Railway Track Inspection and Maintenance Scheduling For Addis Ababa Light Rail Transit

Addis Ababa University Institute of Technology
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Railway Track Inspection and Maintenance Scheduling For Addis Ababa Light Rail Transit.

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A thesis submitted to the school of graduate studies, Addis Ababa University,
At Addis Ababa Institute of Technology in partial fulfillment of the requirements for the degree of masters of Science in civil engineering. (Railway)

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CERTIFICATION

I, the undersigned below, certify that I read and hereby recommend for the acceptance by the Addis Ababa University a dissertation entitled: Railway Track Inspection and Maintenance Scheduling for Addis Ababa Light Rail Transit: in partial fulfillment of a degree of Masters of Science in Railway Civil Engineering.

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Thesis Advisor

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A Thesis submitted to the school of graduate studies, Addis Ababa University, At Addis Ababa Institute of Technology in partial fulfillment of the requirements for the degree of masters of Science in Railway civil engineering.

Date defended: ______________________________

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Declaration:

Kidus Matiwos declares that this thesis titled; **Railway Track Inspection and Maintenance Scheduling for Addis Ababa Light Rail Transit**, is my original work. This thesis is my individual work and it has not been presented before for any other institute and I will not present it to any other university for similar or any other degree award.

Signature________________

ABSTRACT

Ethiopia has recently finished constructing the first Light Rail Transit (LRT), in the history of the country. Our new experience demands other pioneer countries' huge experience on LRT track inspection methods, frequency and maintenance tolerance limits. In this study, different track safety standards, maintenance standards and best practices from the railroad industry are surveyed to keep the Addis Ababa LRT track performance satisfactory.

Rail failures generally occur from fatigue cracks that form and grow in the rail steel as a result of cyclic forces caused by the repeated passage of train over the rails which may cause a train to derail. There are many sources that influence Track defects and failure. These effects include bending and shear stresses, wheel/rail contact stresses, thermal stresses, residual stresses and dynamic effects

This study on scheduling inspection of railway track first addresses defects which affect the safe running of the railway. A list of the common defects which may be found whilst inspecting the permanent way are included. After defects are identified, prioritization are made based on their relative perceived urgency. To do that, inspection parameters are discussed with their tolerance limits compared in different railway manuals and standards. Then the unique features of AA LRT are described, such as its track specs, technical and rolling stock parameters. The effect of those unique features on track inspection are also explained. Finally, an optimum frequency of track inspection is provided for the Addis Ababa LRT considering the design and operational parameters of our new light rail and comparing it with other railway standards.

It was found that, different railway agencies has different track maintenance tolerance limits and frequencies of inspection based on factors like track class, track material properties, service defect rate, defect experience and defect growth rate. But in the case of AA LRT, since it is a new railway line, defect experience and defect growth rate are not considered to calculate optimum frequency of inspection. Accordingly, fixed schedule are provided based on the most commonly used standards.

Current track inspection methods, techniques and best practices in the railroad industry are covered in detail, including visual inspections, several automated and remote inspection options, so that the best inspection technology that suits the Addis Ababa LRT can be chosen to maintain a safe railway network. The cheapest and most efficient way is to catch problems before they get too large, and repair them before they cause a derailment. Inspection methods are chosen considering cost, efficiency, and availability with the specific conditions of the Addis Ababa LRT.

KEY WORDS: Railway Inspection, Inspection parameters, Inspection Frequency, Maintenance Priority, Track Defects, Tolerance limits

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ABBREVIATIONS

APTA - American Public Transportation Association

CSA - Canadian Standard Association

CWR - Continuous Welded Rail

DB **-** Deutsche Bahn

FRA - Federal Railroads Administration

FTA - Federal Transit Administration

AREMA - American Railway Engineering and Maintenance-Of-Way Association

IS - Indian Standard

LRT - Light Rail Transit

MBTA **-** Massachusetts Bay Transportation Authority

MOW - Maintenance of Way

NDT **-** Non-Destructive tests

NTSB **-** National Transportation Safety Board

RTS - Rail Transit System

S & C - Switch and Crossing

SCRRA - Southern California Regional Rail Authority

TGMS **-** Track Geometry Measuring Systems

TMS - Track Maintenance Standard

TOC - Train Operating Conditions

TSS - Track Safety Standard

TERMS AND DEFINITIONS

ALIGNMENT is the horizontal location of track as described by curves and tangents.

BALLAST Granular material placed in the track bed to support and restrain the track.

CANT The inward inclination of a rail, and is affected by the use of inclined- surface or tie plates, usually expressed as a rate of inclination, such as 1 in 40 etc.

CORRECTIVE ACTION identifies action to be taken to correct immediate defects and correct the root cause to prevent recurring defects. Corrective action addresses systemic or chronic problems. Corrective action includes procedures for investigating the cause of nonconforming work and procedures for analysis to detect and eliminate potential causes of nonconforming work.

CRITICAL FAILURE is a failure that could result in injury to persons or that prevents an item from performing an essential mission.

CROSS-LEVEL The vertical relationship of the top of one running rail to that of the opposite running rail at any point in the track.

DEFECT is the non-fulfillment of an intended usage requirement or reasonable expectation.

DERAIL is a track safety device designed to cause rolling equipment to leave the rails as a means of protection against collisions or other accidents.

DERAILMENT is the condition of rolling equipment leaving the rails

FEDERAL RAILROAD ADMINISTRATION (FRA) is a government authority under the U. S. Department of Transportation.

FROG is a device used where two running rails intersect, providing flangeways to permit wheels and wheel flanges on either rail to cross the other.

GRADE is the ratio of rise and fall of the grade line to its length.

GRADE CROSSING is a crossing or intersection of a railroad and a highway at the same level or grade.

GUARD RAIL is a rail or other structure laid parallel with the running rails of a track to control a derailed train, or at turnouts to hold wheels in correct alignment to prevent their flanges from striking the points of turnout or crossing frogs or the points of switches

HEADWAY is the time interval between the passing of successive (one-way) trains in a similar direction at a specific point on the rail system (Usually expressed in terms of minutes or seconds).

INSPECTION is the checking or testing for condition, performance, and safety of equipment against established standards.

LIGHT RAIL TRANSIT (LRT) is a light capacity transit mode utilizing predominately semi exclusive right-of-way and electrically propelled rail vehicles capable of multiple unit operation.

MAINTAINABILITY is the ability to retain or restore an item to a specified functional state within a given time period when maintenance is performed in conformance with prescribed procedures and resources.

RESTRAINING RAIL is Rail added to the inside running rail on curves to reduce the possibility of derailments attributed to the leading outside wheel climbing the outside rail and to reduce outside rail wear.

RAIL is a rolled steel shape designed to be laid end-to-end in parallel lines as part of a track.

RAILROAD is a travel way made of track.

RAIL SECTION is the shape of the cross section of a rail at right angles to its length.

RIGHT-OF-WAY (ROW) is the strip of land on which the transit vehicles operate.

ROADBED is the earth bed that supports the ballast, ties and rail of a track structure.

RUNOFF is the term applied to that part of the precipitation which is carried off from the land upon which it falls. And/Also, the transition zone in lifting track, between track which has been raised and track which has not been raised.

SHOULDER is that portion of the ballast between the end of the tie and the toe of the ballast slope.

SPLIT WEB is a longitudinal or diagonal transverse crack in the web of a rail.

STOCK RAIL is a running rail against which the switch rail operates. And/Also the rail against which the point of a switch, derail or movable point frog rests.

SUB BALLAST is a granular material, superior to most sub grade materials, which is spread on the finished sub grade before top ballast is applied, to provide drainage, prevent frost heaving and distributing load over the top of the sub grade.

SUB GRADE is the finished roadbed surface upon which is laid the ballast and the track structure.

SUPERELEVATION is the intended increase in elevation of the outer rail above the inner rail in a curve.

SWITCH is a track structure used to divert rolling stock from one track to another.

SWITCH, FACING POINT is a track switch, the points of which face toward traffic approaching.

SWITCH, POINT is a movable tapered track rail, the point of which is designed to fit against the stock rail

SWITCH, TRACK is a pair of switch points with their fastenings and operating rods providing the means for establishing a route from one track to another.

TANGENT is the Straight portion of railway alignment.

THREAD The top surface of the head of a rail that contacts wheels.

TIE, CROSSTIE is the transverse member of a track structure to which the running rails are fastened, which is centered on the track and designed to cushion, distribute, and transmit the stresses of traffic from the rail to the ballast

TOLERANCE is an allowable variation from dimensions or requirements specified.

TRACK is the rail, ties, rail fastenings, hardware and roadbed between points four feet outside of a parallel pair of rails so configured as to support and allow the movement of rolling stock and other on-track equipment.

TRACK, MAIN LINE is a track designated by route name and direction for the purpose of carrying revenue passengers.

TRAIN is a set of one or more System vehicles coupled together and operated as a single unit.

TRANSVERSE DEFECT For defects found by detector cars, a tentative group classification, applied prior to the breaking of the rails, of all types of rail defect, which have transverse components, such as transverse fissures, compound fissures and detail fractures.

TRANSVERSE FISSURE A progressive crosswise fracture starting from a crystalline center or nucleus inside the head from which it spreads outward as a smooth, light or dark, round or oval surface substantially at a right angle to the length of the rail. The distinguishing features of a transverse fissure from other types of fractures or defects are the crystalline center or nucleus and the nearly smooth surface of the development that surrounds it.

TURNOUT is an arrangement of a switch and frog with closure rails by means of which trains may be diverted from one track to another.

UNIT CONVERSION TABLE

Symbol	Converted From	Multiplier	Converted To	Symbol
in	inches	25.4	millimeters	mm
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
ft	feet	0.305	meters	m
m	meters	1.09	yards	yd
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
km	kilometers	0.621	miles	mi

1 INTRODUCTION

1.1 Background

Effective planning, scheduling and staffing of inspection and maintenance for the railway track, has a great influence upon the service life of the whole track and the safety of the passengers. The components of the track structure are effective for a particular operational life after which they need to be replaced or reconditioned. Generally, it's important to schedule track inspections such that the potential defects are captured as much as possible within minimum times to increase safety to the maximum.

Researches indicate that the track reacts to the forces imposed by passing traffic with damage to, or rail flaws, loosening of fastenings, erosion of the underside of the sleepers, fouling of ballast, inadequate drainage systems or an insufficient ballast bed also reduce the carrying capacity of the track system. All these faults can be eliminated by special planning and scheduling inspection and maintenance. A rail defect that goes undetected and results in a train derailment can cause considerable, additional costs such as excessive service interruption, extensive traffic rerouting, environmental damage, and even potential injury and death.

Ethiopia is currently constructing the first Light Rail Transit (LRT), in the history of the country. Our new experience demands other developed countries' huge experience on LRT track inspection and scheduling maintenance. This study will cover the planning and scheduling of inspection frequencies to keep the LRT track performance satisfactory.

Inspection of permanent way should specifically address defects which affect the safe running of the railway and should be periodical. Track maintenance covers all the measures and re-establishing the normal condition, as well as the measures for determining and assessing the actual condition in a technical system. (Koogan 1992)

Since the components of the track structure are effective for a particular operational life after which they need to be replaced or reconditioned. Scheduling inspection and maintenance operations should always be properly planned and be aimed at keeping high quality of track, at lowering track deterioration rate and, thus, at extending the service life of the track. (Lichtbenger 2002)

Inspection and Maintenance system safety should be the primary focus of all rail transit activities. It is therefore a must that all track inspectors and maintenance staff be fully qualified to fulfill the responsibilities of their positions, by classifying the defect types, their priority and submitting clear inspection data.

1.2 Statement of the Problem

Scheduling inspection and maintenance, and determining the best inspection method is a challenge for all Railway institutions, particularly new agencies with no railway maintenance history. After the completion of the new LRT in Addis Ababa, the next important thing to focus on will be the operation and maintenance part. But, since our country is new for the LRT technology, there is no specific and detailed standard on scheduling inspection and maintenance.

The absence of a detail planning on the frequency of inspection and maintenance will be a huge problem in respect to:

- Shortening the service life of the track
- Increasing track deterioration rate which causes extensive traffic re-routing
- Affecting passenger safety and discomfort
- Incurring high operation cost
- Increasing travel time of Light Rail Vehicles
- Resulting in higher energy consumption.

1.3 Objective of the Study

1.3.1 Main Objective

The main objective of this thesis is to provide appropriate inspection frequency and inspection methods for the Addis Ababa Light Rail Transit by referring other standards and recommended practices of the experienced countries and comparing their compliance with the AA LRT considering track design parameters, track material, and tramcar properties.

1.3.2 Specific Objectives

- Compare other experienced countries maintenance tolerance limits by considering their track material properties and design parameters which are similar with the AA LRT's local parameters.
- Determine the common and possible defects which may be found whilst inspecting the permanent way,
- Compare the current track inspection methods and technologies, and then recommend the best inspection technology that suits the Addis Ababa LRT.
- Considering the materials used and design parameters on Addis Ababa LRT and the experience of other countries, provide adequate track inspection frequency.

2 LITERATURE REVIEW

2.1 Introduction

2.1.1 History of Track Inspection

Track inspection was originally done by track inspectors walking the railroad and visually inspecting every section of track. This was hazardous as it had to be done while trains were running. It was also manpower intensive, and inspectors were limited in the amount of track they could inspect on a given day. Manual instruments had to be used to measure various parameters of the track.

Visual inspections will only detect external defects and sometimes the subtle signs of large internal problems. Many sources cite that the need for a better inspection method became a high priority because of a derailment at Manchester, NY in 1911, in which 29 people were killed and 60 seriously injured. In the U.S. Bureau of Safety's (now the National Transportation Safety Board) investigation of the accident, a broken rail was determined to be the cause of the derailment. The bureau established that the rail failure was caused by a defect that was entirely internal and probably could not have been detected by visual means. The defect was called a transverse fissure. The railroads began investigating the prevalence of this defect and found transverse fissures were widespread. (NDT Resource Center 2014)

With increased rail traffic at higher speeds and with heavier axle loads today, critical crack sizes are shrinking and rail inspection is becoming more vitally important.

In 1927, Dr. Elmer Sperry built a massive rail inspection car under contract with the American Railway Association. Magnetic induction was the method used on the first rail inspection cars. This was done by passing large amounts of magnetic field through the rail and detecting flux leakage with search coils. Since then, many other inspection cars have traversed the rails in search of flaws. (NDT Resource Center 2014)

Railroads have always inspected track visually to detect rail failures, and have been using crack-detection devices in rail-test vehicles since the 1930s. Meanwhile, the railroad industry has trended towards increased traffic density and average axle loads. Current rail integrity research recognizes and addresses the need to review and update rail inspection strategies and preventive measures. This includes the frequency interval of rail inspection, remedial action for identified rail defects, and improvements to the performance of the detection process. (Federal Railroad Administration 2014)

2.1.2 Why periodic inspection and maintenance?

Rail inspection is the practice of examining rail tracks for flaws that could lead to catastrophic failures. According to the United States Federal Office of Safety Analysis, track defects are the second leading cause of accidents on railways in the United States. 9,764 of the 30,195 train accidents in the United States from January 2000 to January 2010 occurred due to defects in the tracks. Track defects were responsible for causing 32% of the 3,185 railroad incidents in the United States during 2007 alone. With these figures becoming increasingly alarming, it is of prime importance to efficiently inspect the tracks on a regular basis and prevent untimely accidents that may result in injuries or death. (Shah 2010)

One of the major problems that railroads have faced since the earliest days is the prevention of service failures in track. As is the case with all modes of transit, failures of an essential component can have serious consequences. With increased traffic at higher speed, and with heavier axle loads, rail track inspection and periodic maintenance is more important today than it has ever been.

Periodic Track inspection and maintenance protects the track and eliminates costly emergency track repairs with ongoing railroad track inspections and a scheduled track maintenance program. Taking a preventive approach saves money in the long run, eliminates safety risks and minimizes the chance of early track deterioration. It also helps to forecast the amount of budget needed for track maintenance expenses.

By increasing the reliability of rail flaw detection, through improvements and technology enhancements, a reduction in inspection costs and derailments can be achieved. The resulting annual savings has been estimated to be approximately $40 million (U.S) in United States alone.

According to Track Guy Consultants, Railroad Safety has improved significantly over the last 25 years due to the improvement of rail track inspection and maintenance. There has been a 62% drop in Train Accidents and Employee Injury Rate has decreased 77%. (Zuspan 2015)

It is recommended that a comprehensive track inspection should be performed by a qualified track inspector on a scheduled basis to meet the operating requirements. A thorough track inspection involves walking the entire track, or using automated inspection vehicles to visually observe and evaluate the subgrade, rail, ties, ballast, switches and turnouts. If a track deficiency is identified, the inspector will immediately notify facility management so that appropriate action can be taken. Within a few days of the inspection, the assigned inspector will present a detailed report featuring an overall track evaluation and an assessment of each track facility.

2.2 Current Track Inspection Practices and Technologies

The railroad industry currently uses a number of procedures and practices to maintain a safe rail network. Some of these procedures, including visual inspections and several automated inspection techniques, are required by the railroad agencies for different classes of track. However, other automated systems exist besides those addressed below, which are used voluntarily by many railroads. The following sections outline various practices and procedures, both manual and automated that are currently used by the railroad industry.

2.2.1 Visual Inspections

The railroad industry currently conducts regularly scheduled visual inspections. Visual inspection is a common method of quality control, data acquisition, and data analysis. Visual inspection, used in maintenance of tracks, means inspection of geometry and structures using raw human senses and/or any non-specialized inspection equipment. These visual inspections are either conducted on foot or in a hi-rail vehicle. An inspection may be conducted by a single inspector or multiple inspectors. For example, if multiple tracks are being inspected from a hi-rail vehicle, two inspectors may conduct the inspection together; therefore, each can focus his or her attention on a single track.

Visual inspections are labor intensive and lack the ability to easily record and compare data needed for trend analysis. Moreover, they are subject to variability and subjectivity in different inspectors' abilities and interpretation of what they observe. Also, it is impractical to manually catalog the condition of such a large number of track components, thus it is difficult to develop a quantitative understanding of exactly how the noncritical or symptomatic defects may contribute to the occurrence of critical defects or other track problems.

Inspectors are expected to look for all track defects. Some of the defects that they find, such as broken ties, may be readily apparent even to a track inspection beginner. On the other hand, other track defects are more subtle and require alertness and proper training in order to be detected. For example, loose bolts on joint bars normally cannot be seen from a hi-rail vehicle; however, an experienced inspector can often detect a loose joint from the sound that is generated as the hi-rail vehicle traverses the joint.

Detecting an ineffective fastener system or rail seat abrasion (RSA) is another example of a defective track condition that requires a track inspector with specialized skills. Oftentimes, directly seeing such a condition from a hi-rail vehicle can be difficult or impossible, but the ineffective fastener or RSA can sometimes be detected through other indirect, visual signs. When a loaded rail car traverses such a defect, there may be a tendency for the rail to roll slightly, resulting in a shift of the tread line on the rail. A trained inspector will be able to notice such a shift in the tread line on the rail and, after ground verification, will be able to attribute it to the proper defective condition.

Other example of visual inspection is gauge measurement and track surface deviation. Standard gauge is 56 ½ inches (1435mm), which is measured 5/8 of an inch under the top of the rail. There are three types of track surface conditions we should watch for; crosslevel, profile, and warp. The tool we use to make these measurements is called a track level. The following pictures show manual measurement of gauge and track surface deviations.

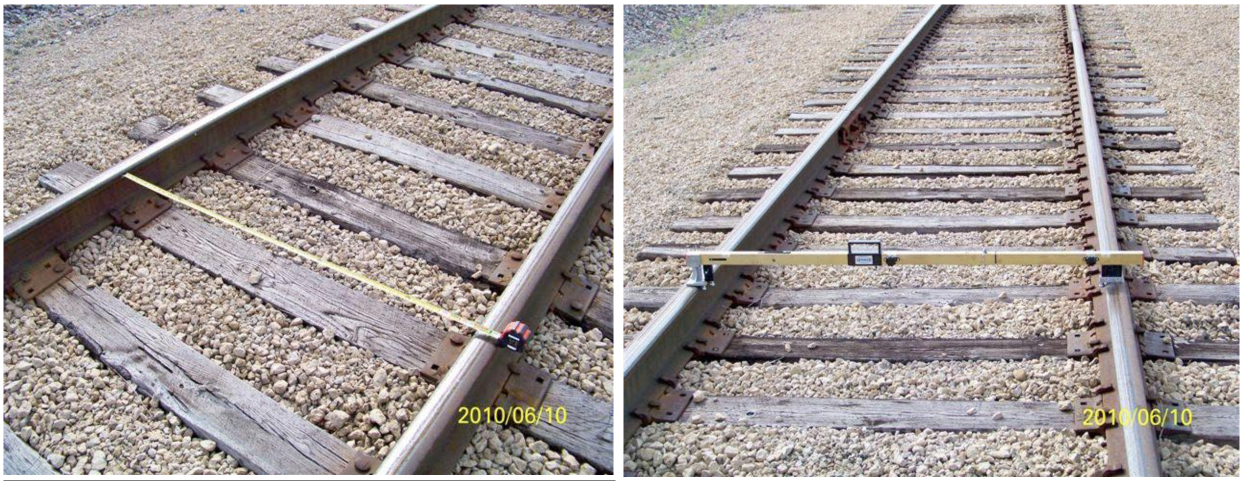


Figure 2-1 Measuring gauge with a standard tape and gauge measurer (CN 2014)

Figure 2-2 Measuring track surface deviation with a Track Level (CN 2014)

2.2.2 Automated Inspection Systems

In addition to visual inspections, the railroad industry uses a variety of automated inspection and monitoring systems. Over the past couple of decades, three primary inspection systems have emerged and been adopted by the industry: internal rail inspection, track geometry inspection, and gage restraint measurement systems (GRMS).

