{i=1}^{N} Xi}{N} - b\,\frac{\sum_{i=1}^{N} Yi}{N}$

$$b = \frac{\sum_{i=1}^{N} XiYi - \sum_{i=1}^{N} Xi \sum_{i=1}^{N} Yi}{\sum_{i=1}^{N} Yi.Yi - (\sum_{i=1}^{N} Yi)(\sum_{i=1}^{N} Yi)/N}$$

yi = ln{-ln(1- F(ti))}

xi = ln(ti)

weibull shape parameter, $\beta = {}^{1}/_{b}$

weibull scale parameter, $\eta = e^{{}^{a}/_{b}(\frac{1}{ß})}$

Thus by using those formula and excel tamp let iterate until suitable value of 'β' and 'η' are obtained.(Refer Excel tamp let in appendix)

The Facts For A Weibull Plot		
i-values	Expected failure	median rank
1	25	0.109375
2	50	0.265625
3	75	0.421875
4	100	0.578125
5	125	0.734375
6	150	0.890625

Data To Use For Excel Regression	
Yi-value	Xi- Value
-2.15561601	3.218876
-1.17527042	3.912023
-0.60154355	4.317488
-0.14728704	4.60517
0.2819178	4.828314
0.79433683	5.010635

Excel Regression out put

β=	**1.610**
η=	**102.148**

Table 3.3 Weibull Analysis using Excel tamplet

Step-5. Calculate weibull failure rate

Weibull failure rate, $\lambda(t) = (\frac{\beta}{\eta})\,(\frac{t}{\eta})^{\beta-1}$ …………… substituting value from step-4

$$\lambda(t) = (\frac{1.61}{102.15})\,(\frac{100}{102.15})^{1.61-1}$$

$$\lambda(t) = 0.0155$$

Step-6. Expected number of failure, $\mathrm{E}\big(\mathrm{N}(\Delta t)\big)$

$$\mathrm{E}\big(\mathrm{N}(\Delta t)\big) = \int_{t1}^{t2} \lambda(t)dt = \lambda {t_2}^{\beta} - \lambda {t_1}^{\beta} \;\; ; \quad \text{Where } t_2 = 100, t_1 = 0$$

$$\mathrm{E}\big(\mathrm{N}(\Delta t)\big) = \lambda {t_2}^{\beta} = .0155 * 100^{1.61}$$

$$\mathrm{E}\big(\mathrm{N}(\Delta t)\big) = 26$$

Step-7. Distribute expected number of failure to degrade failure and critical using reliability function

Reliability, $R(t) = \int_{t}^{\infty} f(x)dx = \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right]$

$$= \exp\left[-\left(\frac{100}{102.15}\right)^{1.61}\right]$$

=0.38=38%

Thus, Number of degraded failure, N_d = 0.38*26= 10

Number of Critical failure, N_c = (1-0.38)*26= 16

3.1.2 THE FAILURE AND MAINTENANCE MODEL

Failure records in reliability data bases are often classified into severity classes, e.g., *critical and degraded*. Here *critical* will mean loss of a major function, and *degraded* means that some degradation has started for some part of the AALRT railway track component, but that the component is still capable of Performing its function(s).

If a component has a degraded failure it often follows that a critical failure is more likely to occur, and that some repair should be carried out. So when a degraded failure is repaired this may act as a Preventive Maintenance (PM) with respect to the corresponding critical failure mode, i.e., with respect to the *function of the component.* Further, by such a repair a *censoring* occurs with respect to this critical failure, and this is a *dependent* censoring, as these censoring occurs close in time to the critical failure that would occur if no repair was carried out.

The existence of any dependence between the occurrence of degraded and critical failures should, however, affect the estimates of these rates of occurrence of failure. The *standard* estimate for a specific failure category (i.e., failure mode and severity class) equals the total number of observed failures of that category, divided by the total operational time ('exposure time'). This means that the standard approach does not account for a possible dependence between various failure types. Further, the standard approach makes no efforts to model the effect of the *maintenance* on the observed failure rates, and it becomes problematic to directly combine data from various installations in a proper way.

The degraded failure is seen as a 'warning' that a critical failure will soon occur unless a repair is carried out. Thus, the repair of a degraded failure could act as a censoring of a critical failure, and then the frequency of degraded failures (and the strategy for repairing these) will affect the rate of critical failures. Further, the so-called *naked* failure rate is here introduced, defined as the rate of critical failures that would be observed if *no* repair was carried out by detection of degraded failures. A major advantage of investigating this naked failure rate is that this provides a characterization of the railway track component being more *independent* of the preventive maintenance performed.

In the present paper the standard estimates for the rates of *degraded* and *critical* failures are reviewed taking into account that there is dependence between the degraded and critical failures. This dependence is here explicitly modeled by specifying a failure *mechanism*, using a Markov process approach where the states correspond to the degree of degradation.

The Maximum Likelihood Estimates (MLE) for relevant failure intensities is found and the Meantime Between Failure *(MTBF)* is derived. As usual the *MTBF* is defined as the Mean Time To Failure *(MTTF)* plus the mean down time following a failure. For a railway track components the down time essentially equals the time elapsing from the occurrence of failure until detection of the failure in a test, i.e., Mean Time To Detect *(MTTD).* The mean repair time *(MTTR)* is usually very small compared to this *MTTD* and can be ignored. Thus, letting *MTTR* = 0, the *MTBF* is here formally defined as the mean time from the component being repaired until the next time a failure is *detected* in test, i.e., *MTBF = MTTF + MTTD.* The relation to the *inherent* rate of occurrence of failures (i.e., the *naked* failure rate) is also pointed out.