2.2.2.1 Internal Rail Inspection systems

The purpose of internal rail inspection is to detect rail flaws which develop inside the rail. Such flaws are not detectable from a visual inspection of the rail surface. Internal flaws develop for various reasons, and they often initiate at high-stress areas, such as the rolling contact interface between the wheel and rail. As the rail experiences repeated cyclical loading, these small initiation cracks grow in size and will eventually result in a complete rail break (also known as a service failure) if not detected and removed from the track.

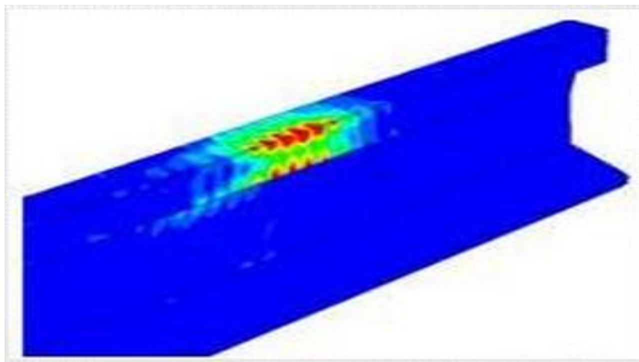
Undetected internal flaws pose a serious risk to the railroad. An undetected defect can result in rail failure causing disruption of service and the potential risk of catastrophic consequences such as derailment. In fact, in 2008, there were 9,759 rail breaks on U.S. Class I railroads with 132 of the incidents resulting in train derailments (FRA 2010). The following are some of the common internal rail inspection methods with their advantages and drawbacks.

Ultrasonic Rail Flaw Testing

Ultrasonic testing is the most widely used method of rail-flaw detection in the United States. It is currently the most efficient and effective technology to detect internal defects. Ultrasonic systems produce ultrasonic waves that are transmitted into the specific medium being tested, which in this application is the rail. Discontinuities in the material alter the wave paths and a transducer is used to detect these reflected waves to find flaws or boundaries in the material. Current technology requires physical contact between the ultrasonic wave source and the material being inspected; however, recent developments include using lasers to produce ultrasonic waves and air-coupled transducers to allow non-contact inspection (Sawadisavi 2010)

Ultrasonic testing has a number of advantages because of its deeper scanning depth than other current non-destructive testing (NDT) methods and accuracy in determining the position, size, and shape of defects. Disadvantages include the need for significant skill and training to analyze the results and great difficulty associated with inspecting non-homogeneous materials. Defects beneath another defect closer to the surface may be difficult to detect, because the waves are reflected by the closer defect, thereby obscuring the ones below. In addition, defects oriented parallel to the path of the waves are difficult to detect. Multiple wave generators have been used to partially overcome these limitations. In terms of rail inspection, ultrasonic testing is used primarily to find internal rail-flaws, including, but not limited to: split heads, head and web separations, bolt -hole breaks, detail fractures, transverse fissures, and transverse compound fissures. (Sawadisavi 2010)

Evaluation of U.S. Rail road records of detected rail flaws and rail service failures suggest that certain types of flaws are more difficult to find by conventional contact ultrasonic rail inspection methods. These include transverse defects under damaged rail surface conditions such as shells, spalling, flaking, base cracks, corrugation, engine driver burns, thermite weld flaws and head checking. Other conditions that are encountered that may influence test results are heavy lubrication or debris on the rail head. Many products have been developed to perform ultrasonic testing, ranging from hand-held testers to self-propelled automated cars.



Problems in track surface show up as variance in color

Figure 2-3 Ultrasonic Inspection showing defects (Zuspan 2015)

Eddy Current

Eddy current inspection is also used for rail-flaw defect detection. Eddy current uses the principle of electromagnetic induction, where an alternating current is passed through one conductor, generating a magnetic field that induces an electric current (the eddy current) in the second conductor. Flaws in the second conductor change the magnetic field produced by the eddy current, enabling detection of defects. Among the advantages of this approach are the ability to inspect without contact, sensitivity to small cracks and other defects, and equipment portability. Disadvantages include a limited inspection depth that only allows detection of surface or near-surface defects and the inability to inspect non-conductive materials or detect flaws that are parallel to the probe coil winding and probe scan direction (NDT Resource Center, n.d.a). It is used for finding surface defects in the rail head, rail base, rail welds, bolt holes, and the side of the rail (Sawadisavi 2010).

Radiography

Radiography is used to detect defects in certain sections of the rail, such as bolt holes or thermite welds. The radiographic procedure creates images of the rail section using x-rays or gamma rays, which have a much shorter wavelength than visible light. These shorter wavelengths allow inspection through thick materials with complex geometry while still maintaining a high level of sensitivity. The advantage of this method is that it can penetrate completely through the rail to provide an image of the internal structure. Unfortunately, radiographic techniques require either a powerful electrical generator to produce x-rays or a radioactive isotope (with its associated health and safety concerns) to produce gamma rays.

2.2.2.2 Track Geometry Measuring Systems (TGMS)

TGMS is the second type of inspection system used widely in the railroad industry**.** Track geometry generally characterizes the vertical and lateral deviations of each of the rails as well as the gage and cross-level measurements, which are, respectively, the horizontal and vertical relationships between the two rail heads. Maintaining proper gage and cross-level is essential, as gage or cross-level that is too large or small could result in a derailment.

Track geometry generally characterizes the health of the track structure. Non-standard gage and lateral deviation values can be indications of poor lateral restraint, which is often the result of failed ties and/or rail fasteners. Likewise, non-standard cross-level and vertical deviation values can be the result of degraded ties, ballast, and foundation support. While manual methods can measure gage and cross level as well as vertical and lateral alignment, automated measurement is more efficient and accurate.

Furthermore, automated measurements supplied by a TGMS are obtained by applying a load on the track. As a result, a TGMS measures loaded geometry, which is more desirable, as it shows the ability of the track to withstand a significant vertical load. While manual measurements can take into account evidence of movement under load, manual measurements do not apply a vertical load on the track and, therefore, do not provide the same degree of insight into how the track may be deformed by a load. For these reasons, automated measurement of track geometry has become more widely used over the past couple of decades. Most of the major railroads have specially equipped railcars, typically called "track geometry cars," on which they implement an automated TGMS. Railroads usually deploy their track geometry cars one to three times per year over a given section of track

Track Geometry Car

Also known as a track recording car is an automated track inspection vehicle on a rail transport system used to test several geometric parameters of the track without obstructing normal railroad operations. Some of the parameters generally measured include position, curvature, alignment of the track, smoothness, and the crosslevel of the two rails. The cars use a variety of sensors, measuring systems, and data management systems to create a profile of the track being inspected.

The primary benefits of track geometry cars are the time and labor saved when compared to doing manual inspections of track. Current track geometry cars may cover large portions of the system in a single day. Mostly maintenance gangs will follow the geometry car and fix defects as the geometry car moves along the track. Because track geometry cars are full-sized rail cars (with the exception of some lighter hi-rail geometry cars), track geometry cars also provide a better picture of the geometry of the track under loading. Manual measurements do not apply a vertical load, so they do not provide the same degree of insight into how the track may be deformed by a load. Finally, track geometry data is generally stored and can be used to track trends in the degradation of track. This data can be used to pinpoint and predict trouble spots in the track and plan maintenance programs accordingly. Some Track geometry cars (like those used by the New York City subway) also measure: Corrugation of running rail surface, Tunnel and station platform clearances, and the Vertical gap between third rail and protective board.

Accelerometers

Inertial accelerometers are used to determine track geometry, such as alignment, surface, and cross-level, and provide ride-quality measurements. They use sensors that measure accelerations, which are mounted on an inspection vehicle, standard railcar, or a locomotive. Poor geometry often causes undesirable movement of the vehicle, which causes accelerations that are detected by the accelerometers. This technology, like the split -load axle, has the advantage of being a performance-based test, but the disadvantage of being less useful on lighter vehicles such as high-rail inspect ion cars, as their inertial characteristics are not representative of most rolling stock (Sawadisavi 2010). Furthermore, the accelerometers on the car body can be used for non-safety related functions, such as quantifying ride quality.

2.2.2.3 Gage Restraint Measurement System (GRMS)

GRMS is a third type of inspection system that is used widely in the railroad industry. GRMS measures the ability of the track structure to maintain its gage under a constant, vehicle-applied gage-spreading load; by doing so, it quantifies the strength of a track's gage. GRMS vehicles include a third axle that applies a constant lateral, as well as vertical, load on each of the rails. GRMS typically measures the gage at two points: the first near the third axle and the second several feet away at an unloaded point. Based on the applied loads, the gage strength is then quantified by comparing the loaded and unloaded gage measurements. Measurement of gage strength, through the use of GRMS technology, allows railroads to effectively focus their tie and fastener replacement programs. L/V Ratio, which is the numerical ratio between the applied *Lateral* load and the applied *Vertical* load at the same point on the rail. *L/V > 0.8 must operate with caution* due to potential of wheel climb.

Split-load Axle

Split-load axle technology is used for the measurement of gauge restraint. It uses a specially designed, hydraulically-powered wheel set capable of applying variable vertical and horizontal loads to the rails. As a vehicle equipped with this technology moves along the track, it uses the powered wheel set to apply a set of vertical and horizontal forces to the rails, and measures the resulting changes in gauge (Clouse and Kesler 2003). If too much gauge change is observed—indicating poor lateral restraint—a problem with the ties or fasteners is likely. An advantage of this method is that it is a performance-based test. However, to properly test gauge restraint, loading conditions similar to those occurring in regular service must be replicated, making it impossible to use this technology on small inspection vehicles such as high-rail vehicles. In addition to split-load axle technology, there exist portable, handheld gauge-restraint measurement systems that can be used to verify results from a split-load axle. Still, these handheld systems only provide loading in the horizontal direct ion and cannot be used to get a true measure of gauge holding performance under normal field conditions.

Other new systems are also used by the railroad industry, but their use is not as extensive as internal rail defect detection systems, TGMS, and GRMS. Some of those are listed below.

Ground Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) is used to inspect railroad ballast. Inspection entails first transmitting radio waves into the ballast. The differing electromagnetic characteristics of ballast layers affect the reflection of the radio waves, which when analyzed, then provides a profile of the ballast. This profile supplies information on the thickness, lateral and longitudinal extent of the ballast layers, and giving insight into several different track problems including the effects of trapped water, weak substructure conditions, and inadequate substructure layer thickness (Sawadisavi 2010).

Light Detection and Ranging (LIDAR)

Light Detection and Ranging (LIDAR) uses a laser to reflect light off of the objects to be inspected. The properties of the scattered, reflected light are then analyzed to determine the object's distance from the source. LIDAR systems in use by the railroads employ a rotating laser emitter that has high cross-sectional resolution due to the large number of sampling points along the inspect ion arc. However, the longitudinal resolution along the track is dependent on the speed of the inspect ion vehicle. To allow for greater resolution at high speeds, LIDAR systems have been improving their laser emitters to use multiple beams or to rotate at higher speeds; however, these features also increase the cost. An advantage of this technology is the ability to accurately measure an entire cross section at high speed irrespective of light level. Disadvantages include the relatively low longitudinal resolution at high speeds, and the inability to obtain measurements from objects at oblique angles or from wet surfaces (Sawadisavi 2010).

Machine Vision/ Video Inspection

Machine-vision systems are currently in use or under development for a variety of inspection tasks, both wayside and mobile, including inspection of sleepers, fastenings, and joint bars, surface cracks in the rail, rail profile, and gauge. Machine-vision systems have three main sub-systems. The first element is the data acquisition system, in which digital cameras are used to obtain images or video in the visible or infrared spectrum. The next element is the image analysis system, where the images or videos are processed using machine-vision algorithms to detect and identify items of interest and assess the condition of the detected items. The last element is the data analysis system, which is used to verify whether the condition of items complies with the appropriate specified parameters.

The advantages of machine vision include greater objectivity and consistency compared to manual, visual inspection, and the ability to record and organize large quantities of visual data in a quantitative format. These features, combined with data archiving and recall capabilities, provide powerful trending capabilities in addition to the enhanced inspection capability itself. Some disadvantages of machine vision include difficulties in coping with unusual or unforeseen circumstances and the need to control and increase lighting conditions (Sawadisavi 2010).

Remote inspection options

Gaining access to busy tracks to check for defects is increasingly difficult and expensive. Cheaper alternatives to conventional track inspection methods are starting to emerge. The disadvantages of dedicated inspection trains or individual vehicles include high capital cost and the occupation of paths that may otherwise be available for commercial traffic. Not only that, but specialist staff are required to operate the trains and maintain the monitoring equipment.

In practice, only relatively large railway organizations can afford their own inspection trains, but pressure on costs has prompted a search for alternative methods to inspect track and other infrastructure at lower cost.

Remote inspection options can be fitted to trains running in revenue service, something which has become possible thanks to improvements in electronics, component reliability and wireless technology. Small components allow measuring equipment to be installed in bogies with links to compact processors that are easily accommodated within a locomotive, passenger vehicle or wagon. Additionally, remote inspections have the following advantages

- A dramatic increase in inspection frequency and a significant reduction in operating costs.
- Data is available as often as the host vehicle runs over the track. Frequent operation over dedicated routes, and the resulting regular flow of measurement information, ensures that managers and engineers are supplied continuously with up-to-date condition reports.
- Provides warnings of sudden changes in the infrastructure and allows the rate of deterioration at any location to be monitored, enabling a more accurate prediction of when track components will need replacing. Taken a stage further, it becomes possible to calculate the different rates of deterioration for various types of asset, setting the stage for a move from corrective to predictive maintenance.
- Immediate feedback is obtained about the quality of track maintenance work.

The only disadvantage, if counted, is that remote inspection poses the problem of handling huge amounts of data, it is suggested that this may be a constraint to wider adoption of the technology.

Generally, these methods and technologies must be capable of performing an accurate, reliable, and effective test in an ever-changing environment while at an acceptable speed that will not interfere with the service functionality of the railroad. Current detection methods that are performed in the railroad industry use various types of processes with human involvement in the interpretation of the test data. (Federal Railroad Administration 2014) These include

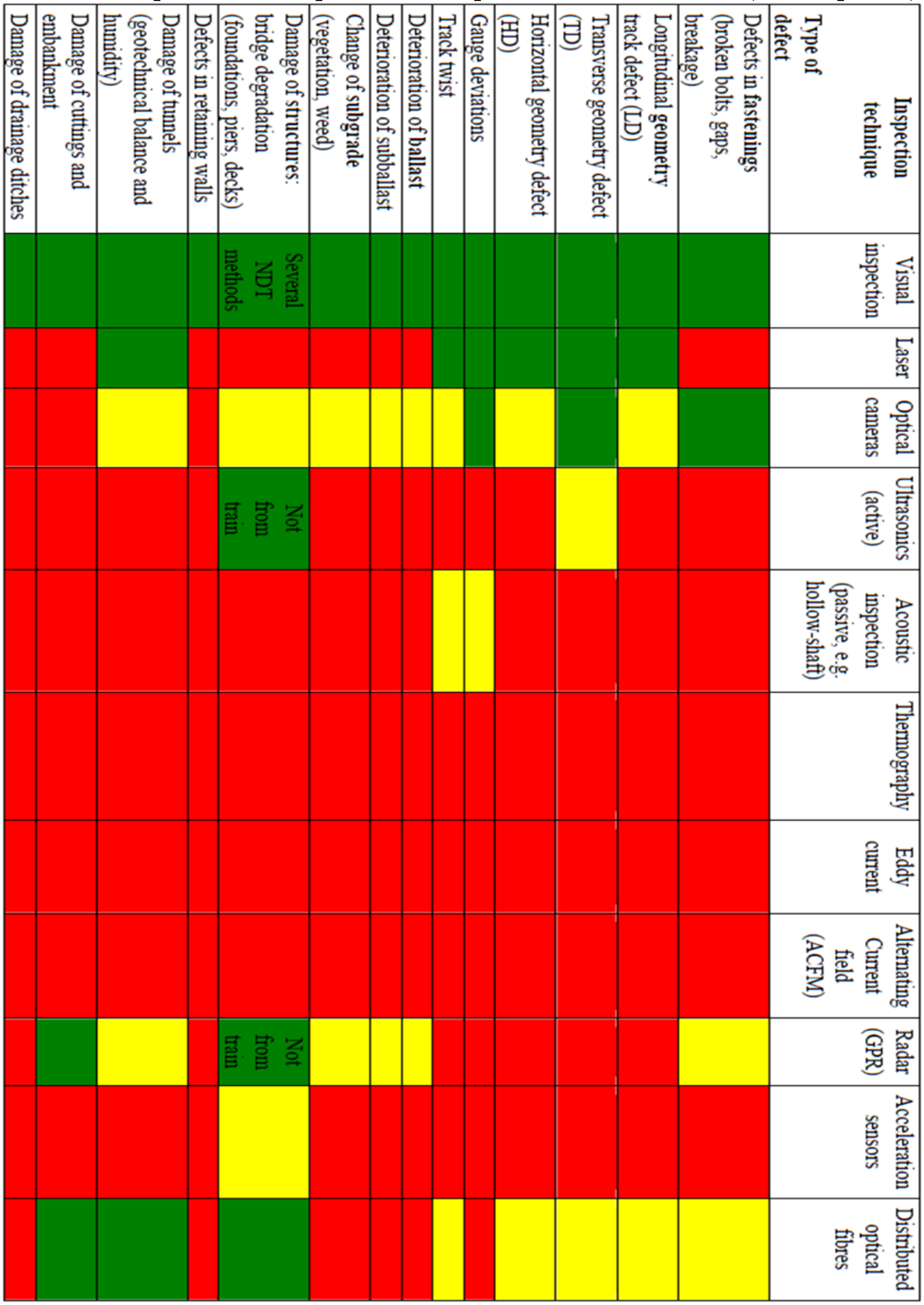
- ✓ **The portable test process**, which consists of an operator pushing a test device over the rail at a walking pace while visually interpreting the test data on a flaw detector;
- ✓ **The start/stop process**, where the test equipment is vehicle-based and operated at a slow speed while gathering data that is presented to the operator on a test monitor for interpretation;
- ✓ **The chase car process**, which consists of a lead test vehicle performing the flaw detection process in advance of a verification chase car; or
- ✓ **The continuous test process**, which consists of operating a high-speed vehicle-based test system nonstop along a designated route, analyzing the test data at a distant centralized location, and subsequently verifying suspect defect locations.

(ACEM-RAIL) uses several measurements and evaluation techniques to evaluate track defects. Measurements techniques widely used to evaluate rail profile are: Ultrasonic, induction and Radiograph. The inspection of sleepers is currently a human driven operation. Fastenings can be inspected by visual cameras. The main goal for using images of the track is to eliminate, or reduce as much as possible, the visual inspection carried out by workers walking along the track to detect faults, missing components, etc. Switches are the most complicated and delicate component of the track. Inspections in switches and crossings have been purely manual until now because no instrument able to deliver the large number of measurements required.

The following table summarizes the applicability of inspection and monitoring techniques to find a specific kind of defect (Railcorp 2010). The green color indicates that the defect can be identified by the corresponding technique. The red color shows that an identification of the defect is not possible. If it is still unclear if a specific technique is able to find the defect or not, the yellow color is used instead. In some case additional remarks are also given.

Inspection technique / Type of defect	Visual inspection	Laser	Optical cameras	Ultrasonics (active)	Acoustic inspection (passive, e.g. hollow-shaft)	Thermography	Eddy current	Alternating Current field (ACFM)	Radar (GPR)	Acceleration sensors	Distributed optical fibres
Damage in **rails**: Longitudinal vertical crack (UIC 113)							only surface-near				
Tache ovale (UIC 211)					expected						
Horizontal crack (UIC 212)											
Running surface disintegration (UIC 221)											
Short-pitch corrugation (UIC 2201)											
Long-pitch corrugation (UIC 2202)											
Lateral wear (UIC 2203)											
Running surface shelling (UIC 2221)											
Gauge-corner shelling (UIC 2222)											
Head checks											
Bruising (UIC 301)											
Faulty machining (UIC 302)											
Transverse and horizontal cracks in weldings (UIC 411, 412, 421, 422, 431, 432)						only surface-near	only surface-near	only surface-near			
Rail wear (**Track profile** deformation)											
Damage of **sleepers** (timber, steel, concrete)											

Table 2-1 Inspection techniques to find a specific rail track defects (Railcorp 2010)



2.3 Inspection Frequency levels

There are three main levels of vehicles and rolling stock that inspection technologies are implemented on, and these are defined by their inspection frequency. (FRA 2010)

The first level consists of **geometry cars**, which provide track geometry information for the railroads. The FRA does not specify an inspect ion frequency for geometry cars on track classes lower than class 7, so these cars inspect track as necessary on the order of once or twice per year, depending on tonnage and other factors. There are a relatively small number of these cars, allowing the technologies implemented on them to be very specialized and expensive, with cars often incorporating additional technologies to measure items such as ride quality, rail profile and track gauge restraint. The high level of technical sophistication of the geometry car leads to an operating crew that is technically proficient in order to maintain and troubleshoot the inspection hardware and software (Sawadisavi 2010).

The next inspection frequency level includes **defect detector cars.** These cars perform internal rail flaw detection, typically using ultrasonic testing. These cars are operated on the basis of tonnage, so their inspection frequency varies widely. The FRA mandates that inspections for internal rail flaws on FRA class 4 and 5 track are conducted either every 40 MGT or once a year, whichever is shorter. The training necessary to interpret ultrasonic data and maintain the inspection equipment leads to these cars being staffed by personnel with a high level of technical proficiency. This inspection level is the most likely candidate for an initial field implementation of this system due to a relatively high inspection frequency and a crew that would be more accustomed to handling advanced inspection equipment, especially during its developmental phases. (FRA 2010)

Finally, the last and most frequent level of inspections are conducted using **hi-rail vehicles.** These have the advantage of running the most frequently: twice per week for class 4 and 5 tracks as required by the FRA. These vehicles are occasionally equipped with advanced inspection systems, such as ENSCO's joint bar inspection system, but are primarily used to allow a track inspector to visually inspect the track and its components (FRA 2010). High-rail vehicles are staffed with crew members that are well-trained for their specific duties, but in general are not as technologically proficient as those that operate geometry cars and rail defect detector cars. (Sawadisavi 2010)

2.4 Defects to look for while inspecting

The term "Defect" is defined as any anomaly in the shape or internal structure of an element and/or material(s) which adversely affects its functional capacity or service life. (Waterfront 1999) During inspection process we will face different rail track conditions present; there are a significant number of potential defects possible; and the task has to be performed with some speed to reliably inspect the whole track, and to protect the safety of passengers and freight.

There are many sources that influence Track defects and failure. These effects include bending and shear stresses, wheel/rail contact stresses, thermal stresses, residual stresses and dynamic effects.

Track defects have become the leading cause of train accidents in the United States since 2009. In all, 658 of 1890 (34.8%) train accidents were caused by track defects in 2009, incurring a $108.7 million loss (Qing He 2014). Therefore, it is vital to understand the deterioration process of railway track systems and facilitate track maintenance planning.

According to the United States Federal Office of Safety Analysis, track defects are the second leading cause of accidents on railways in the United States. 9,764 of the 30,195 train accidents in the United States from January 2000 to January 2010 occurred due to defects in the tracks. Track defects were responsible for causing 32% of the 3,185 railroad incidents in the United States during 2007 alone. (Shah 2010)

In the United States, geometry cars generally classify each defect as either "Class II" or "Class I" (though the exact name may vary by the railroad). A class II defect is known as a maintenance level defect, meaning that the track doesn't meet a particular railroad's own standards. Each railroad has its own standard for a maintenance level defect. A class I defect is a defect in violation of the track safety standards (Federal Railroad Administration 2009). Railroads must fix these defects within a certain period of time after their discovery or else they risk the safety of passengers and being fined.

In general, most manuals and standards classify Track defects into problems that involve:

i. **Track Structure:** these may include defects in the rails, ballast structure, defects (including missing parts) in the cross-ties, tie-plates, fasteners, bolts, rail-joints, etc.
ii. **Track Geometry:** these defects includes deviation from the ideal gage measure, deviation of curved/tangent track, and misalignment during re-laying of tracks, etc.

2.4.1 Track Structure Defects

2.4.1.1 Rail defects

There are several factors that can influence the expected duration of rail service. The service life is affected primarily by the chemical composition of the rail, track maintenance programs, speed, and tonnage. All of these factor into the development of vertical and lateral head wear, plastic flow or deformation of the rail head, and development of rail defects.

Rail defects develop in any type of rail, or rail welds, as a result of several conditions. These conditions normally will originate from the rail manufacturing process; cyclical loading; and impact from rolling stock, rail wear, and plastic flow. The development of rail defects can be influenced in modern steel through an extensive maintenance program that will prolong the timeframe before the rail is subjected to the Effects of excessive wear and plastic flow. This would include friction control methods and proper rail profile. However, it is impossible to accurately predict rail service life or defect development. (FRA, Office of Railroad Safety 2015)

Defect development identification is determined by the type of defect, origin, and direction of development in relation to the planes of the rail section. These are identified as transverse, vertical and horizontal planes of development.

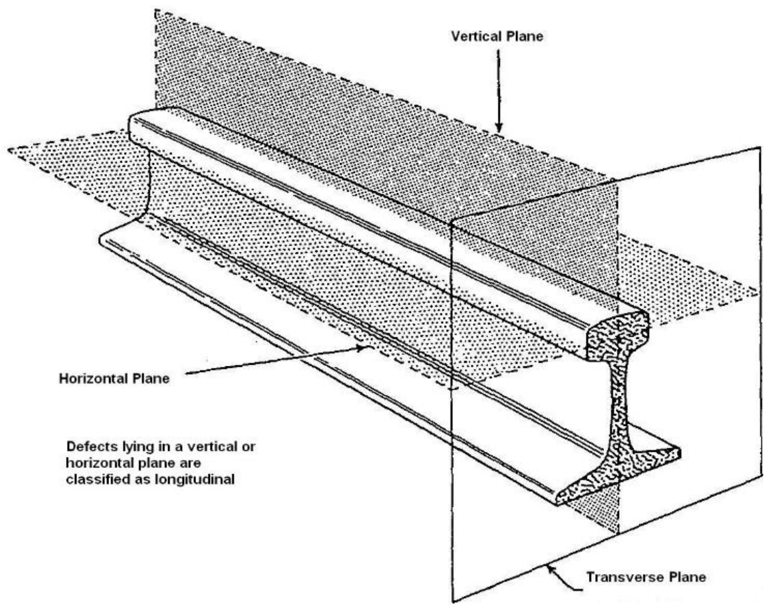


Figure 2-4 Terminology Used to Identify Defect Planes in Relation to Rail Section
(FRA, Office of Railroad Safety 2015)

When the defective portion of the rail is closely examined, certain characteristics provide information that will allow the type of growth identification the defect had experienced. Transverse growth is normally referred to in three types of classifications: (FRA, Office of Railroad Safety 2015)

Normal Growth – Defect development over a period of time in gradual stages. Normal development is typically progressive and can be uninterrupted. The defect will show a smooth and polished fracture with no granular structure.

Rapid Growth – Signifies recent development in numerous small stages. The small, polished, well-defined fracture is surrounded by a rough granular surface, which shows the outline of several growth rings of gradual increasing size.

Sudden Growth – Signifies recent development in a few large stages. The small, polished, well defined fracture is surrounded by a rough granular surface, which shows the outline of one or two growth rings. The distance between rings will increase directly with the rate of growth.

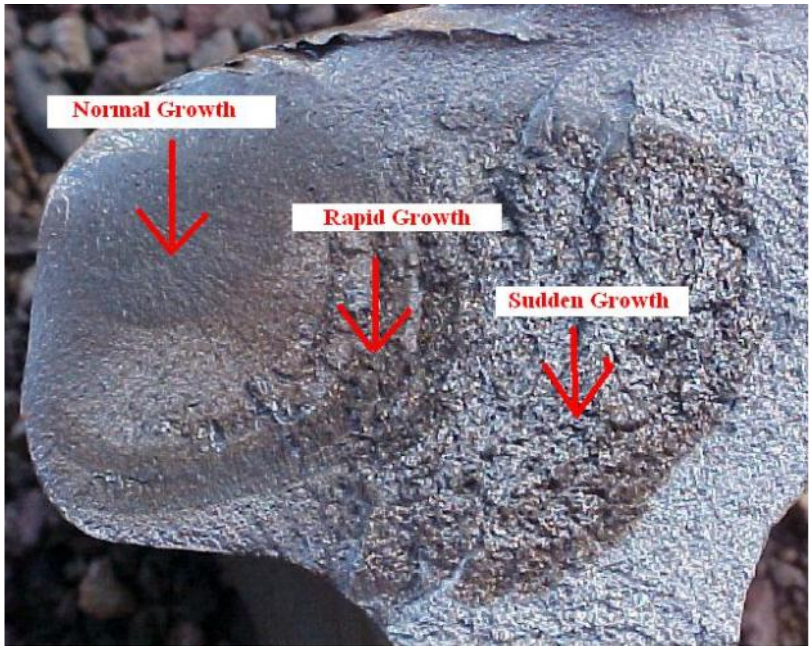


Figure 2-5 Detail Fracture Showing Normal, Rapid and Sudden Growth patterns
(FRA, Office of Railroad Safety 2015)

Federal Railroad Administration (FRA) generally classifies rail defects in to four major categories. (FRA, Office of Railroad Safety 2015)

i. **Transverse Defects in The Rail Head:** A transverse defect is a type of fatigue that has developed in a plane transverse to the cross sectional area of the rail head. Development can be normal or in multiple stages prior to failure. The transverse defect is only identified by the nondestructive inspection process (methods described in chapter 2), unless the defect has progressed to the rail running surface and has cracked out. (FRA, Office of Railroad Safety 2015) some of the transverse defects in the rail are:
   - Transverse Fissure,
   - Compound Fissure,
   - Detail Fracture,
   - Engine Burn Fracture, and
   - Ordinary Break.

   Detail explanation of these defects are available at APPENDIX-A

ii. **Longitudinal Defects in The Rail Head:** are classes of rail defects that are lying in the vertical and horizontal plane, Which consist of horizontal and vertical split head as explained in detail on APPENDIX-A

iii. **Web Defects** are defects along the side of the web. The most common web defects in the railroad are; (Detail explanation of these defects are available at APPENDIX-A)
- Head and Web Separation,
- Split Web, and
- Piped Rail.

iv. **Miscellaneous Defects** are defects that cannot be categorized in the above three or the combination of the above three. Some of those defects that FRA Classifies in this section (as explained in detail on APPENDIX-A) are:
- Broken base/base fracture
- Defective weld
- Bolt hole crack
- Flattened rail
- Damaged rail
- Crushed head

2.4.1.2 Sleeper and Fastener Defects

According to (FTA, Federal Transit Administration pocket guide 2010) **Concrete sleepers/ties** should be inspected for the following:

- Cracks: Concrete ties will not sustain unusually high repeated shock loadings. Engine burns, and battered and open rail joints should be corrected promptly or they will produce cracks and result in a rapid failure of the concrete tie.
- Center bound ties are produced by improper tamping methods, poor drainage, foul ballast, and an inadequate depth of ballast to a poor subgrade. Pumping track must be corrected promptly to avoid damage to the tie.
- Any displacement of, or damage to tie pads or insulators on rail fastenings should be corrected promptly to maintain electrical insulation of concrete ties from rail.
- If surface spalls, chips, or broken out areas expose the pre-stressed reinforcing wire in the concrete tie, the concrete tie is to be replaced.
- Any tie with a longitudinal crack running through a vertical plane that affects the structural integrity of the tie should be replaced.
- Any crack in the rail base area of a concrete tie that is large enough to be easily seen should be deemed sufficient for the tie to be replaced.

- Tie center cracks are not cause for the tie to be replaced unless it causes the loss of bearing under the rail or the loss of gauge holding capabilities.
- Any rail holding device that is loose in the concrete tie should be considered defective and require replacement of the tie.

Rail fastener inspection for defects should be carried out as part of the regular weekly track inspections. These inspection practices cover all ballasted track in addition to direct fixation track, anchor bolts, and rail fasteners. (FTA, Federal Transit Administration pocket guide 2010)

- All anchor bolts or inserts must be solidly bonded to the track structures. If these anchor bolts are found to be loose or broken, they must be reset with an approved procedure.
- Direct fixation fasteners should be kept clean of all metal filings, debris and other foreign matter which may contribute to corrosion or loss of electrical isolation.
- Direct fixation fasteners are considered defective from a safety point of view when the rail holding feature is defective or missing so that gauge and/or critical geometry cannot be maintained.
- If the fastener does not provide gauge under loading and experiences excessive vertical or lateral movement under load, the fastener is considered defective from a safety point of view.
- Direct fixation fasteners are considered defective from a maintenance point of view when:
    - ✓ The rail clip is broken;
    - ✓ Two anchor bolts are missing, broken, or so loose as to be rendered ineffective on one pad;
    - ✓ Two anchor bolt inserts are stripped or otherwise unusable on one pad;
    - ✓ The pad or plate is corroded, deteriorated or broken such that the rail fasteners or anchor bolts no longer provide lateral or vertical support; or
    - ✓ The concrete supporting the fastener is deteriorated or impaired such that it does not provide proper support.
    - ✓ The elastomer is poor or separated from any of its components.
    - ✓ Any fastener component is bent, cracked or broken.
    - ✓ The rail hold down is defective or missing so that the gauge cannot be maintained.

Defective fasteners as defined above must be repaired or replaced. The following table identifies support unit fastener restrictions that apply for all track per 100 feet of rail according to (FTA, Federal Transit Administration pocket guide 2010)

Table 2-2 Sleeper Support Unit Fastener Restrictions

Maximum Allowable Speed*	Maximum No. of Defective Rail Support Units Per 100 Feet of Rail
50 miles per hour	8
40 miles per hour	10
15 miles per hour	12
Supervise Operation	>12

2.4.1.3 Ballast Defects

Railroad ballast deterioration is responsible for the majority of differential settlement of tracks, resulting in poor track geometry. Traditionally, ballast is replaced only when it has visually deteriorated, resulting in the planning and programming of maintenance and renewals currently being condition driven. However, there is a significant potential cost saving if ballast deterioration can be detected earlier by inspection methods like Ground Penetrating Radar (GPR) (MBTA 2000)

Over time, ballast becomes worn, and loses its angularity, becoming rounded. This hinders the overlapping of pieces of ballast with one another, and thus reduces its effectiveness. Fine pieces of granite, like sand, are also created by attrition, known simply as "fines". Combined with water in the ballast, these fines stick together, making the ballast like a lump of concrete. This hinders both track drainage and the flexibility of the ballast to constrain the track as it moves under traffic. (MBTA 2000)

Unless the track is structurally supported, all Ballast regardless of the material, must satisfy the following four requirements, (Federal Railroad Administration 2014)

- Transmit and distribute the load of the track and railroad rolling equipment to the subgrade;
- Restrain the track laterally, longitudinally, and vertically under dynamic loads imposed by railroad rolling equipment and thermal stresses imposed by the rails;
- Provide adequate drainage for the track; and
- Maintain proper track Crosslevel, surface, and alignment.

When track has been disturbed, such as due to maintenance activities, the track must be examined. If the track does not conform to the requirements outlined in this section, the maximum authorized speed must be reduced, until a proper section has been restored. (FTA, Federal Transit Administration pocket guide 2010)

Ballast must be kept from touching the rails after compaction. A space of at least one inch between the ballast and the base of the rail must be maintained to provide clearance between the rail and the ballast. (FTA, Federal Transit Administration pocket guide 2010)

The ballast and roadway will be inspected as part of the regular inspection of the track. Inspectors should consider the overall condition of a track when citing fouled ballast. Because ballast conditions can be subjective in nature, inspectors should also look to other indicators, such as a geometry condition.

2.4.2 Track Geometry Defects

GAGE VARIATION

A gage/gauge is the distance between the rails. Over time, rail may become too wide or too narrow due to the different forces applied on the trail. In most sections of the world, Standard gauge is 56 ½ inches (1435mm). This is measured 5/8 of an inch under the top of the ball of the rail (MBTA 2000). Different manual set the minimum and maximum gauge spacing which each railway agency is abided by. Where line or surface irregularities are observed by the inspector, the gage should be measured.

ALIGNMENT DEVIATION

"Alignment is the projection of the track geometry of each rail or the track center line onto the horizontal plane," (FRA Definition). Also known as the "straightness" of the tracks. During manual measuring, a 62-foot or a 31-foot piece of string is used and stretched with each end held against the gage face of one running rail. The measurement (offset) that is recorded in the middle of the string is the measurement that is applied to the table, or taken as a deviation. The point of greatest alignment deviation usually can be detected visually or may be located by moving the chord along the track in increments until the point with maximum deviation is found.

TRACK SURFACE DEVIATIONS

Allowable deviations in track surface include runoff at the end of a raise, deviation from uniform profile, deviation from zero crosslevel at any point on tangent or reverse crosslevel elevation on curves, and the difference in crosslevel between any two points less than 62 feet apart (referred as track warp).

Under load, the track structure gradually deteriorates due to dynamic and mechanical wear effects of passing trains. Improper drainage, unstable roadbed, inadequate tamping, and deferred maintenance can create surface irregularities. Track surface irregularities can lead to serious consequences if ignored.

Curvature is the maximum change in cross level over a predetermined chord length. The amount by which the rail deviates from being straight or tangent. The geometry car checks the actual curvature (in Degree of curvature) of a curve versus its design curvature. On straight or tangent track, ideally there should be no variation, while on curves, a cant is generally desired.

2.4.3 Remedial Action Plan

Based on the outcomes of the track inspection, the track inspector may take immediate action to correct identified deficiencies or may implement a remedial action plan if the defect is beyond the immediate capabilities of the track inspector and/or work crew. In both instances, the actions taken by the track inspector must be identified on the track inspection form. (TCRP Synthesis 2014) If the defect cannot be immediately corrected, it must be reported to the track maintenance department so that the required repairs can be scheduled and made. This will typically require that the rail transit agency issue a work order. The date of when the final repairs are made should be added to the track inspection form once completed. (TCRP Synthesis 2014)

2.5 Frequency of Track Inspection

It is important to schedule track inspections such that the potential defects are captured as much as possible within minimum times to increase safety to the maximum.

Railroads have always inspected track visually to detect rail failures, and have been using crack-detection devices in rail-test vehicles since the 1930s. One of the objective of this study is to provide appropriate Inspection frequency for the Addis Ababa Light Rail Transit by referring other standards and recommended practices of the experienced countries and comparing their compliance with the AA LRT considering track design parameters, track material, tramcar properties and operational parameters. Some of these standards and best practices are cited as follows;

- ✓ ***AREMA (American Railway Engineering and Maintenance-of-way Association)***
- ✓ ***FTA (Federal Transit Administration)***
- ✓ ***APTA (American Public Transportation Association)***
- ✓ ***FRA (Federal Railroad Administration)***
- ✓ ***MBTA(Massachusetts Bay Transportation Authority)***
- ✓ ***RailCorp Engineering Manual***
- ✓ ***CSA (Canadian Standard Association)***

Review will be made to all the standards concerning the frequency of track and component inspections, the following are some of the standards selected to review their practice on track inspection frequencies.

2.5.1 Green Line LRT, Track Maintenance and Safety Standard (MBTA 2000)

Track Inspection: All LRT track must be inspected a minimum of **three times per week**, with at least one calendar day interval between inspections.

Rail Inspection: At least **once a year** a continuous search for internal rail defects (ultrasonic and/or induction testing) must be made of all rail in all track with operating speeds of 40 mph or greater. Inspection equipment must be capable of detecting defects between the joint bars in the area of the rail enclosed by joint bars. Each defective rail must be marked with highly visible marking on both sides of the web and base.

Switch, Turnout and Crossing: Each switch, turnout and track crossing must be inspected on foot at least **monthly**.

Special Inspection: In the event of fire, flood, severe storm or other occurrence which might have damaged the track structure, a special inspection must be made of the track involved as soon as possible after the occurrence.

Each inspection must be made on foot or riding over the track in a vehicle at a speed that allows the person making the inspection to visually inspect the track structure for compliance with the regulations and standards set. If a vehicle is used for visual inspection, the speed of the vehicle may not be more than 5mph when passing over grade crossings or special track work.

2.5.2 APTA, American Public Transportation Association

Track inspection: Tracks used by revenue trains shall be inspected **weekly** on foot or by riding over the track in a vehicle at a speed that allows detection of noncompliance with standards. In the unusual event that a walking or riding inspection cannot be performed a qualified person must inspect from a revenue vehicle in a position in full view of the roadbed. **An interval of at least three but not more than eleven calendar days must elapse between inspections.**

Rail inspection: Ultrasonic rail flaw detection of mainline track shall be performed **at least once per year**. Defective rails shall be clearly marked on each side of the rail web and base.

CWR inspection: Special inspections of CWR shall occur when the ambient temperature causes the rail temperature to meet or exceed the neutral temperature of the rail. When daily cycles of extreme temperature fluctuations occur, consideration shall be given to repeated inspections.

Geometry inspection: The geometry of mainline standard gauge track shall be inspected and recorded **at least once per year** by an automated track inspection or measurement vehicle; this inspection will supplement the weekly visual inspection of track.

Switch and Crossing Inspection: Main Line switches shall be inspected for defects **monthly.** Switches that failed to operate properly due to a track cause or an undetermined cause shall be inspected by both signal and track qualified inspectors to determine the cause and ensure the repair is complete.

2.5.3 FRA, Federal Railroad Administration

Track Inspection: FRA specifies the minimum frequency at which inspections must be Conducted as, weekly with at least 3 calendar day's interval between inspections. Each inspection performed must be made on foot or by riding over the track in a vehicle at a speed that allows the person making the inspections to visually inspect the track structure for compliance. An inspection made from a vehicle driven alongside the track does not constitute an inspection performed at the required frequency.

Rail Inspection: a continuous search for internal defects shall be made of all rail in Classes 4 through 5 track, and Class 3 track over which passenger trains operate, at least once every 40 million gross tons (mgt) or once a year, whichever interval is shorter.

Geometry Inspection: If annual tonnage on Class 4 and 5 main track and Class 3 main track with regularly scheduled passenger service, exceeds 40 million gross tons (mgt) annually, at least twice each calendar year, with no less than 160 days between inspections.

Switch and Crossing Inspection: each switch, turnout, track crossing, and moveable bridge lift rail assembly of other transition device shall be inspected on foot at least monthly. Turnouts and track crossings visually inspected from a vehicle must be accomplished at a speed not exceeding 5 mph.

Special Inspection: In the event of fire, flood, severe storm, or other occurrence which might have damaged track structure, a special inspection shall be made of the track involved as soon as possible after the occurrence and, if possible, before the operation of any train over that track.

2.5.4 FTA, Federal Transit Administration

Track Inspection: For tracks used by revenue trains; Inspect at least **once weekly** on foot or, Inspect by riding over the track in a vehicle at a speed that allows detection of defects. Inspect from a revenue vehicle at least once a week. Inspection interval of at least three calendar days between walking inspections.

Rail Inspection: Inspect rails **once a year** using ultrasonic rail flaw detection. Mark defective rails on each side of the rail web and base. If rail defects are found during daily walking track inspections, use specifications listed in the rail defect remedial action chart to determine appropriate action.

Geometry Inspection: Inspect and record the geometry of mainline standard gauge track at least **once a year** by an automated track inspection or measurement vehicle. This inspection will supplement the weekly visual inspection of track.