3.1.2.1 SEVERITY CLASSES AND FAILURE MECHANISMS

In the modeling of the present paper a component has four states:

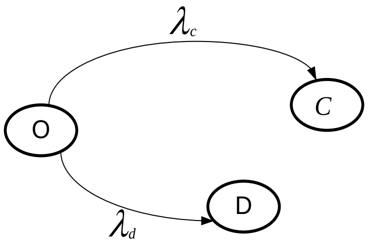
O = The component is O.K. (good as new)
D = The component has a failure classified as *degraded*
C = The component has a failure classified as *critical*
F= The section of track is considered condemned.

Here *degraded* and *critical* are names of *severity* classes, and in a *standard* analysis these failure categories are treated as being completely independent.

Note that the objective of the periodic testing/inspection is two-fold. First critical failures of the railway track component shall be detected and repaired, so that the components main function is regained. This may be considered as a corrective maintenance, even if this is part of the PM programmed and no system failure has occurred. Secondly, the degraded failures will be detected and repaired, and with respect to the function of the track component this is truly a preventive maintenance task. It is one of the objectives of the present paper to model the effect on the rate of critical failures of performing this preventive maintenance. There are four failure mechanisms to determine rate of critical failure and degraded failure.

a. Standard approach

Figure 1 illustrates typical model assumptions of the *standard* approach for the estimation of the 'failure rate.



Flow chart.3.1. 'Standard' model.

A new component starts in state O, and there is a constant rate λ_d for entering D, and a constant rate λ_c for entering C, respectively. After a transition to either D or C has occurred, the component is Immediately repaired and placed back in state O. Following some components in a total time T, we observe a number of Time To Failures *(TTF)* that are independent and exponentially distributed with Parameters $\lambda_d + \lambda_c$. If there are observed N_d degraded and N_c critical failures in this operational time, and the failures are detected immediately, this standard analysis results in the following estimators:

$$\lambda_c = \frac{N_c}{\mathrm{T}} = \frac{16}{100} = 0.16$$

$$\lambda_d = \frac{N_d}{\mathrm{T}} = \frac{10}{100} = 0.10 \quad (6)$$

In particular, one set of assumptions that makes these the *exact* MLEs are:

1. Critical (C) and degraded (D) failures occur independently of each other, with constant rates λ_c and λ_d, respectively.
2. Components are as good as new after each failure/repair.
3. All failures (even degraded) are detected and repaired *immediately.*

In this model the mean time between two failures (of any category) equals $1/(\lambda_d + \lambda_c) = 0.808$, and in the long run the fraction (relative number) of critical failures equals $\lambda c / [\lambda d + \lambda c]=0.615$. The third assumption above assures that there is no reduction in the 'exposure time', T, either for the critical or for the degraded failures.

Note that one of the consequences of this modeling is that in spite of the fact that D and C failures Represent *competing risks*, they do not in any way affect each other (e.g., the value of λ_d does not in any way affect the occurrence of critical failures, and vice versa). The reason is that it is both assumed that the failure rates are *constant* and that there is an *immediate* repair by failure *(MTTR* = 0). Thus, at *any* time there is a constant rate, λc, of C failure, and a constant rate, λ_d, of D failure, irrespective of occurrences of the other type of failure. So by adopting this model it is implicitly assumed that there is no effect on the components main function (critical failures) by performing repair of degraded failures D. First failure mechanism I *(FMI)* is defined, which essentially equals the standard approach described above, but being modified to explicitly account for the assumption that failures are detected in tests only. Next, other failure mechanisms are defined, which account for the possibility that there is a direct relationship between degraded and critical failures.

b. Failure mechanism I

If failures are not immediately restored, the exposure time (T) in the estimates (6) should be reduced. If the length of the test/inspection period is τ, the exposure time is then *approximately* reduced by τ /2 with each failure, and an *approximate* estimate for λc is

$$\lambda_c \approx \frac{N_c}{T - \frac{1}{2}\,\tau N_c}$$

$$= \frac{16}{1200 - \frac{1}{2}4*16} = 0.0137\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

Flow chart.3.1could still apply, actually implying that each failure mode censors the other (i.e., C cannot occur if the component is in state D and vice versa).

However, in a sensible modeling, the occurrence of C should still be possible after D has occurred, see Flow chart.3.2. Thus, the exposure time of the estimate for λ_d in (6) should be modified to give the following rather *approximate* result.

$$\lambda_d \approx \frac{N_d}{T - \frac{1}{2}\,\tau(N_d + N_c)}$$

$$= \frac{10}{1200 - \frac{1}{2}*4(10+16)} = 0.00871\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(8)$$

In practice, (6) would often be used rather than (7) and (8) for this model, usually giving very similar results. The model denoted *Failure Mechanism I (FMI)* is illustrated in Flow chart.3.2.

This is based on the assumption that all critical failures C occur as shocks, completely independent of whether a D failure is present. Thus, the C and D failures have different causes. In addition to assumptions 1 and 2 for the standard model, it is here assumed that

4. The failures (D and C) are detected at tests only.
5. The occurrence of failure C represents a censoring for D failures, but not vice versa. Thus, note that failures C occur with a constant rate λc, whether or not the component is degraded.
6. The *MTTRs* are assumed to be short and are ignored. Thus, by test the component is immediately brought to state O.