Switch and Crossing Inspection: Inspect each main line switch, turnout, track crossing and moveable bridge lift assembly or other transition device should be inspected on foot **at least monthly**. Inspect switches for defects as part of the normal walking inspection. Perform detailed turnout inspection **monthly.**

Special Inspection: In the event of fire, flood, seismic activity, severe storm, or other occurrence, which might have damaged the track and/or structure, make a special inspection of the affected track and structure as soon as possible after the occurrence. Investigate defects reported by the public and employees as soon as possible. Take appropriate corrective action.

2.6 Maintenance Priority for Inspected Defects

Prioritization is essentially performed in a sequential manner by first enlisting the maintenance projects required to be executed. Once projects are identified, the next step is to prioritize the projects based on their relative perceived urgency. Projects with the highest priority are executed until all finances are expended. Remaining projects are re-prioritized together with the new projects upon availability of funds.

Different track safety and maintenance standards will be covered in the following sub sections, about track condition reporting system and prioritization for the tracks that do not comply with the standards.

2.6.1 RailCorp Engineering manual

According to **RailCorp Engineering manual**, (Railcorp 2010) all defects are categorized in one of six standard defect categories. Each category has its own inspect and verify response with time frame action to be taken. Emergency 1 (E1) is the highest priority defects and remedial actions should be taken prior to the passage of the next train. As we go down the table the priority decreases according to (Railcorp 2010).

Table 2-3 RailCorp prioritization system

Response Category	Inspect and verify response	Action
Emergency 1 (E1)	Prior to passage of next train	Prior to passage of next train
Emergency 2 (E2)	Within 2 hrs or before the next train, whichever is the greater	Within 24 hrs
Priority 1 (P1)	Within 24 hrs	Within 7 days
Priority 2 (P2)	Within 7 days	Within 28 days
Priority 3 (P3)	Within 28 days	Program for repair
Normal (N)	Nil	Routine inspection

2.6.2 American Public Transportation Association, APTA

According to (APTA 2004) the condition prioritization system shall be as described in the following table; and any Rail Transit System that knows or has notice that the tracks do not comply with the standards shown herein shall report the condition using this hierarchy and take the required corrective action. If a condition prioritization system is used, it shall confirm to the following: (APTA 2004)

Table 2-4 APTA prioritization system

Priority	Description [1]
1	The qualified person(s) detecting such condition shall make every effort to correct the condition immediately, and must also evaluate whether to allow operations to continue under supervision or to place the track out of service immediately. If operation is allowed to continue, the person(s) making the decision must not leave the scene until relieved or until the defect is repaired. When "walking" trains over such a condition, each train shall be stopped short of the defect and the person on the ground shall communicate the situation to the train operator. Movements shall be made at "Restricted Speed with Extreme Caution"; that is, proceeding no faster than 15 mph; prepared to stop at least two car lengths short of a visible object on the roadway; ready to make a fast stop; watching rails and switches for the route and looking for anything on the roadbed that is unsafe to pass.
2	Conditions that require inspection by a qualified person within 24 hours of the time of the detection of the condition. The investigating person shall immediately determine whether a slow speed order is necessary and what work is required, and shall base these decisions on findings and other factors, such as the type of defect, the location and permanent speed of the track in question. Every effort shall be made to correct these defects as soon as practicable.
3	Such designation alerts to a track condition that affects the ride comfort qualities of the track and that may degrade to a worse condition if left uncorrected. Work programs shall be established for the correction of these defects.
4	Conditions that do not require any immediate action. These conditions may affect ride comfort qualities of the track, should they degrade to a worse condition. Uncorrected defects shall be recorded and the reports shall be used for scheduling future work.

2.6.3 Federal Transit Administration, FTA

The Federal Transit Administration track condition reporting system focuses on the serviceability of the track components. A serviceable object (structure) is one that is capable of carrying out its intended function. Transit track represents a structure consisting of several key components; longitudinal steel rails fastened to cross members or to slabs and supported by an elastic foundation of ballast or other sub-grade. This type of structure requires the determination of serviceability necessary to insure its safe and efficient operation. (FTA, Federal Transit Administration pocket guide 2010)

There are four levels of serviceability according to (FTA, Federal Transit Administration pocket guide 2010), operational, limited operations, restricted operations, and out of service:

1. Fully Operational

A satisfactory condition of serviceability exists when the track structure is maintained within serviceable limits. These defects reflect that the component is not in pristine condition but trains can operate at maximum authorized speed. These conditions may affect ride comfort qualities of the track, should they degrade to a worse condition. Uncorrected defects should be recorded and the reports should be used for scheduling future work. This condition is noted in the charts and tables as **(G)** and will be color-coded **Green**. (FTA, Federal Transit Administration pocket guide 2010)

2. Limited operation

A limited operations condition of serviceability exists when one or more of the components of a section of track are damaged or worn to the point that the components are no longer in their original condition. (FTA, Federal Transit Administration pocket guide 2010)

This condition is not immediately dangerous or threatening. Such designation alerts to a track condition that affects the ride comfort qualities of the track and that may degrade to a worse condition if left uncorrected. Work programs should be established for the correction of these defects. This condition is a state of caution. It requires placing a speed restriction on the section of track affected until the problem is scheduled for repair and repaired. This condition is noted in the charts and tables as (**Y**) and will be color-coded **Yellow**. (FTA, Federal Transit Administration pocket guide 2010)

3. Restricted Operations

A restricted operations condition of serviceability exists when one or more components of a section of track have failed to an extent that could lead to derailments of rolling stock, and/or damage, and/or injury. These are conditions that require inspection by a qualified person within 24 hours after the detection of the condition. (FTA, Federal Transit Administration pocket guide 2010)

Immediately determine whether a slow speed order is necessary and what work is required, base these decisions on findings and other factors, such as the type of defect, the location and permanent speed of the track in question. The inspector, upon determining that a condition of restricted operations exists, should immediately impose the proper slow order, notify his immediate superior of the nature of the defect, and monitor/supervise operations until relieved. Note this condition in the charts and tables as (**R**) and will be color-coded **Red**. (FTA, Federal Transit Administration pocket guide 2010)

4. Out of Service

An out of service condition of serviceability exists when a section of track has deteriorated to the point where no train movement is allowed. This condition has one or more components that have exceeded code red limits. The qualified person(s) detecting such condition should make every effort to correct the condition immediately, and must also evaluate whether to allow operations to continue under supervision or to place the track out of service immediately. If operation is allowed to continue, the person(s) making the decision must not leave the scene until relieved or until the defect is repaired. (FTA, Federal Transit Administration pocket guide 2010)

When "walking" trains over such a condition, each train should be stopped short of the defect and the person on the ground should communicate the situation to the train operator. Movements should be made at "Slow Speed with Extreme Caution"; that is, proceeding no faster than 15 mph; prepared to stop at least two car lengths short of a visible object on the roadway; ready to make a fast stop; watching rails and switches for the route and looking for anything on the roadbed that is unsafe to pass. This condition is noted in the charts and tables as (**B**) and will be color-coded **Black**. (FTA, Federal Transit Administration pocket guide 2010)

2.6.4 Massachusetts Bay Transportation Authority

According to **Massachusetts Bay Transportation Authority, Green Line LRT** (MBTA 2000), Color coded maintenance threshold limits should be used to govern reaction to detected track defects.

GREEN coded track conditions do not necessarily require immediate remedial action. GREEN coded conditions should be, at a minimum, verbally communicated to the responsible section foreman and/or supervisor. This level condition should be monitored on a going basis for deterioration to the next level. (MBTA 2000)

YELLOW coded track conditions have reached or are closely approaching the maintenance limit for train operation at normal posted speed. As such, YELLOW coded conditions are classified as track defects and remedial action should be scheduled to correct the deficiency before it escalates to the next level. (MBTA 2000)

RED coded track conditions are defects which generate speed restrictions (slow orders) and at the most severe level are grounds for removing effected track from service until repairs can be made. In most cases, RED coded defects should be scheduled for immediate remedial action. These effects are by definition the highest repair priority. (MBTA 2000)

A combination of track conditions, especially YELLOW coded conditions, can act in concert with operator error and/or vehicle malfunction to cause a derailment. This is especially true in special track work, where the overwhelming majority of derailments occur. Conditions such as negative super elevation, irregular track surface and/or alignment, abrupt gage transitions, non-uniform wheel restraint, poorly finished gage side welds and others which may create a dynamic imbalance in certain operating environments should be closely monitored. (MBTA 2000)

When performing maintenance operations in LRT track, especially LRT track worn close to permissible limits through repeated normal use, a very important principle must be kept in mind. *Adjustments made to, or components replaced on one side of a switch or curve will have a direct and substantial effect on the opposite side of the switch or curve.* Care must be exercised to ensure that existing conditions are not put into an imbalanced state through well intentioned and well executed maintenance work. Imbalance of track conditions through maintenance of only one side of worn track leads to differential distribution of vehicle forces which may result in wheel climb, component failure and derailment. (MBTA 2000)

Under certain circumstances, logistical constraints make it impossible to perform maintenance activities so that track conditions do not become imbalanced. In such circumstances, it is almost always preferable to work on the inside of the switch or curve first. Experience has shown that lateral wheel forces are far more successfully managed by restraint to the back of the inside wheel flange that at the gage corner of the outside wheel. The use of test trains and speed restrictions is almost always warranted in cases of unavoidable imbalanced track conditions. (MBTA 2000)

2.6.5 Deutsche Bahn (DB)

The "Deutsche Bahn" (DB) maintains its networks superstructure, rails and track geometry according to the principles of a company guideline named Ril821. This document defines a three-tier threshold system, which specifies three fixed values of maximum disturbance for each measurement parameter and speed. Those three values are called SR-values (germ. Störgröße/Reaktion = Disturbance/Reaction) and are ordered by raising criticality: (Christian Linder 2013)

1. SR_A - *Attention threshold for an economic maintenance*

When measurements reach that limit, it should be expected that maintenance is needed in the near future. Corresponding maintenance tasks need to be scheduled for optimal cost efficiency.

2. SR_{100} - *Technical and economical threshold for maintenance*

This limit defines the threshold on which the track geometry has reached the maximum tolerable condition with which the rail operation can still be carried out without interference. Maintenance must to be carried out before the next interval based inspection. While there are no more inspections until the repair is done, it cannot be assured that the failure does not reach SR_{Lim} in the meantime.

3. SR_{Lim} – *Limit threshold for safety reasons*

When track geometry measurement parameters reach or cross the SR_{Lim} values, it must be assumed that the functionality of track or superstructure is affected. Appropriate measures must be taken to ensure safety (mainly those results in a reduction of maximum speed). Maintenance must be carried out at earliest possible time.

2.6.6 European Standard EN13847

In contrast to national regulations, there is a norm that aims to align the trans-European maintenance specification and also has a three-tier limit value system. There is and alert limit, intervention limit and the immediate action limit. But this is different in such a way that it separates failures by wave length of 3m - 25m (D1), 25M - 70m (D2), and 70m - 150m (D3). (Christian Linder 2013)

2.7 INSPECTION PARAMETERS

In the global field of railroad track, different inspection philosophies and approaches exist. According to (FRA 2010) Inspection threshold levels (the limits beyond which a condition is considered defective) are established using one of two approaches: 1) prescriptive; and 2) performance-based. Subparts addressing roadbed and track structure, generally contain prescriptive standards. Prescriptive standards can be considered ones that describe a particular condition, such as an "ineffective tie." Prescriptive standards are sometimes referred to as "hard standards." Hard standards describe conditions that are discrete, meaning the condition is either there or not there. An example is a missing spike. "Hard conditions" are generally easier to detect visually; therefore, visual inspections are often used to detect such conditions. Hard conditions may be somewhat subjective, however, and may require a person's judgment, such as identifying when a tie is "ineffective." (Federal Railroad Administration, 2010)

Performance-based standards, such as the track geometry standards, generally require quantitative measurements. As a result, they are typically less subjective, although they are still subject to measurement errors introduced by human error or imperfect machine sensors. Generally speaking, prescriptive standards are more suitable for visual inspections, while performance-based standards are more suitable for automated inspection systems, which are capable of accurately and efficiently taking measurements separated uniformly in space (such as every foot) or in time (such as every millisecond). It would require an excessive amount of time for an inspector to continually take such frequent, uniform measurements.

Performance-based measurements are suitable for detecting "soft conditions." Unlike a hard condition, described previously, the term soft condition refers to a condition that takes on a continuum of values. Therefore, a soft condition is always there, and the number of values it can take on is infinite. To make the idea of a soft condition less abstract, one can think of gage measurement as a soft condition. As long as there are two rails, gage will always exist and can take on any value. Due to the measurement that is required to quantify the severity of a "soft issue," it is often more practical to use mechanized systems to detect such issues. This can be evidenced by the widespread popularity of automated track geometry measurement systems (TGMS).

We can generally classify inspection parameters in to two, those related to track geometry and those of track structure parameters. The tolerances of each parameter vary between railway agencies depending on the track class, the overall material and operational characteristics of the each track.

2.7.1 TRACK GEOMETRY

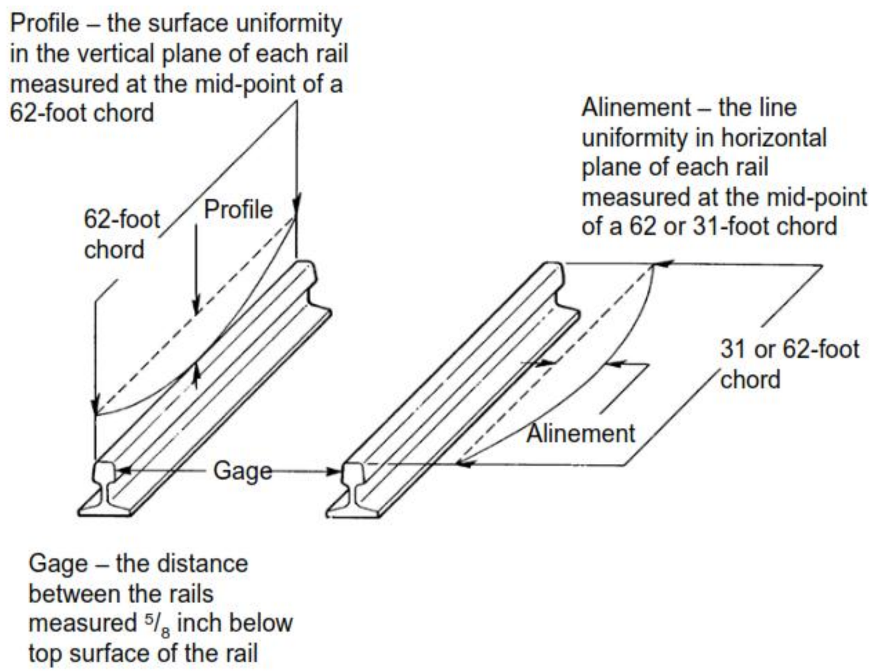


Figure 2-6 Some Track Geometry Parameters (Federal Railroad Administration 2014)

GAGE/GAUGE: Gage is measured between the heads of the rails at right angles to the rails in plane five-eighths of an inch below the top of the rail head.

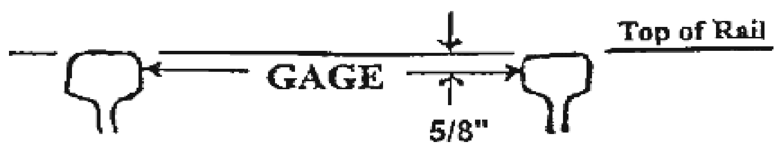


Figure 2-7 Rail Gauge/Gage (MBTA 2000)

Inspectors will make measurements at sufficient intervals to assure that track is being maintained within the prescribed limits. Particular attention should be given to track gage in turnouts or locations where high lateral train forces are expected or evident. These areas include the curved closure rails, the toe and heel of frogs, the curved track behind the frog and several feet ahead of the switch points.

2.7.1.1 TRACK ALIGNMENT

Alinement/Alignment is the variation in curvature of each rail of the track. On tangent track, the intended curvature is zero; thus, the alinement is measured as the variation or deviation from zero. In a curve, the alinement is measured as the variation or deviation from the "uniform" alinement over a specified distance.

Variation in alignment for 62-foot cord on tangent (straight) track: During manual measuring, a 62-foot piece of string is used and pulled taut with each end held against the gage face of one running rail. The measurement (offset) that is recorded in the middle of the string is the measurement that is applied to the table, giving the maximum speed that a train may operate.

Variation in alignment with a 31-foot cord in tangent: The same principles apply as in Item 2, but using a 31-foot cord instead of a 62-foot cord. (TCRP Synthesis 2014)

The point of greatest alinement deviation usually can be detected visually or may be located by moving the chord along the track in increments until the point with maximum deviation is found. A 31-foot chord is particularly necessary for determining short alinement deviations. Inspectors must be aware that a 62-foot chord may be "blind" to short alinement conditions, whereby a 31-foot chord can detect those noncomplying conditions.

Degree of curvature is the angle subtended at the center of a simple curve by a 100-foot chord. Degree of curvature can be conveniently measured using either a 31- or a 62-foot chord. In curves, super elevation is measured by subtracting the relative difference in height between the top surface (tread) of the inside (low) rail from the tread of the outside (high) rail.

2.7.1.2 TRACK SURFACE

Track surface is the evenness or uniformity of track in short distances measured along the tread of the rails. Under load, the track structure gradually deteriorates due to dynamic and mechanical wear effects of passing trains. Improper drainage, unstable roadbed, inadequate tamping, and deferred maintenance can create surface irregularities. Track surface irregularities can lead to serious consequences if ignored.

Allowable deviations in track surface include runoff at the end of a raise, deviation from uniform profile, deviation from zero crosslevel at any point on tangent or reverse crosslevel elevation on curves, and the difference in Crosslevel between any two points less than 62 feet apart (referred as track warp), are specified in the track surface table. (Federal Railroad Administration 2009)

- **Runoff (ramp) in any 31-foot segment** at the end of a raise where the track is elevated as a result of automatic or manual surfacing or bridge work. This criterion expresses the maximum transition in 31 feet to accomplish that activity based on a particular speed. Trains encountering a ramp (up or down) will experience a vertical pitch or bounce if the change in elevation occurs in too short a distance. The following figure illustrates the measurement of the runoff of raised track.

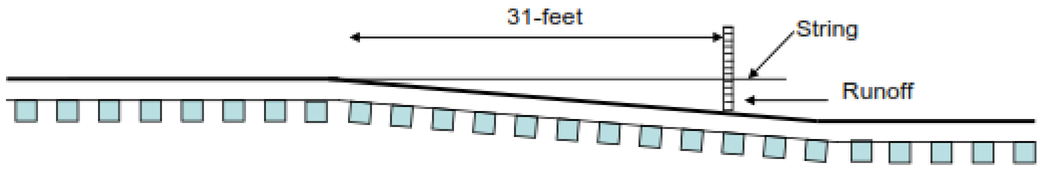


Figure 2-8 Measurement of runoff, FRA 2014

- **Deviation from uniform profile**, relates to the elevation of either rail along the track. When trains encounter short dips or humps in the track it can result in vertical separation of couplers, broken springs, bolsters, and truck frames. Dips can result from mud spots, or develop at the ends of fixed structures (e.g., bridges, highway rail grade and track crossings). A profile is determined by placing the mid-point of a 62-foot chord at the point of maximum measurement, irrespective of vertical curves. The following figure illustrates the measurement of profile conditions.

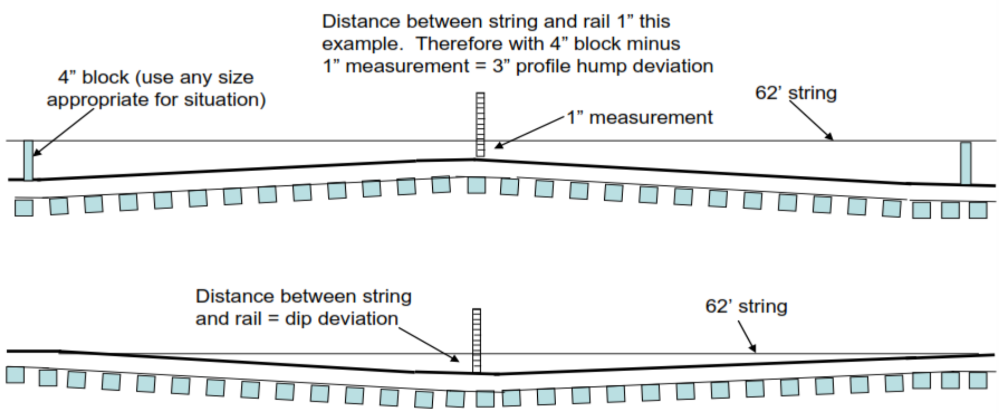


Figure 2-9 Measurement of profile conditions, FRA 2014

- **"Variation" in crosslevel between two points 31 feet apart,** when encountering a spiral that does not have a sufficient length to "runoff" elevation in accordance with the warp parameter, the inspector must determine if the "short spiral" is a result of a man made or other natural obstruction. In short spirals, the amount of warp is determined by measuring the "variation" in crosslevel between two points 31 feet apart. (Esveld 2001)
- **Deviation from zero crosslevel at a point or reverse crosslevel in a curve.** Crosslevel, utilizing a level board, is measured by subtracting the difference in height between the top surfaces (tread) of one rail to the tread of the opposite rail. On tangent track both rails by design should be the same height, a term known as zero crosslevel. (Federal Railroad Administration 2009)

- **Difference in cross level between any two points less than 62 feet apart** is commonly referred to as "warp" parameter. This parameter provides maximum change in crosslevel between two points within specific distances along the track. The warp parameter is the most critical of the surface parameters. Excessive warp contributes to wheel climb derailments.