Observe that assumption 3 above does not apply for *FMI* and is replaced by assumption 6. Also note that the failure model *FMI* is introduced here because it represents a formalization of the standard approach, *not* because it is claimed to be a realistic model. The exact MLEs are simple to derive for *FMI.* Let T, be the time until a C failure (exponentially distributed with parameter λc), and let Ta be the time until the occurrence of a D failure (exponentially with parameter λ_d), then we have the following probabilities for *observing a D (C)* failure at a test:

$$p_d = p(T_d < \tau, T_c > \tau)$$

$$= [\,1 - \exp(-\lambda_d)].\exp(-\lambda_c \tau)$$

$$= [\,1 - \exp(-0.00871)].\exp(-0.0137 * 4)$$

$$= 0.06$$

$$p_c = p(T_c < \tau)$$

$$= 1 - \exp(-\lambda_c \tau)$$

$$= 1 - \exp(-0.0137 * 4)$$

$$= 0.053 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (9)$$

Strictly following the Markov diagram of Flow chart.3.2, the *Pc* should be
derived from the following expression

$$p_c = p(T_{1c} < \min(T_d, \tau)) + p(T_d < T_{1c}, T_d + T_{2c} < \tau) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10)$$

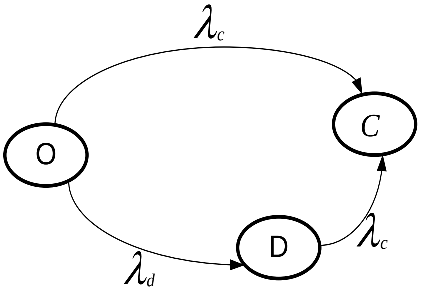
Where T_{1c} and T_{2c} are exponentially distributed with parameter λc, and represent the times until critical failure, starting in states O and D, respectively.

However, it can be shown that this equals the expression in (9), obtained from a more direct argument. In total n tests/inspections are performed, and at least approximately n = T/τ. Then the MLEs for these probabilities are:

$$p_c = \frac{N_c}{n} = \frac{16}{300} = 0.053\,,$$

$$p_d = \frac{N_d}{n} = \frac{10}{300} = 0.033 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (11)$$

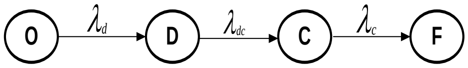
Using (9), the MLEs for λ_c, and λ_d now immediately follows,



Flow chart 3.2 Failure Mechanism I

c. Failure mechanism II

Often a failure mechanism completely different from FMI will apply. The D failures could represent a 'warning' that a C failure is likely to happen unless a preventive maintenance is carried out soon. This is in the present paper modeled as failure mechanism *II (FMII)*, see Fig.3.3. Here the critical failures are the result of a degradation process, and D and C failures have the same root cause. Also in this model there is a constant rate, λ_d of going from O to D. In addition there is a constant rate, λ_{dc}, of going from D to C. If the degraded failure is detected in a test/inspection before a C failure has occurred, the component is brought back to state O without a critical failure occurring. With the rate of λ_c, the track component goes automatically to failure (F) without returned to state O. Also if a critical failure is actually observed it is known that a D failure has occurred during the test period. Assumptions 2, 4 and 6 above still apply for *FMI1*.



Flow chart3.3. Failure Mechanism II.

Quite *approximate* estimates, valid for small and moderate λ's and τ are given by

$$\lambda_d \approx \frac{N_d + N_c}{T} = \frac{10 + 16}{100} = 0.26$$

$$\lambda_{dc} \approx \frac{N_c}{(N_d + N_c).\tau/2} = \frac{16}{(16+10).0.33/2} = 3.73 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(12)}$$

In particular, the estimate for λ_{dc} is based on a very approximate expression for the actual exposure time, but may give a good starting value for the numerical iterations to calculate the exact MLE (see Appendix). The above approximate estimates are presented here also due to their intuitive appeal, thereby enhancing the understanding of the model. In order to observe a C failure it is necessary that the component has first been in state D. Thus, $N_d + N_c$ is the total number of times the component has been in state D, and this is the reason why Nc is included in the λ_d estimate in (6). To motivate the estimate for λ_{dc}, observe that $(N_d + N_c).\tau/2$ is *approximately* equal to the total time that the railway track components have spent in state D. The exact MLEs, given in the Appendix, are based on the following probabilities for finding a component in the *D(C)* state by a test.

$$p_d = p(T_d < \tau, T_d + T_{dc} > \tau)$$

$$p_c = p(T_d + T_{dc} < \tau) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(13)}$$

Here T_d and T_{dc} are exponentially distributed with parameter λ_d and λ_{dc}, respectively.

d. Failure mechanism III

A realistic modeling should allow both the above failure mechanisms (FMI and FMII) to occur. This Leads to *FMIII,* illustrated in Flow chart 3.4. Here, two completely independent failure mechanisms are assumed for critical failures. One of these directly causes a critical failure C^{I} (with rate λ_c), e.g., by a shock, and the other causes a critical failure C^{II} via a degradation process, requiring that the component first enters the state D. Thus, there are two types' of critical failures, having different root cause.

Observe that the state D represents a degradation eventually leading to the critical failure C^{II}. The transition from D to C^{I} in Flow chart 3.4 just indicates the possibility that a shock (i.e., transition to C^{I}) can occur even if the component is degraded. In order to estimate all three parameters, λc, λ_d and λ_{dc} of this model it is required that those C failures that occur 'without warning' at rate λc can be distinguished from those that occur at rate λ_{dc} from state D. For many data sets we are able to do this, at least with a certain degree of accuracy. Let N_C^{I} be the number of C failures that have occurred by failure mechanism I, and N_C^{II} be the number of C failures that have occurred by failure mechanism II.