2.7.2 TRACK STRUCTURE

2.7.2.1 CROSSTIES AND FASTENING SYSTEM

Crossties are evaluated individually by the definitional and functional criteria set forth in the regulations as "non-defective ties or fasteners in 39 feet" or "maximum defective ties in a row for variable curve radius". Crosstie "effectiveness" is naturally subjective and requires good judgment in the application and interpretation of this standard. The soundness and durability of a crosstie is demonstrated when a 39-foot track segment maintains safe track geometry and structurally supports the imposed wheel loads with minimal deviation. Key to the track segment lateral, longitudinal, and vertical support is a strong track modulus, which is a measure of the vertical stiffness of the rail foundation. (TCRP, Transit Cooperative Research Program 2014)

2.7.2.2 RAIL and RAIL JOINTS

Rail wear limits: Neither FRA or APTA have criteria for this. AREMA has recommended practices pertaining to maximum wear limits on the rail.

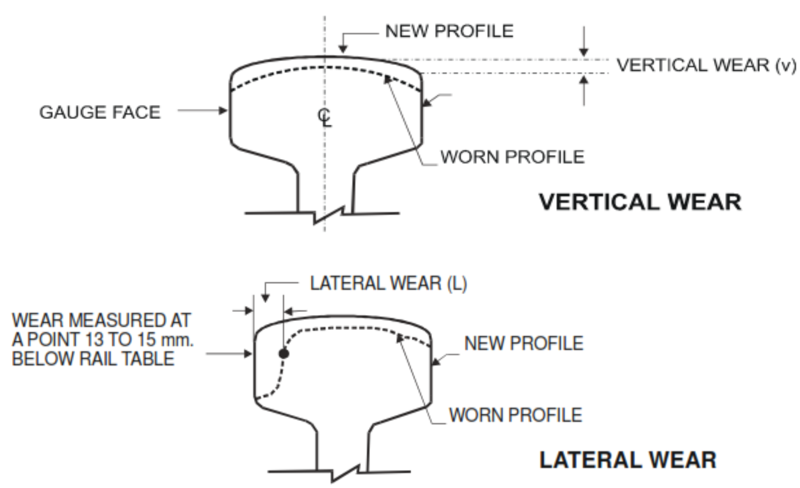


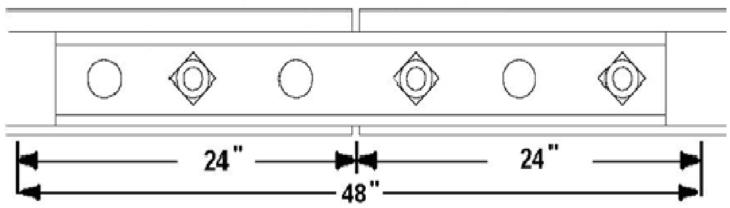
Figure 2-10 Vertical And Lateral Wear

Quarter-cracked joint bars with loose bolts: A quarter crack is a crack in one of the joint bars between the second and third holes in a four-hole joint bar. Or between the third and fourth holes on a six-hole joint bar.

Center-cracked joint bars: This refers to a crack in a joint bar between the middle holes where the two rail ends come together.

Fewer than two bolts per rail for Classes 2–5 and one bolt per rail for Class 1: Each joint must be held tightly together using at least four bolts for Classes 2–5 (two per rail) or two bolts for Class 1 one per rail) in order to comply with this standard. The bolts counted must be tight and secure.

Number of ties within 24 inches of the center of a joint: There must be at least one good tie within 2 feet of the rails coming together. This distance is measured from the center of the joint to the center of the tie. (TCRP, Transit Cooperative Research Program 2014)



Tread mismatch: When two rails are joined together, if there is a difference in elevation creating a "step," then this parameter applies. (Esveld 2001)

Gage face mismatch: The same principles apply as in the above parameter, but on the gage face of the rail, which creates a blunt end for the flange of the wheel to contact. (Esveld 2001)

Rail end batter: This is similar to the above; the difference is how much the end of one rail is worn compared to the wear measurement 18 inches from the end of the rail. Typically, both ends where the rails are joined are worn to the same degree, creating a "speed bump" at the joint.

2.7.2.3 TURNOUT AND CROSSING

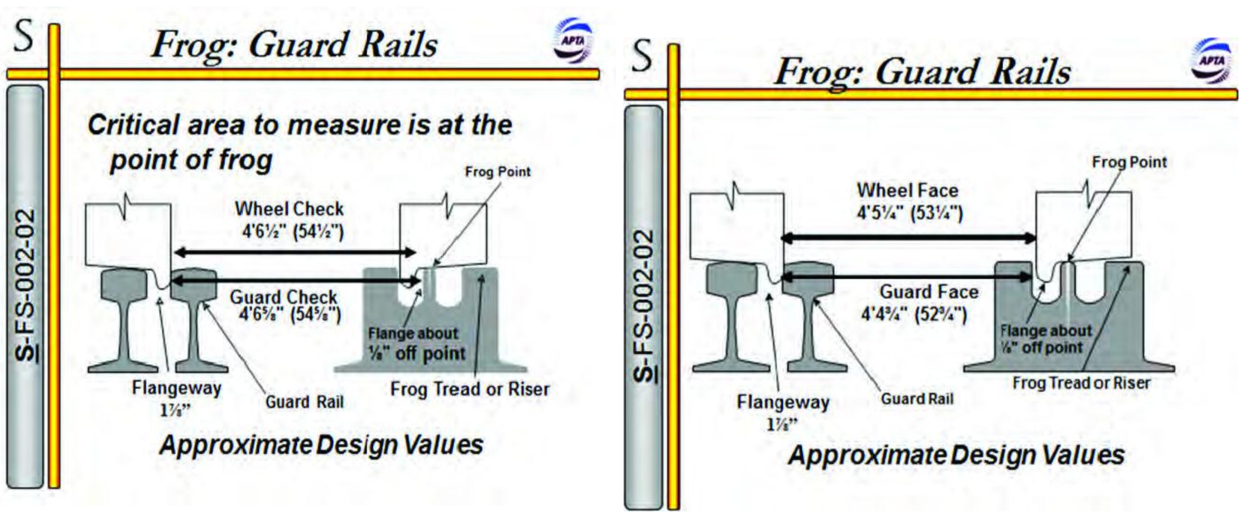


Figure 2-11 Frog, Guard Rails, APTA (TCRP Synthesis 2014)

Restraining rail flangeway: This is the minimum distance between the gage face of the running rail and the back side of the restraining rail (guard rail).

Double guard face gage with restraining rail on both rails: This is a maximum distance measured between both guard faces (from inside to inside). This can be a major factor with different wheel gages. (TCRP Synthesis 2014)

Frog flangeways: The minimum distance between gage line and guard face of the frog creates the flangeway. (Esveld 2001)

Minimum flangeway depth in a frog: This measurement is taken from the tread surface to the bottom of the flangeway in a frog. (Esveld 2001)

Tread wear in frog: this is the same as top wear on rail. The actual measurement is subtracted from the measurement when it was new to give the wear measurement. Typically, the wing rails are not worn at the frog point and can be used as a surface to measure wear with a straight edge.

Guard check gage: This is a measurement from the gage face of the frog to the guard face of the opposing guardrail. This is a minimum measurement. If this measurement is less than the criteria, then there is an opportunity for the wheel operating over the frog to hit the point of the frog or traverse in the wrong direction, causing a derailment.

Guard face gage: This is a measurement taken from the guarding face of the guard rail to the guarding face of the frog. In slang terms, it is called the back-to-back gage. This is a maximum dimension so that the back sides of both wheels do not come in contact with the guarding faces at the same time. (TCRP Synthesis 2014)

2.8 Documentation and Record Keeping

A written record of each track and/or rail inspection required to be performed should be kept on file. The transit agency is required to designate a location where each original record should be retained for at least **two years** after the date of the inspection and for **one additional year** after remedial action is taken (MBTA 2000).

American Public Transportation association (APTA) insists that inspection and maintenance records should be maintained as follows

- Track Inspection: All forms should be complete and retained on file for a **minimum of one year** after the date of inspection. Components of a section of track shall be inspected and their condition recorded on an inspection form, with all deviations or deficiencies recorded on the form. All forms shall be submitted daily for review, file or remedial action. (APTA 2004)
- Rail Inspection: Records shall be maintained for **a minimum of two years after inspection and one year after remedial action.** Records shall show the nature of defects, location of flaw and action taken. Broken rails must be reported using a standard form. (APTA 2004)

Federal Railroad Administration (FRA) contains a requirement that the track owner maintain a record of the inspection data and the exception record for the track inspected in accordance with this section for a minimum of **2 years**. The record must include: (Federal Railroad Administration 2014)

- The date and location of limits for the inspection,
- Type and location of each exception,
- The results of field verification, and
- Any remedial action if required.

The location identification must be provided either by milepost or by some other objective means, such as by the location description provided by the Global Positioning System. (Federal Railroad Administration 2014) According to Federal Railroad Administration, record should be kept and documented as follows;

- The track inspection form will record the section of system walked, date of walk, track walked, and which components are defective. The severity of any defect that might require corrective action. Sign and submit all forms daily to the track supervisor. Keep forms on file for a minimum of **one year** from date of inspection.
- Broken rails must be reported using a standard form. Record on ultrasonic rail flaw detection charts the nature of defects and the location of flaw and the action taken. Maintain ultrasonic rail flaw detection charts for a minimum of **two years** after inspection and **one year** after corrective action.

- Record CWR defects on a track inspection form for a minimum of **two years** after inspection and **one year** after corrective action.
- Maintain geometry records for **three years**.
- Record switch defects on track inspection form and keep forms on file for a minimum of **one year** from date of inspection.

According to (Railcorp 2010) Track Inspection manual, all track defects that are detected MUST be recorded in an identifiable Defect Management System. An auditable trail must exist for all actionable defects from detection/notification to investigation, assessment, repair programming, repair action and certification.

The 'System' must include, as a minimum, the following details: (Railcorp 2010)

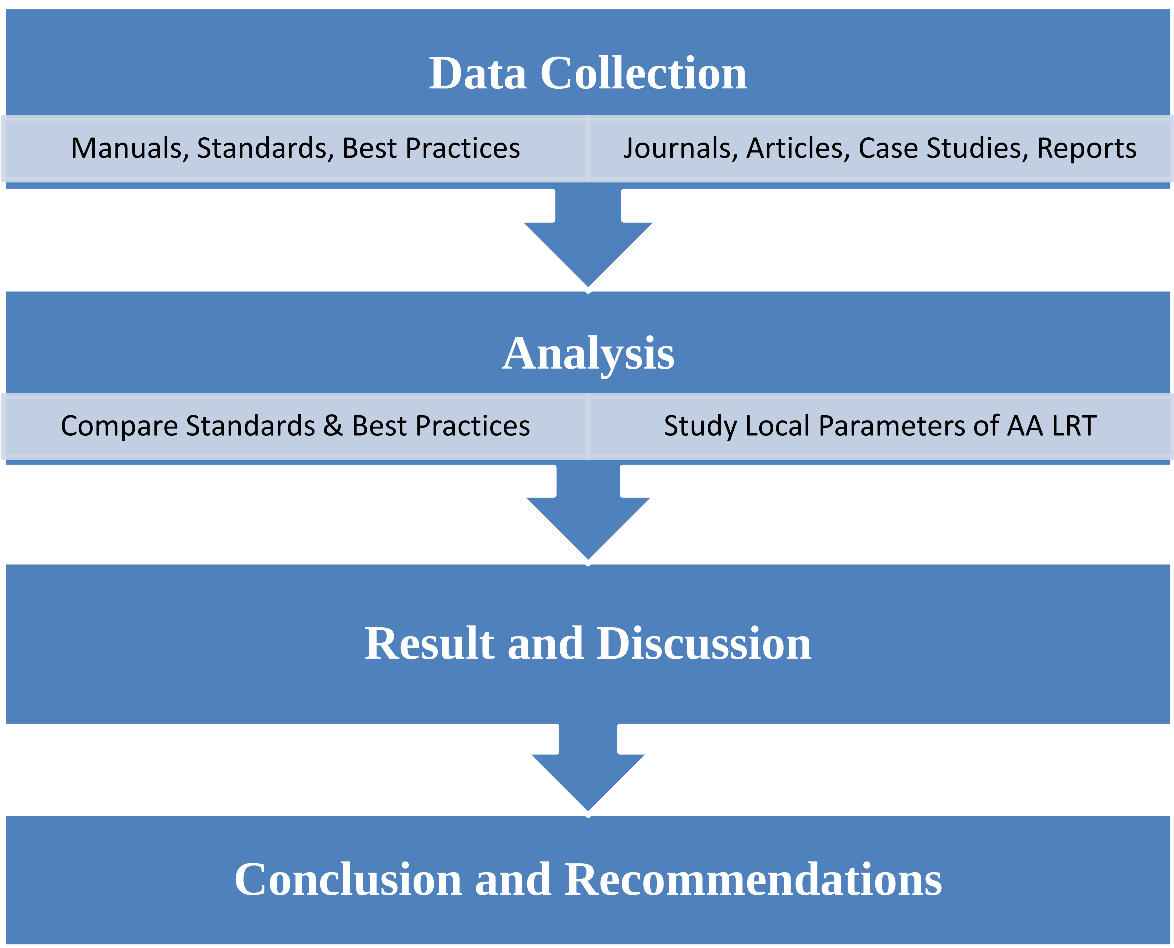
- ✓ Defect
- ✓ Type
- ✓ Size
- ✓ Location (line, track and kilometers)
- ✓ Date found
- ✓ Source of information
- ✓ Action required (includes investigation, assessment, repair)
- ✓ Programmed action date (includes investigation, assessment, repair)
- ✓ Repair action
- ✓ Repair date
- ✓ Repair agency
- ✓ Review of performance

At any time the Civil Maintenance Engineer must be able to demonstrate, through the Defect Management System, current status of all defects recordable on the system.

3 METHOD OF ANALYSIS

First, all the track design parameters, track material specifications, tramcar properties and operational parameters used in the Addis Ababa Light Rail Transit are collected for analysis and compared with other experienced countries' standards. Then track inspection manuals, standards and best practices will be collected reference will be made focusing on track maintenance tolerance limits, inspection frequency and inspection methods. All the available data will also be gathered on inspection and maintenance, like reports, case studies and journal articles on track defects, track inspection frequency and different methods of inspection.

Then all the collected data will be compared based on each specific railway standard's design parameters. Comparison will be then made between other experienced countries standards, and best practices with the AA LRT parameters. Then their compliance and applicability with the local design and operational parameters will be checked. Finally, the best and applicable inspection frequency and method will be recommended for AA LRT.



4 ADDIS ABABA LRT PARAMETERS

4.1 Background

The project is located in Addis Ababa, the capital city of Ethiopia, which currently is the location of the head office of African Union. The altitude of the plateau is 2,400m. With an urban population of over 3,400,000, it takes 24% of the total population of Ethiopia. The urban area is 530.14 km, and the density reached 5,607.96/km in 2012.

To effectively solve the problem of urban transportation, especially that of the downtown area, the government of Ethiopia decides to build a light rail in the city of Addis Ababa. This LRT project has two lines, the east-west line and the south-north line with a total length of 31.048km (Phase I). 2.662 km is the sharing section for both E-W route and N-S route, which has the greatest passenger current.

The E-W Line connects the two ends of tor hailoch and ayat, passing through mexico, meskel square, urael church, megenagna and CMC. The E-W Line has a total length of 17.017km, from which 12.896km lies on the subgrade section, 3.905km elevated section, and the rest 0.197km in the underground section. This line has 22 stations, 6 elevated (including 5 common-track stations), 2 underground and the rest on the ground level. The maximum and minimum interval between stations is 1.26km and 0.435km respectively, with an average interval of 0.798km. there are 41 curved sections in this line (5.53km or 31.8% of the line) with a maximum radius of curve 3004m and the minimum radius of curve 154m.

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

4.2 Unique characteristics of the AA LRT

Before going into the unique characteristics of Addis Ababa Light Rail Transit, let's first see what makes Light Rail Transit different from Heavy Rail Transit system and the unique features of the Addis Ababa Light Rail Transit. The following are some of the characteristic features of Light Rail Transit systems:

- LRT's have frequent traffic and consequently a very small headway time. This makes the LRT's sensitive to the development of defects because small defects will grow faster at frequent traffic conditions.
- LRT must be able to safely travel through restrictive alignments, like sharp curves and steep gradients.
- LRT passes through urban central business districts and some shared right-of-way sections with highway traffic.
- A heavy rail system's trains can handle more people (up to 1500 passengers), and can travel faster than a light rail system. An LRT can hold around 255 people in each vehicle, and it can be linked into a train of two or more cars.
- Light Rail Tramcars, most of the time, put relatively small axle load on the rail than heavy rail transits.

All light rail transit systems have their own unique features. The uniqueness may rise from design elements (like design speed and alignment conditions), rolling stock properties (like axle load and configuration, articulation system and floor height) or operating environments. Accordingly, the following are some of Addis Ababa Light Rail Transit's unique features.

- It uses a 6-axle double-articulated (those sections which are hinged to each other so that the car is able to negotiate short-radius curves.) and 70% low-floor Light Rail tramcar.

- The AA LRT has a total of 87 curved sections, 41 in the E-W line (length of 5.53km or 31.8% of the line) and 46 in the N-S line (length of 6.59km or 39.8% of the line). The minimum radius of curve of main line is 50m and that of depot is 25m.

- LRT has a total of 44 stations (22 in the E-W line and 22 in the N-S line).

- A relatively fewer highway-rail grade crossings. There are a total of 12 highway-rail grade crossings, 7 in the East-West direction (at ayat, summit roundabout, cmc, salitemihret roundabout and gurdshola) and 5 in the North-South direction (at kaliti, saris, adey abeba and meshualekia round about).

- The Addis Ababa LRT transports a lot of passengers, with total two-line passenger flow in initial stage, short-term and long-term of 76924 passengers/day, 14061 passengers/day and 23076 passengers/day respectively. The maximum passenger flows of initial stage, short-term and long-term in peak hours are 10000 persons/hour, 18280 persons/hour and 30000 persons/hour respectively. These numbers are significantly larger compared to other LRT agencies

- Operating environment: Addis Ababa has a humid subtropical mild summer climate that is mild with dry winters, mild rainy summers and moderate seasonality. The mean annual temperature is 15.9 degrees Celsius. Average maximum and minimum temperatures are 23 and 9 degrees Celsius, respectively. Total annual precipitation averages 1089 mm (1089 Litres/m^2).

4.3 Technical Parameters

The following are some of the Addis Ababa Light Rail Transit technical parameters from AA LRT feasibility study report (China Railway Group Limited 2009)

i. **Number of main lines**: Double Lines

ii. **Track gauge**: the standard track gauge of 1.435m. No gauge widening.

iii. **Maximum Running Speed**: 70km/h

iv. **Curve Radius:** minimum radius of curve of main line is 50m and that of depot is 25m.

v. **Rail cant**: rail cant of the whole line is 1:40. Rail cant should not be set at the section where the space between two turnouts is less than 50m.

vi. **Superelevation:** Maximum superelevation of curve is 120mm. in case the superelevation adopted is insufficient, it is allowed to use the unbalanced transverse acceleration of 0.4m/s^2.

Super elevation setting; for the rail curve super elevation of reinforced concrete monolithic track bed at underground section, the outer rail is raised by half of super elevation value, and the inner rail is lowered by half of super elevation value; for the rail curve super elevation of other sections, the outer rail is raised by super elevation value.

vii. **Sleeper arrangement:** for the main line, 1600 pairs of sleepers are arranged per kilometer; sleepers are properly denser at the section where the radius of curve ® is not greater than 800m and the gradient is not less than 2%.

viii. **Load:** train axle load $\leq$ 11t

ix. **Maximum Longitudinal Gradient:** 5.5%

x. **The Transverse Draining Grade** of the track bed level shall not be less than 1.5%

4.4 Rolling Stock Parameters

Tramcar Type

- The vehicles for LRT are operated in two directions, and are 6-axle double-articulated 70% low-floor Light Rail tramcar.

Tramcar Size

- The outside dimension of the tramcar should conform to the metro gauge requirements.
- Tramcar Length: 28400mm
- Tramcar Width: 2650mm
- The Distance between Coupler Central Line and the Rail Surface: the distance would be decided after meetings during design process. The Distance between Tramcar Floor and Track Top:

  Low-Floor Area: 365mm
  High-Floor Area: 865mm
  Low-Floor Rate: 70%
- The Distance between Track Top and Tramcar Top (Tramcar Height) =3700mm
- Wheel Base: 1900 mm for power bogie and 1600 mm for driven bogie
- Wheel Diameter:

  Motor Wheel: 660mm (half-wear: 640mm)
  Driven Wheel: 600mm (half-wear: 580mm)

Main Parameters

- Gauge: 1435mm
- Minimum Curve Radius: 50m for mainlines, 30m for parking garage
- Minimum Vertical Curve Radius: 1000m
- Maximum Gradient: 50‰

Tramcar Performance

- The Highest Speed: 80Km/h
- Weight of Tramcar: 43t
- Weight of Axle: ≤11t
- Average Acceleration for Start-Up: 1m/s^2 (0-40Km/h)
- Average Deceleration for Braking: from 80Km/h to stop
  i. The Average Deceleration of Normal Braking with Rated Load (including control response time): ≥1.0m/s
  ii. The Average Deceleration of Emergent Braking with Rated Load (including control response time): ≥1.5m/s
- Ratio of Acceleration and Deceleration: 0.75m/s^3

4.5 Track Design Specifications

The rail is designed as first-time-laying CWR (Continuous Welded Rail) track according to Chinese urban rail transit light rail standards.

i. Rail

The CWR section of main line is laid with 50kg/m 25mU71Mn hot-rolled non-porous new rail; buffer zone and jointed track section is laid with 50kg/m 25mU71Mn hot-rolled porous new rail. The U71Mn rail, with its tensile strength and yield strength being not less than 880MPa and 457Mpa respectively, enjoys mature welding technology and total-length hardening process.