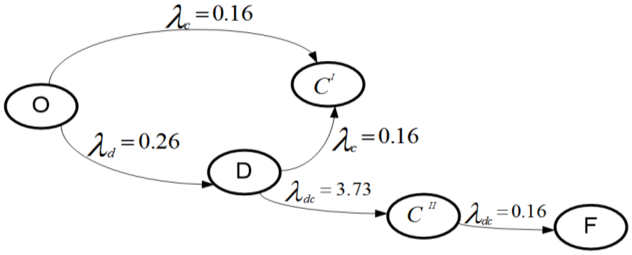
Again a very approximate estimate for λc is obtained from (1) by replacing N_c by N_c^I and approximate estimates for λ_d and λ_{dc} are obtained from (12) by replacing N_c by N_c^{I1}, giving the following starting values for the iterations that provide exact MLEs (see Appendix).

$$\lambda_d \approx \frac{N_c^{II} + N_d}{T} = \frac{16 + 10}{100} = 0.26$$

$$\lambda_{dc} \approx \frac{N_c^{II}}{(N_d + N_c^{II}).\,{}^{\tau}/_{2}} = \frac{16}{(16 + 10).\frac{0.33}{2}} = 3.73$$

$$\lambda_c \approx \frac{N_c^I}{T} = \frac{16}{100} = 0.16 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(14)$$

By inserting N_c^{II}=0 we get the (approximate) results for *FMI*, and by inserting N_c^I = 0 we get the results for *FMII.*



Flow chart 3.4. Complete Failure Mechanism III.

Since FM-III is a combination of FM-I and FM-II it is realistic model. Thus values of rate of failure obtained from FM-III are used for reliability modeling of AALRT track line.

Note: For all the above value of failure rate is for four month inspection interval and it is preferred by comparing critical failure rate, λ_c that obtained for different inspection interval. **See table 3.1**

3.1.3 RELIABILITY PARAMETERS OF THE MODEL

Failure Mechanism III for dormant failures is now investigated further. In particular, parameters like Mean Time To Failure *(MTTF)*, the rate of critical failures and the unavailability are determined for this model.

It is still assumed that the component is repaired to a state as good as new whenever a failure (C or D) is detected in a test. This represents one extreme *PM* strategy. Another extreme is that no repair at all is carried out by detection of degraded failures, and this case will also be treated.

Observe that Mean Time To Failure, *MTTF*, is here defined as the mean time from the component is as *good as new* until a D or C failure occurs. Further, Mean Time To Detect, *MTTD*, is the mean time elapsing from the failure occurrence until the failure is *detected* in test. Further, we let Mean Time Between Failures, *MTBF = MTTF + MTTD.* Observe that the 'failure rates' provided in data handbooks are usually given as the inverse of the *MTBFs.*

3.1.3.1 TIME TO FAILURE DISTRIBUTION AND UNAVAILABILITY

First consider the underlying *TTF* distribution that would be observed if no testing/maintenance were carried out by detection of degraded failures. This distribution for the time to critical failure using *FMIII* is of the well-known phase type (i.e., being a combination of exponentials. As there are two competing failure mechanisms, the time to a critical failure is $X = min\ (T_C\ , T_d + T_{dc})$, and the survival function equals

$R(t) = p(x > t) = R^1(t).R^{11}(t)$ where, $R^1(t) = P(T_c \geq t) = \exp(-\lambda_c.t)$

$$= \exp(-0.16 * 100)$$

$$= 1.18*10^{-7} \quad \text{and}$$

$$R^{11}(t) = P(T_d + T_{dc} > t)$$

$$= \frac{1}{\lambda_{dc}-\lambda_d}\left(\lambda_{dc}e^{-\lambda_d^t} - \lambda_d e^{-\lambda_{dc}^t}\right)$$

$$= \frac{1}{3.73 - 0.26}(3.73 * e^{-0.26} - 0.26e^{-3.73})$$

$$= \mathbf{0.827} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (15)$$

Note that the life time distribution given in (15) could be an attractive alternative to the Weibull distribution. The *MTTF* of this distribution equals

MTTF = $E(x) = \int_0^x R(t)dt = \frac{\lambda_{dc}+\lambda_d+\lambda_c}{(\lambda_d+\lambda_c)(\lambda_{dc}+\lambda_c)} = \frac{3.73+0.26+0.16}{(0.26+0.16)(3.73+0.16)} = \mathbf{2.54\ year}$………………(16)

Further, the availability of the component (with respect to dormant failures) is found from the

well-known formula

$$A = \frac{1}{\tau}\int_0^{\tau} R(t)\, d_t$$

Some calculations then give

$$A = \frac{1}{\tau}\left[\frac{\lambda_{dc}+\lambda_d+\lambda_c}{(\lambda_d+\lambda_c)(\lambda_{dc}+\lambda_c)} - \frac{e^{-\lambda_c\tau}}{\lambda_{dc}-\lambda_d} \times \left(\frac{\lambda_{dc}}{\lambda_d+\lambda_c}e^{-\lambda_d\tau} - \frac{\lambda_d}{\lambda_{dc}+\lambda_c}e^{\lambda_{dc}\tau}\right)\right]$$

$$= \frac{1}{0.33}\left[\frac{3.73+0.16+0.26}{(0.16+0.26)(3.73+0.16)} - \frac{e^{-0.16*0.33}}{3.73-0.26}\right.$$

$$\left.\times\left(\frac{3.73}{0.16+0.26}e^{-0.26*0.33} - \frac{0.26}{3.73+0.16}e^{3.73*0.33}\right)\right]$$

= **0. 988**

Thus, using (16), it is observed that

$$A = \frac{1}{\tau}\left[E(x) - \frac{e^{-\lambda_c\tau}}{\lambda_{dc}-\lambda_d}\left(\frac{\lambda_{dc}}{\lambda_d+\lambda_c}e^{-\lambda_d\tau} - \frac{\lambda_d}{\lambda_{dc}+\lambda_c}e^{-\lambda_{dc}\tau}\right)\right] \ldots\ldots (17)$$

The unavailability, often denoted the Mean Fractional Dead time, is now given as 1- A. We will here use the term Critical Safety Unavailability *(CSU)* for this parameter.

Thus, CSU = 1 – A=1-.988=**0.012**

3.1.3.2 RATE OF CRITICAL FAILURE AND THE NAKED FAILURE RATE

The MTBF is here defined as the mean time to either a critical or to a degraded failure is detected in test/inspection. Observe that this MTBF is identical for the C and D failures. That is, given that it is a C (D) failure that has occurred; this does not affect the MTBF value. Now, to find MTBF, assume that a failure is detected at test number M after the last failure was repaired. Then MTBF=E (M).T, and M has a geometric distribution with the probability p_o of surviving one test interval without failure occurring. This probability equals

$$P_o = e^{-(\lambda_d+\lambda_c)\tau}$$

$$= e^{-(0.16+0.26)*0.33}$$

$$= 0.87 \ldots\ldots (18)$$

For the geometric distribution, *E(M)*= 1/(1-P_o), and

$$MTBF = \frac{\tau}{1 - e^{-(\lambda_d+\lambda_c)\tau}}$$

$$\approx \frac{1}{\lambda_d + \lambda_c} \cdot \frac{1}{\lambda_d + \lambda_c} + \frac{\tau}{2}$$

$$= \frac{1}{0.16 + 0.26} + \frac{0.33}{2}$$

$$= \mathbf{2.55 years} \ldots\ldots (19)$$

The last expression here will, for small/medium λ_d and λ_c, give a very close approximation to *MTBF*. The mean time to departure from state O equals 1/ (λ_d + λ_c) =**2.38years**. Further, τ/2=**0.167years** represents the time elapsed from the time that failure actually occurs until it is detected, i.e., for small λ's, the departure from state O will on the average occur approximately in the middle of a test interval.

If the component -- when leaving state O – enters the degraded state D, it may or may not enter the critical state C before the next test. In both cases the 'life time' ends by the next test, and thus the *MTBF* is *not* affected by λ_{dc}. However, the fraction of critical failures will of course depend also on λ_{dc}. The fraction of failures which are critical then equals.

P_{crit} = p(Critical failure/failure)

$$P_{crit} = \frac{1-e^{-\lambda_c\tau}.R^{II}(\tau)}{1-e^{-(\lambda_d+\lambda_c)\tau}}$$

$$= \frac{1 - e^{-0.16*0.33} * 0.827}{1 - e^{-(0.16+0.26)*0.33}}$$

$$= \mathbf{0.397} \ldots\ldots (20)$$

Where R^{II} (τ) is given in (15). In conclusion, eqn (19) gives the mean time until *any* failure is detected in test/inspection, and (20) gives the fraction of failures being critical. Now, the mean time between two *critical* failures being observed equals

$$MTBF_{crit} = \frac{MTBF}{p_{crit}} = \frac{2.55}{0.397} = \mathbf{6.42 years} \ldots\ldots (21)$$

and the (average) rate of occurrence of critical failures equal

$$\lambda_{crit} = \frac{1}{MTBF_{crit}} = \frac{1}{6.42} = 0.16 \ldots\ldots (22)$$

Next we derive the rate of critical failures that would appear if *no* repair of D failures is performed.

To obtain this naked failure rate, we first find the expression for MTBFcrit which would apply if no repair is carried out when a degraded failure is detected. The time until detection of a failure is a multiple of τ, and this *MTBF* equals

$MTBF_{naked} = \sum_{k=1}^{\infty} k\tau . p\big((k-1)\tau < x < k\tau\big) = \tau \sum_{k=0}^{\infty} R(k\tau))$

Some calculations will give

$$MTBF_{naked} = \frac{\tau}{\lambda_{dc} - \lambda_d} . \left[\frac{\lambda_{dc}}{1 - e^{-(\lambda_c + \lambda_d)\tau}}\right]$$

$$= \frac{0.33}{3.73 - 0.26} * \left[\frac{3.73}{1 - e^{-(0.16+0.26)*0.33}}\right]$$

$$= \mathbf{2.74 Years} \quad \ldots \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(23)$$

Observe that, to a close approximation,

$MTBF_{naked} \approx E(x) + {}^{\tau}\!/_{2} \approx 2.54 + \frac{0.33}{2} = \mathbf{2.71\ years}$……………………………………(24)

Where, *E(X)* is given in (16). The term *τ/2* above accounts for the time elapsing from the occurrence of the critical failure until failure detection (~ *MTTD).*Thus, eqn (27) is a rather obvious relation, since *E(X)* is the mean time to a critical failure occurs.

Now the naked failure rate is given as

$\lambda_{naked} = {}^{1}\!/_{MTBF_{naked}} = {}^{1}\!/_{2.74} = 0.365$ ……………………………………….(25)

giving the rate of critical failures that would be observed if maintenance is only carried out when a critical failure has occurred. Observe that λnaked is slightly dependent on τ (it decreases in τ). The reason is that when τ increases, the time until detection of failures increases, and thus the true exposure time decreases. As a consequence, the actual number of observed critical failures will decrease by increasing τ (when no PM is carried out at tests). This could give an argument for defining λ_{naked} as being equal to *1/E(X)* which is independent of τ. However, it is chosen to define λ_{naked} by (28), as this is the parameter corresponding exactly to λ_{crit}.

However, observe that the relation between λ_{crit} and λ_{naked} is of particular interest, and the *PM-index* is here defined as

$$I_{PM} = 1 - {}^{\lambda_{crit}}/_{\lambda_{naked}} = 1 - {}^{0.16}/_{0.365} = \mathbf{0.56} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(26)$$

Therefore, the frequency of critical failure is reduced by **56%** by carrying out complete repairs by the detection of degraded failures. The value of I_{PM} will very much depend on τ. By shorter τ, there is more PM, and the IPM increases.