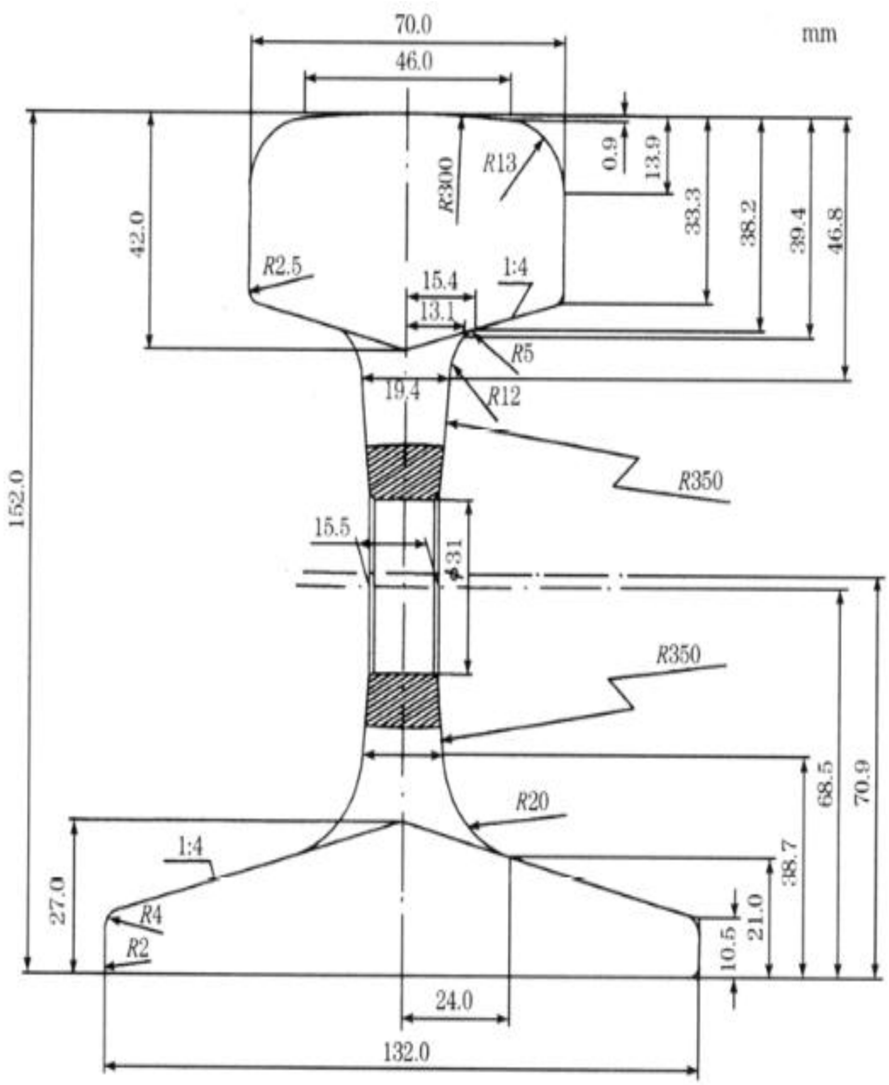


Figure 4-1 the 50kg/m 25mU71Mn Rail Section

ii. Sleepers and fasteners

The ballasted track of main line is laid with 2.5m long new Type-II concrete sleepers and type-I elastic fasteners and elevated section is laid with 50kg WJ-2 small resistance fasteners and monolithic track bed at vertical support rail end.

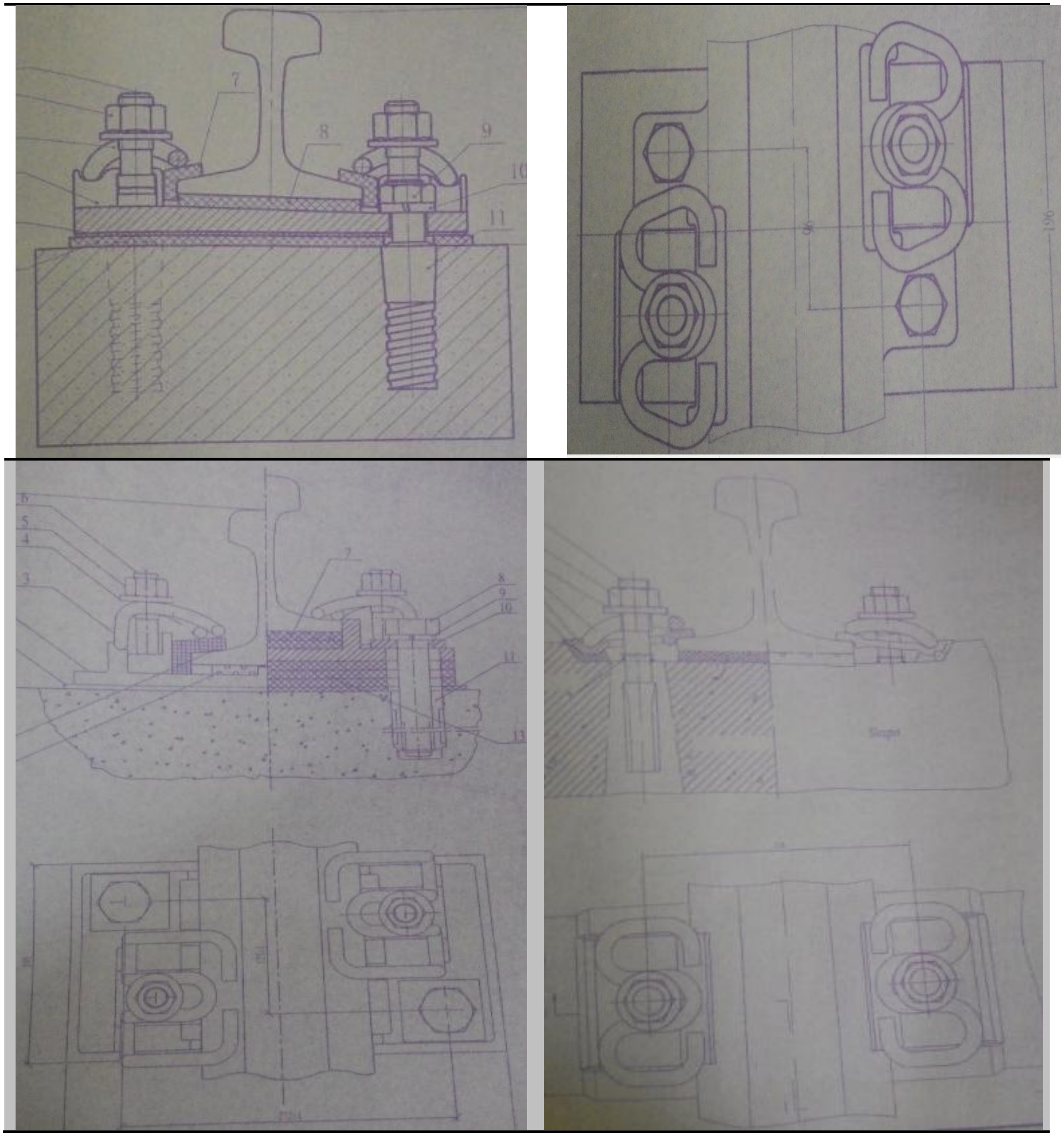


Figure 4-2 WJ-2, Type I Elastic separated and Type I elastic fasteners

iii. Track bed

Ballasted Track Bed is made of 300mm thick single layer gravel ballast. Prestressed concrete sleeper with minimum concrete grade of C60.

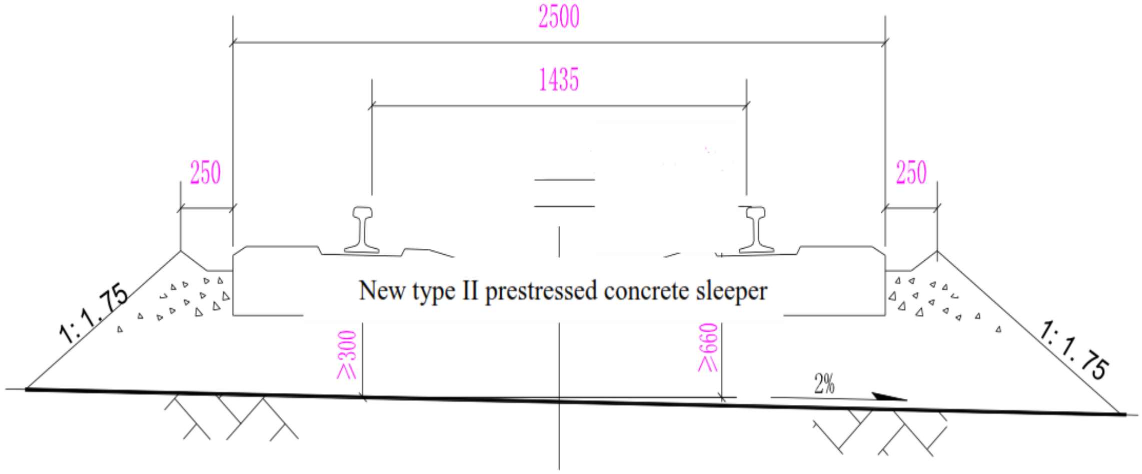


Figure 4-3 Concrete Sleeper Type Ballasted Track Bed for Ground line

In elevated section, the track bed is monolithic track bed on vertical support rail-bed, made of C40 concrete, 800mm wide;

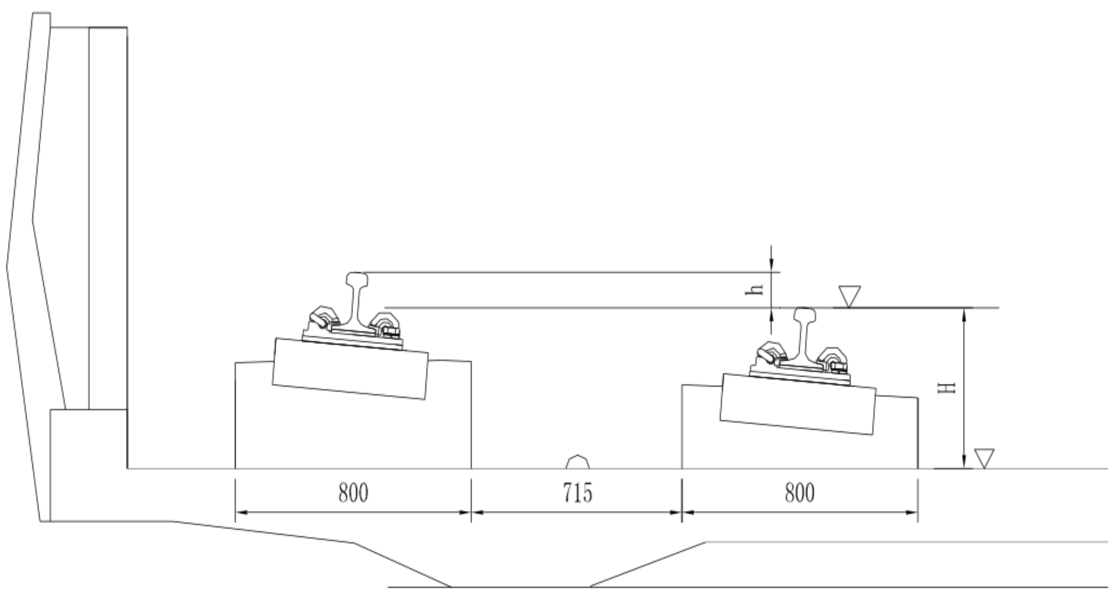


Figure 4-4 Monolithic Track Bed for Elevated Line

In underground section, the track bed is fully-laid monolithic track bed made of C30 concrete. Concrete short sleeper has a minimum concrete grade of C50.

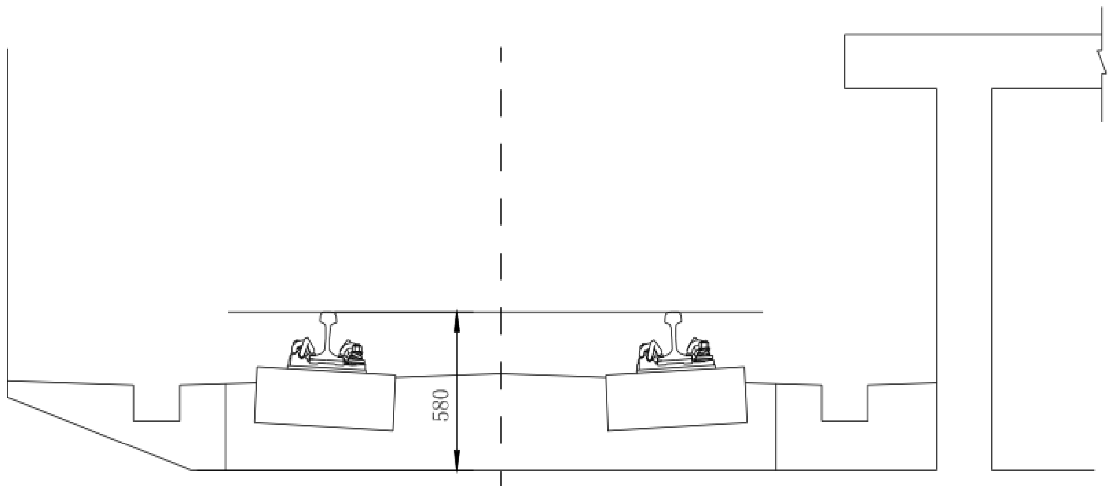


Figure 4-5 Reinforced Concrete Track Bed with Short Sleeper for Underground Line

iv. Turnouts

The selection type for turnouts is determined by vehicles' operation conditions, lines' turnaround capability, convenient maintenance and the saving-land principles.

No.7 turnout with 50kg/m rail

This turnout is mostly used in national railways and subways based on many applicable use suggestions. The lead curve's radius is 150m, the railroad switch uses 50AT curve switch rail, and the heel uses irony separation union swivel for connection. The turnouts uses high manganese steel fixed frog and split guard rail, so the side passing speed is 25km/h. it is equipped with a single point traction, which is suitable for interlocking. It has a total length of 23.627m.

No.3 turnout with 50kg/m rail

The #3 turnout is recommended for single turnout, because the depot land occupation is small and the approach speed is less than 10km/h. This turnout is not standard, so it is designed specially. The sleeper may be wood sleeper or short concrete sleeper (which is the case for AA-LRT), with the lead curve radius of 25m.

5 COMPARISON OF INSPECTION PARAMETERS

In most countries in the world speed-based track classification system is mostly used by the rail transit agencies. Canada and U.S.A, for instance, has a speed based track class identification system, which the maintenance criteria is also depend on. Their classification is as shown below

Table 5-1 Railway Track Class (APTA 2004)

RAILROAD CLASS	Maximum Allowable Train Speed (Mph)	Maximum Allowable Train Speed (km/hr.)
1	15	24
2	30	48
3	60	96
4	80	128
5	90	145

The Tolerance Limits for two selected railway safety standards and 10 railroad agencies are prepared in the following tabular form. Since the Addis Ababa LRT falls under class-3, (having a maximum design speed of 70km/hr. (43mph), only class-3 deviations are taken from the manuals. The details about the items or criteria are explained in the previous section. The surveyed Class-3 railway agencies are:

- Massachusetts Bay Transportation Authority (MBTA)
- San Francisco Municipal Railway (MUNI)
- Edmonton Light Rail Transit
- Minneapolis Metro Transit
- Greater Cleveland Regional Transit Authority
- Maryland Transit Administration
- Metropolitan Transit Authority Of Harris County
- Niagara Frontier Transit Metro System
- Santa Clara Valley Transportation Authority
- Southeastern PA Transport. Auth. (SEPTA)
- Central Puget Sound Regional Transit Authority
- Utah Transit Authority (UTA)

The agencies are selected considering the maximum design speed of 60mph, gauge width (standard gauge), material specification (ballasted tracks, concrete sleepers), and headway time of 4-12 minutes. A total of 12 standards and manuals are referred, from each inspection and maintenance safety standard, track inspection frequency and safety tolerance limits for each inspection parameter, are compared with each other in the following table.

FOR CLASS-3 (passenger speed = 30mph - 60mph)

ITEM	Description of defect		APTA		FRA		MBTA		Maintenance Criteria of Other Agencies in U.S.																	
									1		2		3		4		5		6		7		8		9	
			Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in
1	Variation from standard gauge		- 1/2	1 1/4	- 1/2	1 1/4	5/16	1 1/4	-1/8	3/4	-1/4	1/2	-1/2	5/8	-3/8	5/8	-7/16	1	-3/8	3/4	-1/8	1	-1/2	1 1/4	-3/8	3/4
2	Variation In Alignment	62' chord - Tangent		1 3/4		1 3/4		1 1/2		1/2		NC		3/4		1 1/4		1 1/2		3		NC		1 3/4		1 1/2
		31' Curve		1 1/4		1 1/4		1		1/4		1/2		3/4		1 1/4		1		2 1/2		3/4		1 1/4		1 1/4
3	Runoff in 31'			2		2		1 1/2		1/2		2		NC		1		1 1/2		2 1/2		2		2		1 1/2
4	Surface deviation 62' chord	62'		2 1/4		2 1/4		2		3/4		NC		NC		1		2 1/4		2 1/4		2 1/4		2 1/4		2
		31'		1/2		NC		NC		NC		9/16		7/8		NC		1/2		NC		1 1/4		NC		NC
5	Deviation from zero cross level in 62'			1 3/4		1 3/4		1 1/4		1/2		1 3/4		1/2		1 1/4		1 3/4		1 3/4		1 3/4		1 3/4		1 1/4
6	Warp/Twist	62'		2		2				5/8		NC		NC		1 1/4		2		1 3/4		1 3/4		2		1 3/4
		31'		1 1/2		1 1/4		1		NC		NC		NC		NC		1 1/2		NC		1 1/2		1 1/4		NC
7	Non defective ties or fasteners in 39', [ ] = out of 10		8		8		8		16		8		20 in 62'		[6]		11		8		8		8		8	
8	Non defective ties in 39', for greater than 2˚ curve		NC		10		NC		16		9		20 in 62'		NC		9		9		NC		10		9	
9	Maximum defective ties or fasteners on a row	R>2000'		4		NC				2		2		3		3		4		3		4		NC		3
		2000'>R>1000'		3		NC				2		1		3		2		3		NC		3		NC		NC
		1000'>R		2		NC				2		1		3		1		2		2		2		NC		2
10	Center cracked joint bars		Replace		Replace		Replace		Replace Immediate		Replace Immediate		Replace Immediate		NC		Replace		Replace		Replace		Replace		Replace	
11	Torch cut holes or torch cut rail		Replace rail		Replace rail		Replace rail		NC		Not Permitted		Not Permitted		Not Permitted		Replace rail		Replace rail		Replace rail		Replace rail		Replace rail	
12	No. of ties with in 24'' of the center of a joint		2		2		2		1 within 12"		1 within 18"		NC		NC		2		2		2		2		2	
13	Tread Mismatch			3/16		3/16		5/16		3/16		3/16	NC			1/8		3/16		1/4		3/16		3/16		1/4
14	Gage face mis-match			3/16		3/16		3/16		3/16		3/16	NC			1/8		3/16		3/16		3/16		3/16		3/16
15	Rail end batter			3/16		3/16				1/8		1/4	NC			3/16		3/16		1/4		3/16		3/16		1/4
16	Restraining rail flangeway ( ) = from design		1 1/2		1 1/2		1 3/4		NC		1 3/4	2 3/4	NC		1 1/2		NC		-1/4	1/4	1 1/2		1 1/2			1 7/8
17	Double guard face gauge with restraining rail on both running rails			3/8		NC		NC	NC			3/8	NC		NC		NC		NC			7/16	NC			1 3/4
18	Frog flangeways		1 1/2		1 1/2		1 1/4		1 3/4	2	NC		NC		1 1/2		1 1/2		1 1/2		1 1/2		1 1/2		1 1/4	

Table 5-2 Standards' tolerance limits for deviation of track parameters

ITEM	Description of defect	APTA		FRA		MBTA		Maintenance Criteria of Other Agencies in U.S.																	
								1		2		3		4		5		6		7		8		9	
		Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in	Min in	Max in
19	Minimum flangeway depth in a frog	1 1/2		1 1/2		11/16		1 1/2		1 1/2		NC		1 1/2		1 1/2		1 1/2		1 1/2		1 1/2		NC	
20	Tread wear in frog		3/8		3/8		3/8		NC		NC		3/8		3/8		3/8		3/8		3/8		3/8		3/8
21	Guard check gage	- 1/4		- 1/4		- 1/4		-1/8	3/8	-1/4		-1/4		-1/4		-1/8		-3/8		-1/8		-1/4		-3/8	
22	Guard face gage		3/8		3/8			-1/8	1/4		1/4		3/8		1/4		1/4		3/8		1/8		3/8	NC	
23	Frequency of hi-rail or walking inspection on mainline or siding	weekly		weekly		3 times/week		weekly		Twice weekly		Monthly		Monthly		Twice weekly		Twice weekly		Twice per Month		weekly		Twice weekly	
24	Frequency of Geometry car testing on mainline	once per year		NC		NC		3 times per year		3 times per year		Every 2 years		Twice per year		Twice per year		4 times per year		Once per year		Once per year		Once per year	
25	Switch, and track crossing inspections	NC		NC		monthly																			
26	Frequency of Gauge Restraint (GRMS) test on mainline: >2MGT >30mph pass	NC		Annually		NC		NC		NC		NC		NC		NC		NC		NC		NC		NC	
	<2MGT <30mph pass	NC		24 months		NC		NC		NC		NC		NC		NC		NC		NC		NC		NC	
27	Frequency of rail flaw detection Testing on Mainline	once per year		once/40mgt or once/year whichever is shorter		NC		Twice per year		6 times per year		once per year		Twice per year		Twice per year		Twice per year		Once per year		Once per year		Once per year	
28	Rail wear limits (Gage-top)	NC		NC		NC		5/8	5/8	7/16	1/2	1/2	5/8	5/8	1/2	1/2	1/4	3/4	1/2	NC		NC		7/8	1/2
29	CWR Plan (yes or no)	Yes		Yes		Yes		Yes		Yes		No		Yes		Yes		Yes		No		Yes		No	

Min In = Minimum requirement in inches
Max In = Maximum requirements in inches
NC = No Condition
APTA is the American Public Transportation Association, **FRA** is the Federal Railroads Administration **MBTA** is Massachusetts Bay Transportation Authority LRT

5.1 TRACK GEOMETRY

Although the major principles of LRT geometry design are similar or identical to that of freight/commuter railways, the LRT must be able to safely travel through restrictive alignments, like sharp curves and steep gradients, typical of urban central business districts, including rights-of-way shared with automotive traffic.