Reapeting the same calculations of above by varying inspection interval the following out puts are obtained.

Test interval, τ	$MTBF_{crit}$ (Years)	λ_{crit} (Per year)
1Month	7.71	0.13
4 Months	6.42	0.16
12 Months	8.11	0.12

Table 3.4: Rate of critical failures for different inspection interval

Observe that maximum rate of critical failure occurs when inspection interval is **four moth.**
Thus thus four month inspection interval is governing.

Results for *FMI*

Assuming *FMI* to be the correct failure mechanism,we insert λ_{dc} =0 in the above expressions. The formulas (15)-(17) then reduce to the well-known results for the exponential case. In particular

$$CSU = 1 - A = 1 - \frac{1-e^{-\lambda_c\tau}}{\lambda_c\tau} \approx \frac{\lambda_c\tau}{2} = \frac{0.16*0.33}{2} = 0.026 \ldots\ldots(27)$$

It also follows that

$$\lambda_{crit} = \frac{1-e^{-\lambda_c\tau}}{\tau} = 0.16 = \lambda_c^I \ldots\ldots(28)$$

Further, $\lambda_{naked}=\lambda_{crit}$, and thus, I_{PM}=0. This explicitly shows that the standard model approach is

incapable of modelling the positive effect on the critical failure rate by performing repair of degraded failures before they develop into critical failures.The above expression for λ_{crit} also shows that for *FMI*

$$\lambda_{crit} = A \,.\, \lambda_c = (1 - CSU).\lambda_c = (1 - 0.026) * \ 0.16 = 0.16 \ldots\ldots(29)$$

This is not surprising. Here λ_C is the rate of critical failures for a component, and λ_{crit}, is the actually *observed* rate, which is some what less than λ_c since the component is not exposed to critical failures when it is unavailable, i.e., already failed.

Transition rates for the final AALRT railway track maintenance model are determined as follows:

If there are observed N_d degraded and N_C^I *shoke type failure as well as* N_c^{II} degradation type critical failures in this operational time as well as the operational time of the track is T and inspection period of the track is τ, then the number of tests or inspections throughout the life of the track is:

$$n = \frac{T}{\tau} = \frac{100}{0.33} = 304 \ldots\ldots (30)$$

Finally the repair rate can be calculated as:

$$v = \frac{1}{MTTR} \ldots\ldots (31)$$

Using weibull distribution, mean time to repair (MTTR) is given by the following expression:

$$MTTR = \eta * \Gamma\left(\frac{1}{\beta} + 1\right) = 102.15 * \Gamma(1.62) = \mathbf{5.4years} \ldots\ldots\ldots\ldots\ldots\ldots \quad (32)$$

$$v = \frac{1}{MTTR} = \frac{1}{5.4} = 0.185$$

PM index shows whether or not to maintain a degraded track component or not.The parameters λ_{crit} and λ_{naked} illustrate how the rate of critical failures depends on the amount of PM by tests (i.e., whether or not to maintain a degraded component). They represent two extremes, concerning amount of *PM.* The λ_{crit}, corresponds to *good as new* after a degraded failure is detected, and λnaked corresponds to no maintenance performed after a degraded failure is detected.

The standard model(FMI) λcrit, is essentially independent of the length ofthe test interval, τ. The *FMIII* model, however, givesa λ_{crit}, that increases significantly with increasing τ.

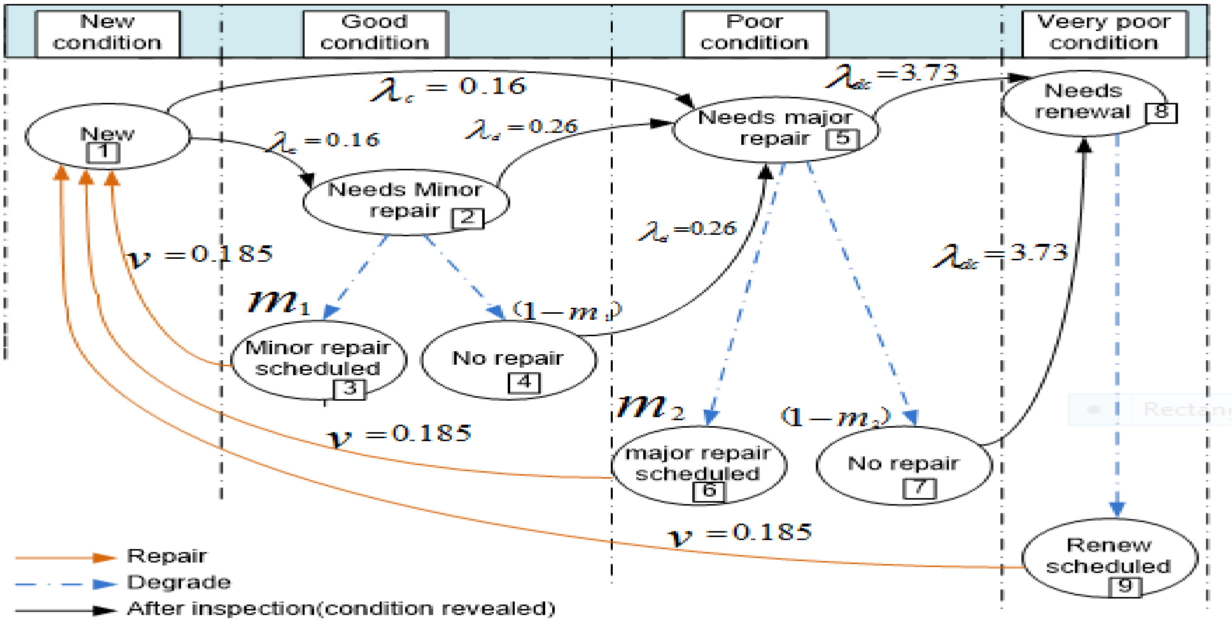


Figure 3.1: Final maintenance model

3.1.3.3 Inspection and Repair Policy

Under normal management, AALRT railway track components are inspected after a certain period of time. At the point of inspection, the current state of the track components is identified. Track components can either reside in a condition that no repair is needed or have reached the condition where a certain type of repair can be carried out. If a change in the state of the element (i.e. the moving of the state from poor to very poor) happens in between two inspections, the failure is unrevealed until the second inspection. Moreover, at this point, a maintenance decision can be made to repair the component or let it continue to deteriorate to a poorer state. Flow chart 3.5 shows **AALRT maintenance model** diagram that was developed to model the deterioration and repair process of an element. The component starts in new condition (State 1) and deteriorates to State 2 where a minor repair can be performed. Following an inspection, if it is revealed that the component is in State 2, the element can either be scheduled for repair (State 3) or left to deteriorate (State 4) which is poorer state. The option to carry out repair is achieved by setting M1=1, this will transfer the probability of a component in the good condition (State 2) to the state where the minor repair is performed (State 3). In contrast, by setting M1=0, the probability of a component in good condition can only be transferred to State 4 (no repair happens) hence the component is left to deteriorate without any repair. A similar process applies when the component deteriorates to a state where a major repair is necessary to return it to the as new condition (State 5), the options for repair or no repair is set by M2 and represented by States 6 and 7. Note that State 8 is when the component is in a very poor condition and cannot deteriorate any further, therefore the only option is to repair (State 9) and M3 should always be 1 since the component should be repaired as soon as it reaches the very poor condition. The effects of the inspection and repair options require the model to be modeled in two phases: the first phase is the continuous phase, modeling the degradation and repair processes, between any two inspections and the second phase is at the point of inspection where the condition of a track element is revealed and the decision of whether to repair or not is made.

There are four maintenance strategies possible in this model and are described in table 3.5.

Strategy Action	**Model parameters**			
Strategy 1	M1= 1	M2= 1	M3= 1	Repair as soon as the component is identified to be in a state where repair is necessary, then it is carried out.
Strategy 2	M1= 0	M2= 1	M3= 1	Repair when the component is identified in the state where a major repair is required i.e. repair when the component reaches poor condition
Strategy 3	M1= 0	M2= 0	M3= 1	Repair when the component is identified as being in the state where renewal is needed i.e. repair when the component reaches very poor condition.
Strategy 4	M1= 0	M2= 0	M3= 0	No repair, component is allowed to deteriorate without any intervention

Table 3.5

CHAPTER-4

4.1 CONCLUSION

The research demonstrate the usefulness of analytic models to optimize Addis Ababa Light Rail Transit (AALRT) railway track maintenance. The major out puts of this research are the following:

Test interval, τ	MTBF$_{crit}$ (Years)	MTBF$_{naked}$ (Years)	λ_{crit}(Per year)		λ_{naked}(Per year)		$I_{PM}= 1-\lambda_{crit}/ \lambda_{naked}$	
			FMI	FMIII	FMI	FMIII	FMI	FMIII
1Month	7.71	2.61	0.16	0.13	0.16	0.38	0	0.66
4 Months	6.42	2.74	0.16	0.16	0.16	0.36	0	0.56
12 Months	8.11	3.14	0.012	0.12	0.012	0.32	0	0.62

Table 4.1: Rate of critical and naked failures for AALRT railway track system:

1. The frequency of critical failure is reduced by **66%,56% and 62%** by conducting one, four and twelve month inspection intervals and carrying out complete repairs by the detection of degraded failures for Addis Ababa Light Rail transit.
2. The **mean time until any failure is detected** by conducting inspection at every four months of interval for AALRT Railway track line (MTBF) is obtained as **2.55 years** .
3. **preventive maintenance** shall be applied based on the maintenance model developed in this research according to the failure rates determined and condition of failure during this years to prevent the occurance of critical failures of a certain AALRT railway track component which couse accidents and high maintenance cost.The maintenance model shows that:

- Effect on the occurrence of critical failures are adress by repairing degraded failures as soon as they are detected.
- The frequency of increased inspections when a degraded failure is detected has less effect on the results.

4. One of the following maintenance strategy shall be applied as discussed before while conducting preventive maintenance for AALRT railway track components.
   - a. Repair as soon as the component is identified to be in a state where repair is necessary.
   - b. Repair when the component is identified in the state where a major repair is required.
   - c. Repair when the component is identified as being in the state where renewal is needed.
   - d. No repair, component is allowed to deteriorate without any intervention.

RECOMMENDATION

The chosen model shall be well adapted to the available information in the future data bases of AALRT railway track. The coupling of C and D failures is modelled in a reasonable and simple way. However, the complexity of the model may eventually be increased as the available information in data bases is detailed.

This research shall be used as a basis for the development of exact AALRT track maintenance model and strategy in the future. Additional research will focus on:

- Determinimg of Inspection Interval
- Taking exact data from data base
- Doing cost- benefit analysis to chose among maintenance startegy

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APPENDIX

MLE of failure intensities

In this Appendix we provide the MLEs for the parameters of the models *FMI-FMIII.* The model *FMI* is obtained by letting $\lambda_{dc}= 0$, and *FMII* by letting $\lambda_c = 0$.