Track geometry can deteriorate because of frequent passage of heavy traffic, climate changes (weather), variations in soil conditions and geotechnical movements. Track geometry degradation may also be caused by re-arrangement of ballast particles due to loads and vibrations from passing train, although rate of degradation is very different from section to section even for apparently identical sections carrying the same traffic.

The interaction between track components under a moving wheel load causes a large impact load, which increases with increasing track irregularity and train speed. This is because impact load increases with an increase in the size of the gap underneath the sleepers. The impact load increases the stresses on the ballast which, as a result, increases ballast settlement and ultimately results in a larger gap underneath the sleepers. Thus, degradation of track geometry tends to get faster. One the most effective way of restoring a track which has lost his geometry is by tamping. However, this may also result in ballast break downs if improperly performed.

5.1.1 Gauge

The Addis Ababa Light Rail Transit is characterized by a lot of curves in its alignment. It has totally 87 curved sections, 41 in the E-W line (5.53km or 31.8% of the line) and 46 in the N-S line (6.59km or 39.8% of the line). So particular attention should be given to those curved sections due to high lateral train expected to be applied on the rail which consequently might cause side rail wear and gauge widening if supported by loose fastenings.

The surveyed railway agencies has a safety tolerance limits ranging from 0.5inch (12.7mm) up to 1.25inch (31.8mm) depending on their own unique design and operational parameters. A relatively small safety tolerance limit for gauge widening of 20mm is suggested considering those high number of curves in the AA LRT in addition to the design speed comparison shown in the table above.

Track maintenance safety standards for tight track gauge are more restrictive, with reduced free play, and a minus tolerance of zero is recommended. Consequently, most inspection and safety standards has a zero minus tolerance. Track gauge narrowing has been specifically employed at small radius curves to reduce the angle of attack and thus noise and gauge face wear. Gauge widening at any curve is not recommended, as such will promote high angle of attack.

Inspectors will make measurements at sufficient intervals to assure that track gauge is being maintained within the prescribed limits. Particular attention should be given to track gauge in turnouts or locations where high lateral train forces are expected or evident, like curved alignment sections.

5.1.2 Track Alignment

The track reacts to the forces imposed by passing traffic with damage or loosening of fastenings, erosion of the underside of the sleepers, fouling of the ballast bed. Inadequate or failed drainage systems or an insufficient ballast bed also reduce the carrying capacity of the track system, as they result in deviation from design track alignment.

Light Rail Transit systems are typically operated in dense urban areas, which frequently results in systems that contain a large number of curves with small radii that can increase wheel and rail wear and increase the potential for flange-climb derailments.

Several factors are likely to contribute to increased bending stresses in the curved concrete tie track. The concrete tie section with joints has track with higher lateral stability on one end and lower lateral stability on the other end. This may cause lateral movement of whole track panel. Rounded ballast and powdery ballast surface conditions will be observed in this area, which is indicative of higher levels of ballast degradation and alignment deviation.

A safety tolerance limit for track alignment in the 31 and 62 feet chord is compared from the standards and a maintenance threshold limit of 35mm for 62 feet and 25mm for 31 feet chord is suggested considering following, in addition to the design speed comparison.

- <u>Number of Curves:</u> The Addis Ababa Light Rail Transit has a lot of curves in its alignment, having a total of 87 curved sections, 41 in the E-W line (5.53km or 31.8% of the line) and 46 in the N-S line (6.59km or 39.8% of the line). Minimum radius of curve of main line is 50m and that of depot is 25m. So particular attention should be given to those curved sections due to high lateral train expected to be applied on the rail which consequently might cause gauge widening and deviation of track geometry.
- <u>Passenger safety:</u> a small tolerance limit for horizontal alignment is allowed since the Addis Ababa LRT transports a lot of passengers, with total two-line passenger flow in initial stage, short-term and long-term of 76924 passengers/day, 140616 passengers/day and 23076 passengers/day respectively. The maximum passenger flows of initial stage, short-term and long-term in peak hours are 10000 persons/hour, 18280 persons/hour and 30000 persons/hour respectively. These numbers are significantly larger compared to other LRT agencies

5.1.3 Track Surface

Under load, the track structure gradually deteriorates due to dynamic and mechanical wear effects of passing trains. Improper drainage, unstable roadbed, inadequate tamping, and delayed maintenance can create surface irregularities. Track surface irregularities can lead to serious consequences if ignored.

The forces exerted on the track must be resisted by corresponding reactive forces: obviously these forces are not only in the vertical direction, but also longitudinal (due to braking and traction in the vehicles) and lateral (due to the effect of guiding the vehicles' path). The magnitude of the forces is a function of axle load, wheel load variation due to curvature of the running path, or due to inequalities in braking and traction effort, and the impact of wheels which are not perfectly round or concentric, or which are out of balance, on a track that itself has imperfections.

The Addis Ababa Light Rail Transit has a Maximum longitudinal gradient of 5.5%. Rail cant of the whole line is 1:40. Maximum superelevation of curve is 120mm. in case the superelevation adopted is insufficient, it is allowed to use the unbalanced transverse acceleration of $0.4m/s^2$.

There are also several stations in our LRT (44 stations, 22 in both sections of the E-W and N-S line). Since these stations are locations of accelerated top-of-head rail wear due to occasional use of track brakes, it increases the rate of tread wear thereby causing track surface deviation.

Several situations can result in twist that can unload one wheel of a truck, like misalignments in the track surface such as a low rail joint that has dropped some measurable distance below the plane of the rails and track superelevation transitions where the profile of one rail is rising relative to the other.

5.2 TRACK STRUCTURE

5.2.1 Crossties and Fastening System

Crossties are evaluated individually by the functional criteria set forth in the regulations as "non-defective ties or fasteners in 39 feet" or "maximum defective ties in a row for variable curve radius". Crosstie "effectiveness" is naturally subjective and requires good judgment in the application and interpretation standards.

The soundness and durability of a crosstie is demonstrated when a 39-foot (12m) track segment maintains safe track geometry and structurally supports the imposed wheel loads with minimal deviation. Key to the track segment lateral, longitudinal, and vertical support is a strong track modulus, which is a measure of the vertical stiffness of the rail foundation.

For the Addis Ababa LRT main line, 1600 pairs of sleepers are arranged per kilometer; sleepers are properly denser at the section where the radius of curve [R] is not greater than 800m and the gradient is not less than 2%. If a track has Less than 8 non-defective sleeper/fastening systems, it cannot provide the expected vertical support and lateral restraint. Restraint must allow no lateral movement of the fastenings relative to the sleeper. Non-defective fasteners should also camp vibrations and impacts caused by traffic as much as possible. Non-defective sleeper must provide gauge restraint and must be one piece that will not separate along its length or transversely.

5.2.2 Rail and Rail Joints

The high contact forces, the effect of wheel slip, and vehicle guidance forces impose heavy demands on the rails. This can lead to rail head defects such as corrugation, wheel slip faults, head checks, and to excessive side wear in curves due to the curving effect of wheels.

Rail wear limits: Wear reduces the overall cross-sectional area of the rail, which increases the magnitude of bending and normal stresses in the rail, thereby weakening the capacity of the rail to carry load. Wear is not a rail defect in the same sense as a crack, which is a stress raiser and intensifies the local state of stress, but it is a cause of rail removal.

Neither FRA nor APTA have criteria for this. AREMA has recommended practices pertaining to maximum wear limits on the rail. The limits for rail head wear are based on the rate of defect growth, how often the rail is inspected, and the fracture toughness of the rail steel.

The limits shown for railroad practice may also be based on economic considerations rather than, or in addition to, fracture strength. In establishing tolerance limits for rail wear, other issues need to be taken into consideration in addition to fracture strength. For example,

- The vertical wear limit may be affected by wheel flange design, design of joint bars (including insulated joints), wheel-operated rail lubricators, etc.
- Side wear limit is affected by flange climb, vehicle dynamics (e.g., wheel conicity and hunting), gauge widening, etc.

Tractive effort and braking forces result in rail wear and deformation of rail head. Stations/stops are usually locations of accelerated top-of-head rail wear due to occasional use of track brakes. It generally takes a very long time for rail to wear out in the LRT environment. Significant wear will usually be observed only in sharp curves or at locations where heavy braking occurs.

Since the Addis Ababa LRT has a lot of stations (22 in the E-W line and 22 in the N-S line) and curved sections (86 curved sections), we should be more restrictive for our case. The effect of tractive efforts and braking forces is even higher with small wheel diameters, like the case of the AA LRT having a minimum tramcar wheel diameter of 600mm. This is due to the continuous rubbing action, a point will got heated and if the diameter is small, that point comes repetitively before it gets cooled off. At that point of high heat the amount of energy dissipated will remain at high level which in turn leads to more rail wear and deformation.

Reduction of wheel/rail wear can be achieved by optimization of wheel/rail profiles, properly designed truck primary suspension, improvement of track maintenance, and application of lubrication.

Rail Joint

According to FRA's accident data, a total of 242 accidents related to joint failures occurred from 2000 to 2009. Most joint bar failures occurred due to cracks initiated from bolt holes or at the bottom or top edges of the joint bars.

Figure 5-1 Bolted rail joint, Addis Ababa LRT

There must be at least one good tie within 2 feet (60cm) of the rails coming together to ensure proper support and to avoid the problem of rail end mismatch in the form of tread mismatch, gauge face mismatch and rail end batter. This distance is measured from the center of the joint to the center of the tie.

Rail End Mismatch

Rail end mismatch tolerance limit, is listed on the regulations in three items; Tread mismatch, gage face mismatch and rail end batter. Tread mismatch parameter applies when two rails are joined together, if there is a difference in elevation creating a "step," then this parameter applies. Gage face mismatch is the same as tread mismatch but on the gage face of the rail, which creates a blunt end for the flange of the wheel to contact. When we talk about the parameter 'Rail end batter,' the difference is that it shows how much the end of one rail is worn compared to the wear measurement 18 inches (45cm) from the end of the rail. Typically, both ends where the rails are joined are worn to the same degree, creating a "speed bump" at the joint. Measurement of gauge and tread mismatch is shown in figure below;

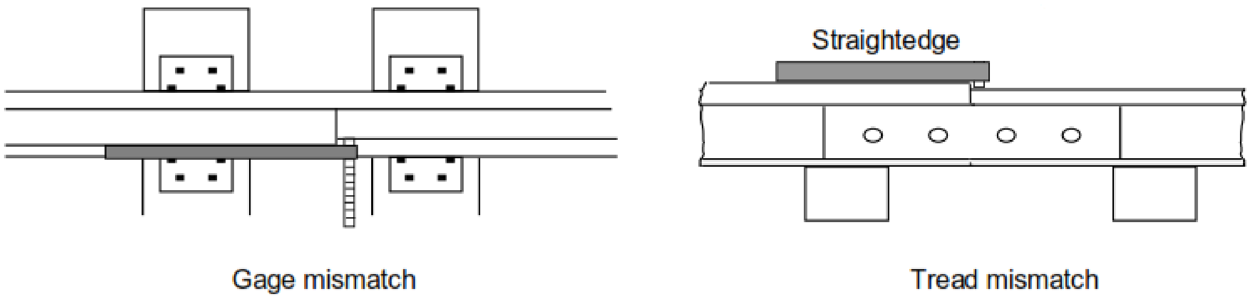


Figure 5-2 Rail End Mismatch, FRA

5.2.3 Turnout and Crossing

The AREMA Portfolio of Track work Plans, Point and Flangeway Dimensions, provides a designed flangeway depth of at least 1⅞ inches. Therefore, the amount of clearance between a worn wheel with a high flange and the bottom of a new frog's flangeway may be as little as three-eighths inch. At higher speeds, if a worn frog has a flangeway less than 1½ inches, the wheel flange could find the lowest point in the flangeway and result in severe damage to the frog.

APTA, FRA and 6 other railroad agencies permit a flangeway depth of 1½ inches in Class 3 track. In such a condition, a wheel that is approaching condemning limits might contact the bottom of the flangeway and it is possible to have evidence of wheel flangeway contact on the bottom of the flangeway caused by compliant wheels.

Flangeway dimension requirements are a function of the wheel profile and curve radius used. The wheel flange width and the back-to-back wheel flange distance determine the appropriate wheel flange clearance. The flangeway depth must be sufficient to accommodate dirt and debris without causing wheel lift. Due to these reasons a minimum flangeway depth of 2 inch (50mm) is suggested for the Addis Ababa LRT.

Restraining rail flangeway is the minimum distance between the gage face of the running rail and the back side of the restraining rail (guard rail). However, the thresholds at which restraining rails are applied varies greatly from system to system, Some transit agencies guard any curves with radii less than 1200 feet [365 meters], while others do not guard curves with radii larger than 300 feet [91 meters]. Depending on the curve radius and the truck factors, the flangeway is typically 1 ¼ to 2 inches [32 to 50 millimeters] wide.

An LRT system using wheel flanges that are short, such as those at AA LRT lines (600mm diameter wheel), will have a greater need for curve guarding than one that uses larger wheels with tall flanges. This is because the lateral wheel loading is distributed over a narrower contact band along the side of the rail head thereby increasing contact stresses and resultant wear on both wheel flange and rail.

The working face of the restraining rail bears against the back side of the flange of the inside wheel, guiding it away from the centerline of track and reducing the lateral contact force between the outside wheel's flange and the outer rail of the curve. This essentially divides the lateral force between two contact surfaces. Experience shows that this greatly reduces the rate of lateral wear on the high rail.

Restraining rails are used to prevent a derailed train from striking other fixed structures or from entering into a danger zone. Restraining rails may be required at the approaches to abutments and portals in some circumstances. Circumstances may include, but are not limited to proximity of special track work, sliding rail joints, horizontal curvature, or the existence of unstable ground conditions.

Restraining rail also, by increasing the rolling resistance force applied along the inner rail, counteracts the tendency of the inner wheels to move ahead of their mates on the opposite end of the axle. This encourages backwards slippage of the inner wheels, rotates the truck in the direction of the curve and thereby reduces the angle of attack between the wheel flange and the outside rail. In all cases, the use of restraining rail in a curve will reduce the tendency of the leading outside wheel to climb the outer rail, thereby preventing possible derailments.

Lower train speeds reduce both lateral acceleration and the consequent lateral forces between the wheel flanges and the rail. This should reduce the lateral component of the L/V ratio, decreasing the probability of a wheel flange climb derailment.

Lubrication of both the gauge face of the outer rail and the top of the inner rail of infrequently used sharp curves has been shown to decrease friction sufficiently to permit safe operation. Transit systems that use short flanges usually have a characteristic stepped wear pattern on the high rail of their curves. Frog flangeways are the minimum distance between gage line and guard face of the frog creates the flangeway.

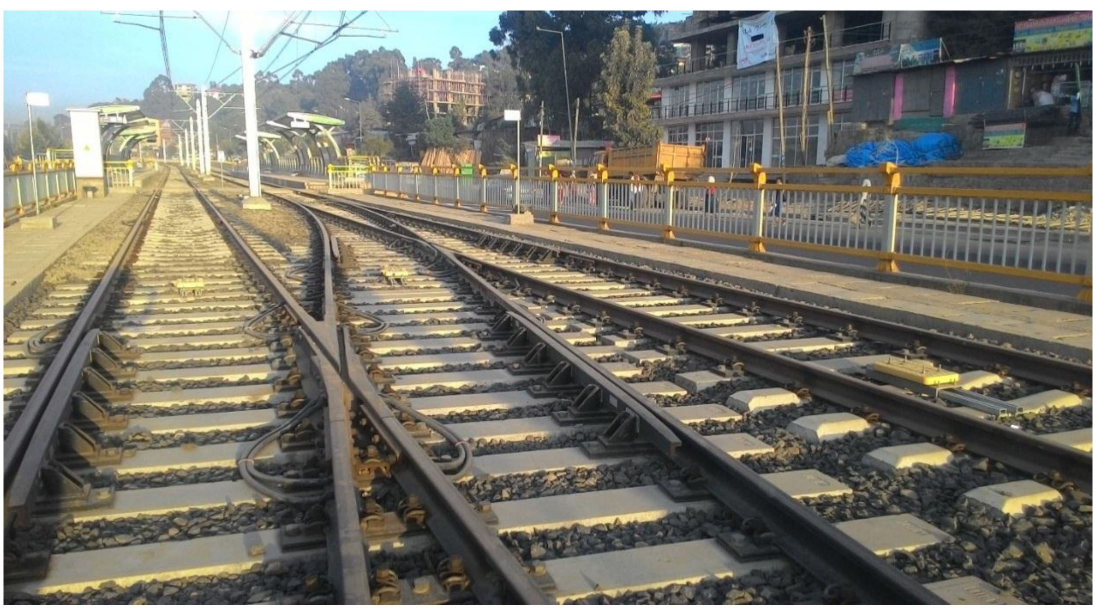


Figure 5-3 Turnout at Addis Ababa LRT, Megenagna

While spring rail frogs have been successfully used for many years, their unique design requires special maintenance attention to avoid derailment hazards to trailing point train movements on the main track. If a spring wing rail is higher than the top running surface of frog at the transition area, a wheel during a trailing move may push the spring wing rail open causing rail roll out or wide gage.

If the tread is worn more than three-eighths of an inch (> ⅜ inch), the corresponding flangeway depth may also be reaching critical limits. Since the manganese frog insert is typically designed to be about 2 inches thick at the wall of the flangeway and about 1⅜ inches or less at the bottom of the flangeway, wear in this condemning range could result in structural failure of the frog.

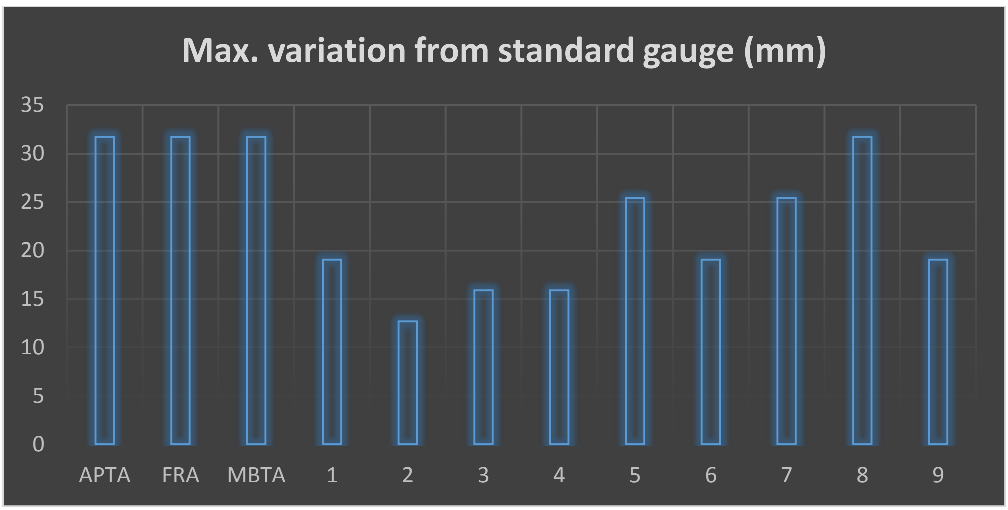
Guard check gage is a minimum measurement. If this measurement is less than the criteria, then there is an opportunity for the wheel operating over the frog to hit the point of the frog or traverse in the wrong direction, causing a derailment.

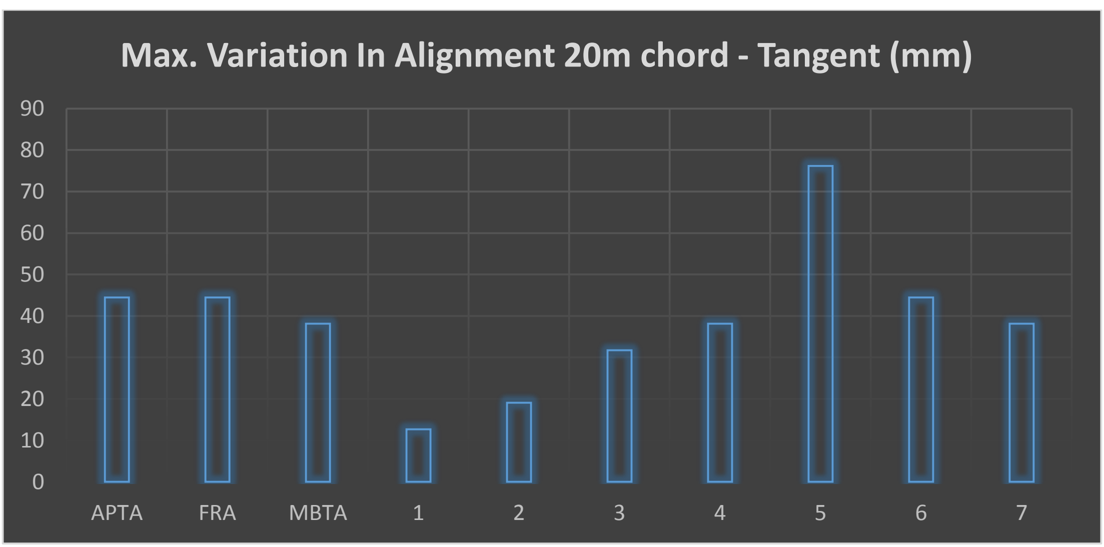
According to FTA, guard rails should be installed for all horizontal curves of radius less than 200 m. Guard rails are installed on the gauge side of the low rail to hold the wheel flange away from the gauge corner of the high rail and prevent excessive wear or derailment.