Assumptions

- T_c, T_d and T_{dc} are all independent and exponentially distributed with parameters λ_c, $\lambda_d$and λ_{dc}, respectively.
- All components are repaired to a state *as goodas new* by failure (and thus according to theMarkov model, are also good as new after eachtest).
- Both *MTTR* and test time = 0.
- D failures are censored by the occurrence of C^Ifailures. The C^I and C^{II} failures are not censored by D failures.

2. Failure mechanism I

Here (N_C^I, N_d) have a trinomial distribution withprobabilities

$P_c = P(T_c < \tau) = 1 - e^{-\lambda_c \tau}$

$P_d = P(T_d < \tau, T_c > \tau) = (1 - e^{-\lambda_d \tau})1 - e^{-\lambda_d \tau}$…………………………………………….(33)

and

$P_0 = 1 - p_c - p_d = exp - (\lambda_c + \lambda_d)\tau$……………………………………………………….(34)

is the probabilityof finding the component without failure. Insertingthis in (36) and solving with respect to λ_c and λ_d weget the following MLEs.

$\lambda_c = -\frac{1}{\tau}\ln\left(1 - \frac{N_c^I}{n}\right)$……………………………………………………………………..(35)

$\lambda_d = -\frac{1}{\tau}\ln\left(1 - \frac{N_d}{n-N^I}\right)$ ..……………………………………………………. (36)

Observe that by performing a Taylor expansion ofthe λ_c estimate in (35) we get

$$\lambda_c \approx -\frac{1}{\tau}\left[-\frac{\tau}{T}N_c^I - \frac{1}{2}\left(\frac{\tau}{T}N_c^I\right)^2\right] = \frac{N_c^I}{T}\left(1+\frac{1}{2}\frac{\tau}{T}N_c^I\right) \text{……………………………………………(37)}$$

Since for small x, we have 1/(1 - x) ~ 1 + x, this is essentially equal to (7).

3. Failure mechanism II

Here the survival function for TTF is given by (when$\lambda_{dc} \neq \lambda_d$).

$$R^{II}(t) = P(T_d + T_{dc} > t) \text{…………………………………………………………(38)}$$

$$= \frac{1}{\lambda_{dc}-\lambda_d}\left(\lambda_{dc}e^{-\lambda_d^t} - \lambda_d e^{-\lambda_{dc}^t}\right)$$

and (N_c^{II}, N_d) have a trinomial distribution withprobabilities

$$P_c = P(T_d + T_{dc} < \tau) = 1 - R^{II}(\tau) \text{ ……………………………………………………….(39)}$$

$$P_d = P(T_d < \tau) - P(T_d + T_{dc} < \tau) \text{ ……………………………………………………(40)}$$

$$= \frac{\lambda_d}{\lambda_d-\lambda_{dc}}\left(e^{-\lambda_d^\tau} - e^{-\lambda_{dc}^\tau}\right)$$

Using the well-known MLEs for *Pd* and Pc, and theobvious result

$$P_d + P_c = P(T_d < \tau) = 1 - e^{-\lambda_d^\tau}$$

it follows that

$$\lambda_d = -\frac{1}{\tau}\ln\left(1 - \frac{N_c^{II}+N_d}{n}\right) \text{ …………………………………………………………(41)}$$

Finally, by rearranging (42) or (43), it is seen thatλ_{dc},. is found numerically from

$$e^{-\lambda_{dc}^\tau} = -\frac{N_d}{n\lambda_d}\lambda_{dc} + \left(1 - \frac{N_c^{II}}{n}\right) \text{ …………………………………………………………..(42)}$$

The value of λ_d as found from (44) is first inserted.The relation (45) then has two solutions in λ_{dc}, theestimator λ_d, being one of them. The other solution isthe actual estimate for λ_{dc}.

4. Failure mechanism IIl

Here N_c^{I}, $N_d$and N_c^{II} have a multinomial distribution with probabilities

$$P_c^I = P(T_c < \tau, T_c < T_d) + P(T_c < \tau, T_c > T_d, T_d + T_{dc} > T_c)$$

$$P_d = P(T_c < \tau, T_d < \tau, T_d + T_{dc} > \tau)$$

$$P_c^{II} = P(T_d + T_{dc} < \min(\tau, T_c)) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(43)$$

Note that a degraded failure is observed only if none of the critical failures have occurred. Some calculations will give

$$P_d = e^{-\lambda_c\tau}\frac{\lambda_d}{\lambda_{dc}-\lambda_d}\left[e^{-\lambda_d\tau} - e^{-\lambda_{dc}\tau}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(44)$$

$$P_c^{II} = 1 - \frac{\lambda_{c.}(\lambda_{dc}+\lambda_c+\lambda_d)}{(\lambda_c+\lambda_d).(\lambda_c+\lambda_{dc})} + \frac{\lambda_d\lambda_{dc}}{\lambda_{dc}-\lambda_d} \, . \, e^{-\lambda_c\tau}.\left[\frac{e^{-\lambda_{dc}\tau}}{\lambda_c+\lambda_{dc}} - \frac{e^{-\lambda_d\tau}}{\lambda_c+\lambda_d}\right] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(45)$$

Further,

$$P_c^I = 1 - P_o - P_d - P_c^{II} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(46)$$

Where, $P_o = \exp(-(\lambda_c + \lambda_d)\tau)$is the probability of no failure having occurred in the test interval. Also observe that the second term in the expression for P_c^{II}equals -λ_cE(X).Note that P_c^I alternatively can be found using therelation

$$P_c^I + P_c^{II} = 1 - P(T_c > \tau).P(T_d + T_{dc} > \tau)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(47)$$

$$= 1 - \exp(-\lambda_c\tau)\,.\,R^{II}\tau$$