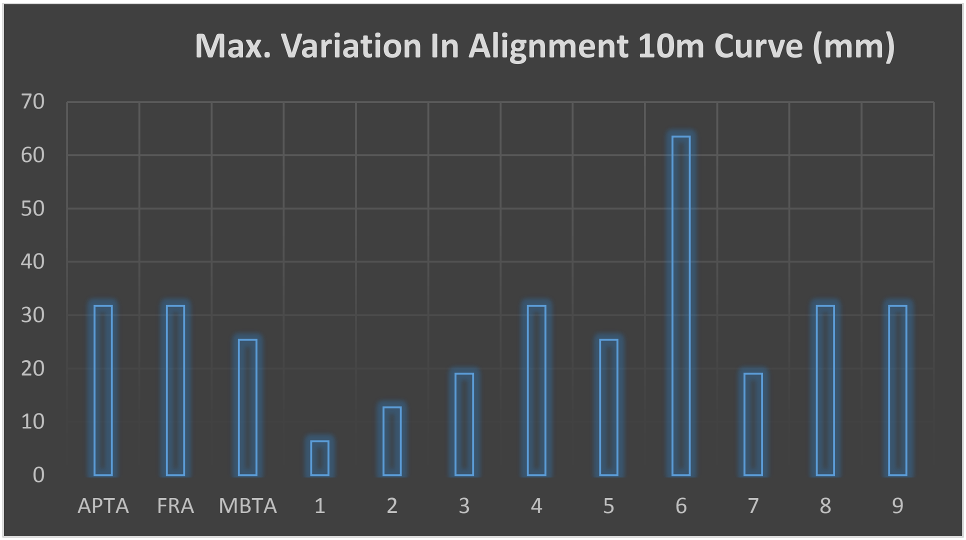
A guardrail must be maintained in the proper relative position to the frog in order to accomplish its critical intended safety function. Inspectors should examine guardrails carefully to see that they are adequately fastened, and when measuring guardrail gage, fully consider any movement of guardrail or frog under traffic conditions. A guardrail is installed parallel to the running rail opposite a frog to form a flangeway with the rail and to hold wheels of equipment to the proper alignment when passing through the frog. Guard face gage is a maximum dimension so that the back sides of both wheels do not come in contact with the guarding faces at the same time.

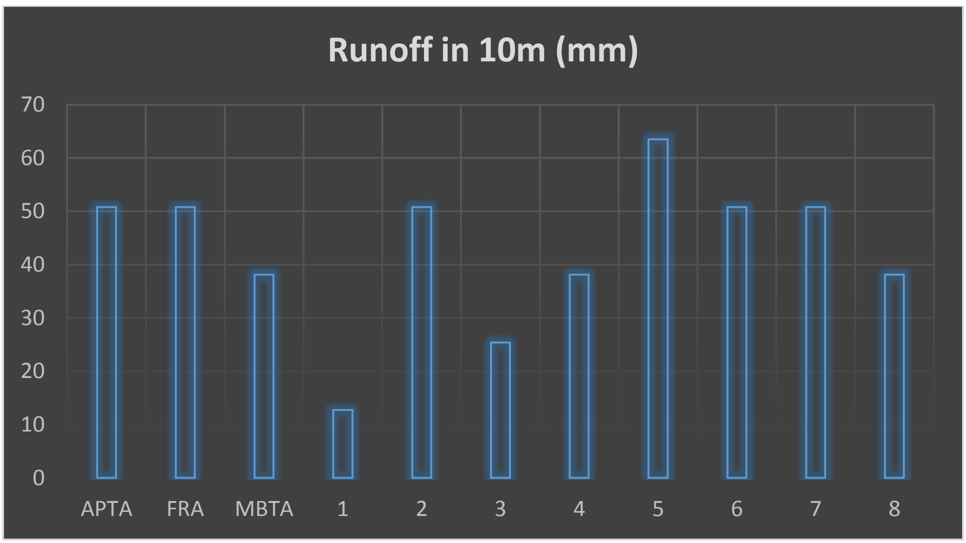
5.3 BAR CHART COMPARISON OF TOLERANCE LIMITS FOR EACH INSPECTION PARAMETER

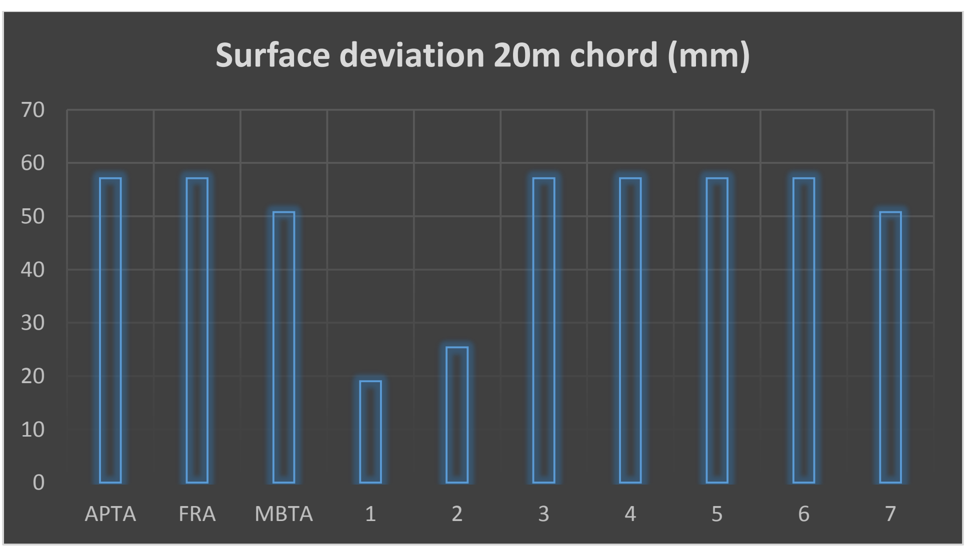
The following bar charts show the maintenance threshold limits for different track inspection parameters and selected railway agencies. The Charts are made so that it can be clearly seen to what extent each railroad agency tolerate a certain defect condition. On the X-axis are the main railroad safety standards with other rail transit agencies numbered from 1-9. The Y-axis shows minimum or maximum values of each criteria used by individual transit authority. At some charts the number of agencies will not be full (i.e. from 1-9) due to the fact that some agencies may not have condition or limit for that specific criteria.

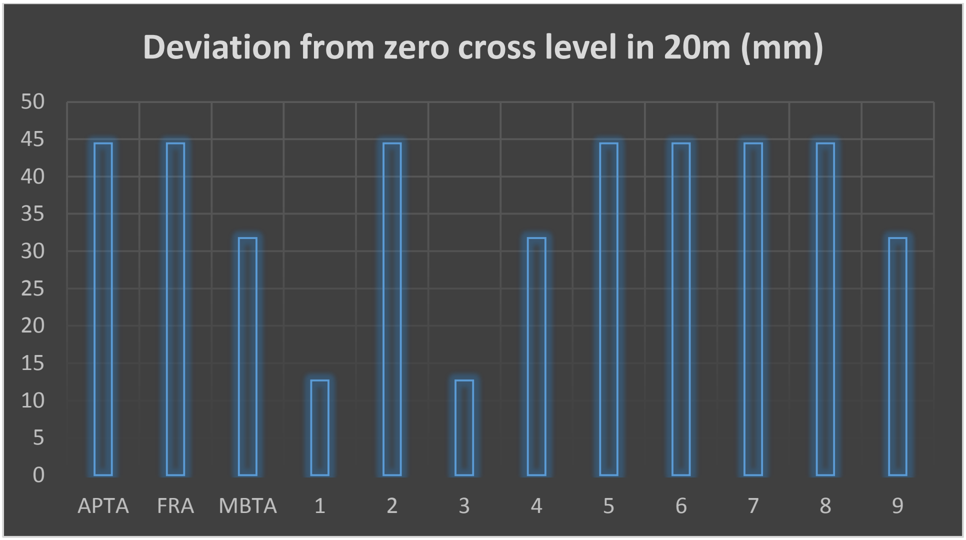


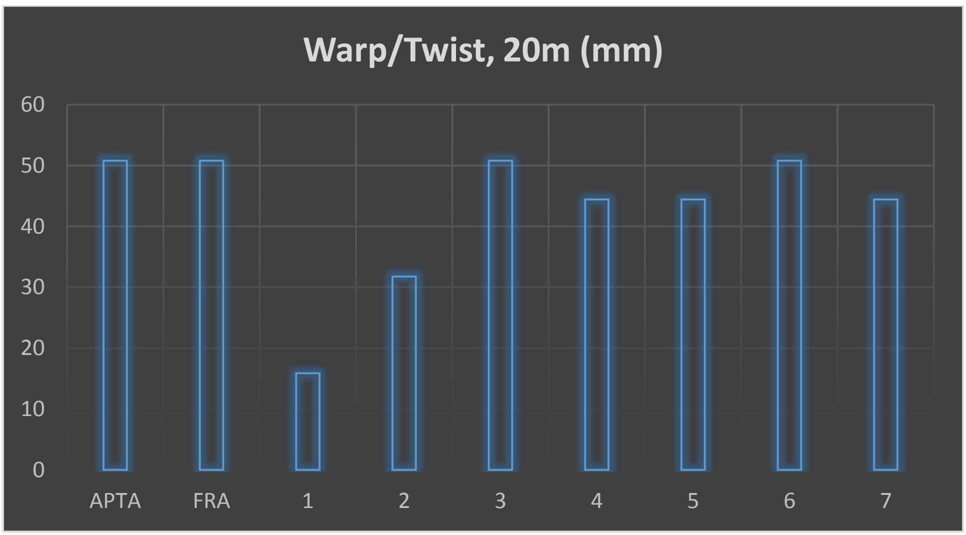


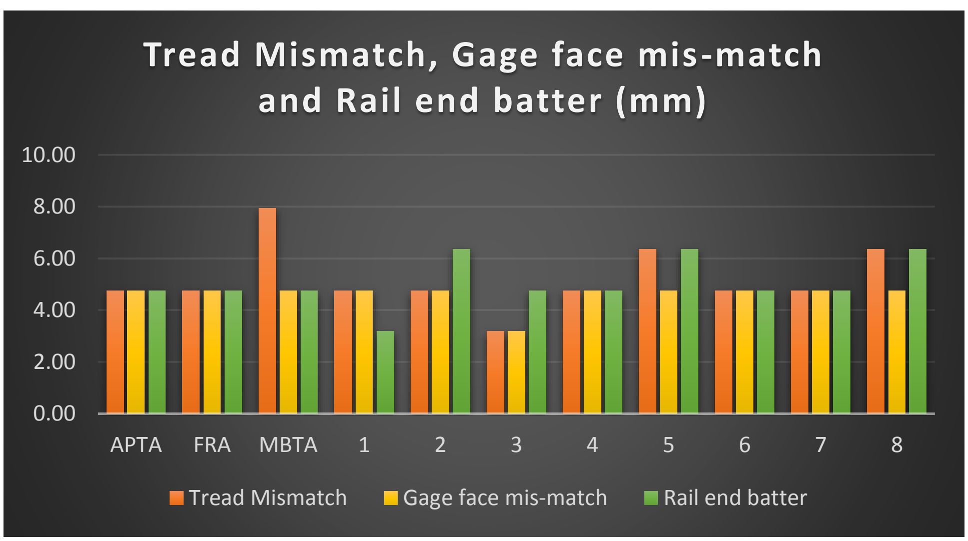

Max. Variation In Alignment 10m Curve (mm)
70
60
50
40
30
20
10
0
APTA
FRA
MBTA
1
2
3
4
5
6
7
8
9

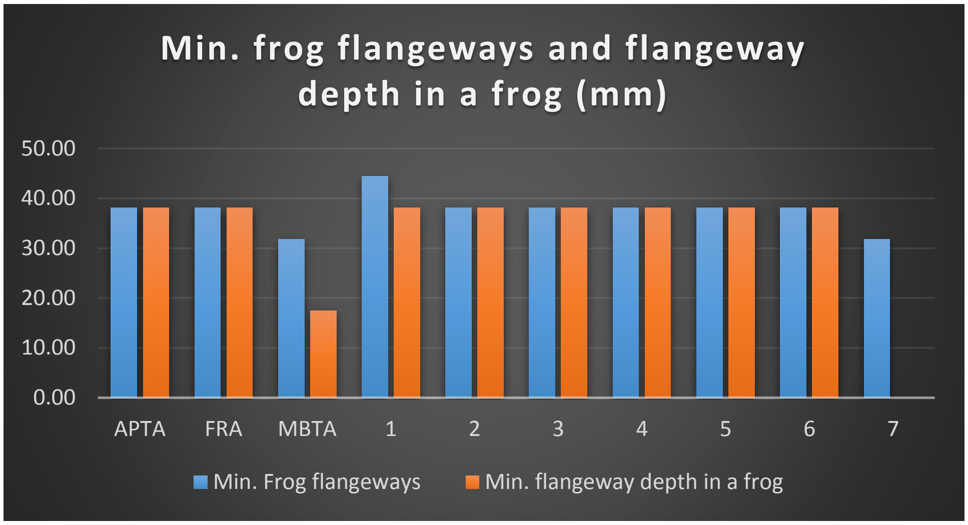

Runoff in 10m (mm)
70
60
50
40
30
20
10
0
APTA
FRA
MBTA
1
2
3
4
5
6
7
8

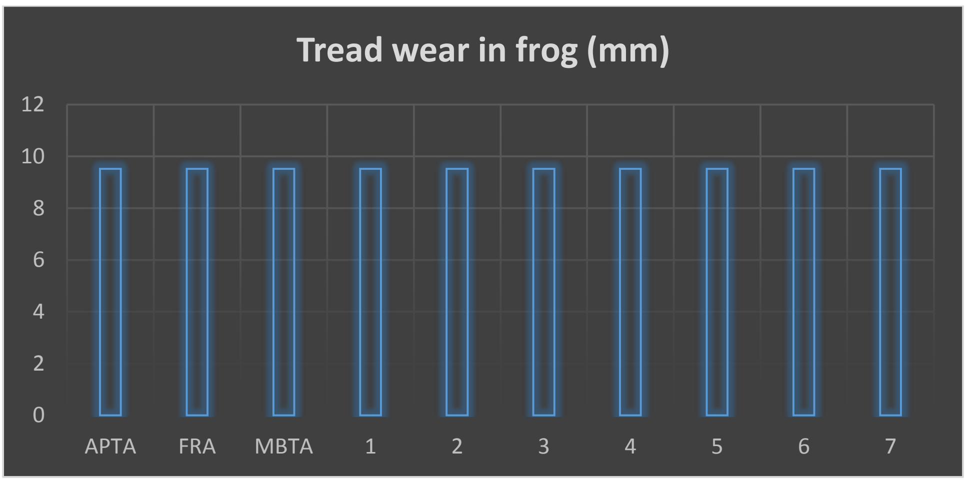

Surface deviation 20m chord (mm)
70
60
50
40
30
20
10
0
APTA
FRA
MBTA
1
2
3
4
5
6
7

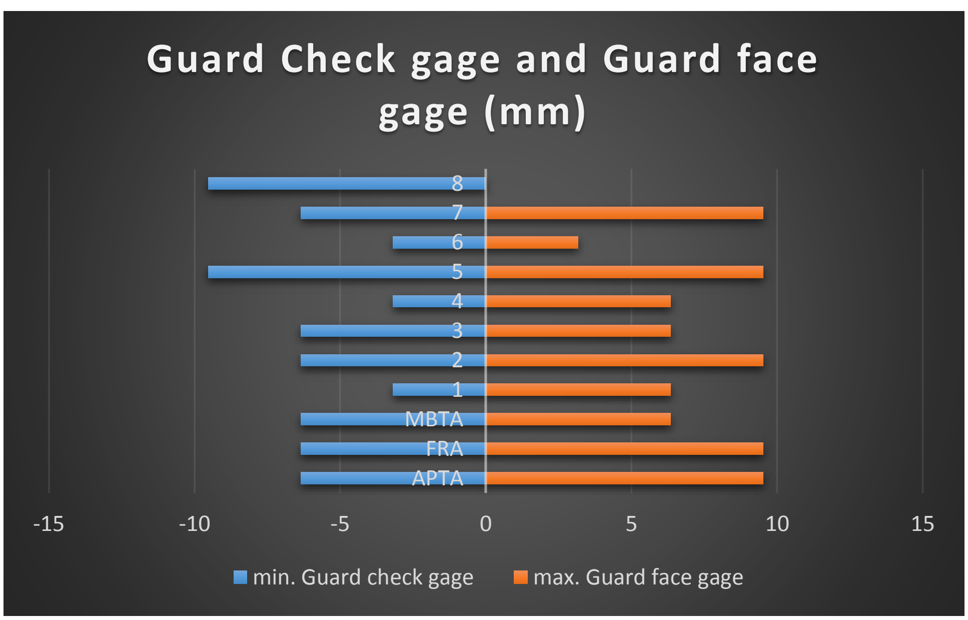

Deviation from zero cross level in 20m (mm)
50
45
40
35
30
25
20
15
10
5
0
APTA
FRA
MBTA
1
2
3
4
5
6
7
8
9


Warp/Twist, 20m (mm)
60
50
40
30
20
10
0
APTA
FRA
1
2
3
4
5
6
7


Tread Mismatch, Gage face mis-match and Rail end batter (mm)
10.00
8.00
6.00
4.00
2.00
0.00
APTA
FRA
MBTA
1
2
3
4
5
6
7
8
Tread Mismatch
Gage face mis-match
Rail end batter


Min. frog flangeways and flangeway depth in a frog (mm)
50.00
40.00
30.00
20.00
10.00
0.00
APTA
FRA
MBTA
1
2
3
4
5
6
7
Min. Frog flangeways
Min. flangeway depth in a frog


Tread wear in frog (mm)
12
10
8
6
4
2
0
APTA
FRA
MBTA
1
2
3
4
5
6
7


Guard Check gage and Guard face gage (mm)
8
7
6
5
4
3
2
1
MBTA
FRA
APTA
-15
-10
-5
0
5
10
15
min. Guard check gage
max. Guard face gage

5.4 INSPECTION FREQUENCY

Selecting an appropriate frequency of rail testing is a complex task involving many different factors which include, but are not limited to, temperature differential, curvature, residual stresses, rail sections, cumulative tonnage, and past rail test results. Inspection frequency also depend on Inspector observations, regarding deteriorating or noncomplying track geometry, and structural conditions.

The frequencies at which rail tests are conducted tend to vary from one railroad to another, but are usually based on either time (i.e., a certain number of times per year) or traffic tonnage (e.g., every 20 million gross tons). But usually, traffic tonnage is not considered in light rail transit agencies. Railroads have evolved their rail testing schedules empirically, based on decades of field experience. The standards of FTA and APTA consider various railroads' track defect compliance history, exception repeatability, degradation rate, and track quality, when selecting their governing frequency of inspection.

Usually inspection and maintenance actions are scheduled at fixed time intervals. In order to not endanger the availability and safety, these intervals are often too short. On the other hand, since inspections usually require a certain amount of human interaction, they are often quite expensive. Therefore, a lot of money could be saved in the long run if the time between inspections could be extended without effecting the availability and safety.

At present there is no up-to-date information available on the true state of components between inspections, which is another reason for scheduling inspections at fixed intervals. However, if information about actual wear would always be available, at least for the critical components, the time between complete inspections could be extended and adapted to the actual need. Foot inspections in the UK depends on speed and equivalent tonnage. Inspections in certain track categories of CWR may be relaxed after risk assessment. Subject to risk up to 75% of CWR may be inspected using suitable on-track vehicle.

The inspection frequency requirements stated in the APTA manual also considers the service defect rate between tests can be controlled by scheduling rail tests in accordance with actual track usage, defect experience, and detection equipment performance. For Class 3 track over which passenger trains operate, the date of the most recent inspection will define the beginning of a new inspection cycle, and before the expiration of time, an inspection for internal rail defects must be conducted.

Inspection frequency for the AA LRT is scheduled at fixed time intervals, since the AA LRT has no specific maintenance history, we cannot put the factors like, service defect rate, defect experience/growth rate, and the date of most recent maintenance.

The new Addis Ababa LRT has totally 87 curved sections, 41 in the E-W line (5.53km or 31.8% of the line) and 46 in the N-S line (6.59km or 39.8% of the line). According to other countries experience on railway and urban rail transit, it is fatigue rather than wear that control the life of normal rails in Straight lines and large-radius curve sections. While in small-radius curve sections, it is wear.

It is also known that it takes a very long time for rail to wear out in the LRT environment, significant wear will usually be observed only in sharp curves or at locations where heavy braking occurs. Thus, the track inspection frequencies for Addis Ababa LRT are taken by taking into consideration its typical lots of curves which relatively needs frequent rail flaw and geometry inspection. There are also several stations in our LRT (44 stations, 22 in both sections of the E-W and N-S line). Since these stations are locations of accelerated top-of-head rail wear due to occasional use of track brakes, it increases the track inspection frequency.

In the Addis Ababa Light Rail Transit system, there are total of 12 highway-rail grade crossings, 7 in the East-West (at ayat, summit roundabout, cmc, salitemihret roundabout and gurdshola) and 5 in the North-South Direction. (At kaliti, saris, adey abeba and meshualekia round about). At these sections there is a huge highway traffic loading in addition to the train loading. Providing a solid subgrade beneath railway/roadway crossings is extremely important due to the double loadings and impact of railway and roadway traffic.

According to (FRA 2010), turnout and crossings are the most common defective parts of the track. Therefore, it should be of prime importance to give special consideration for turnouts and track crossing sections, by frequently inspecting those section for small defects before it propagates into larger and difficult ones. The following chart shows the most common track defects identified by FRA inspectors (FRA 2010).

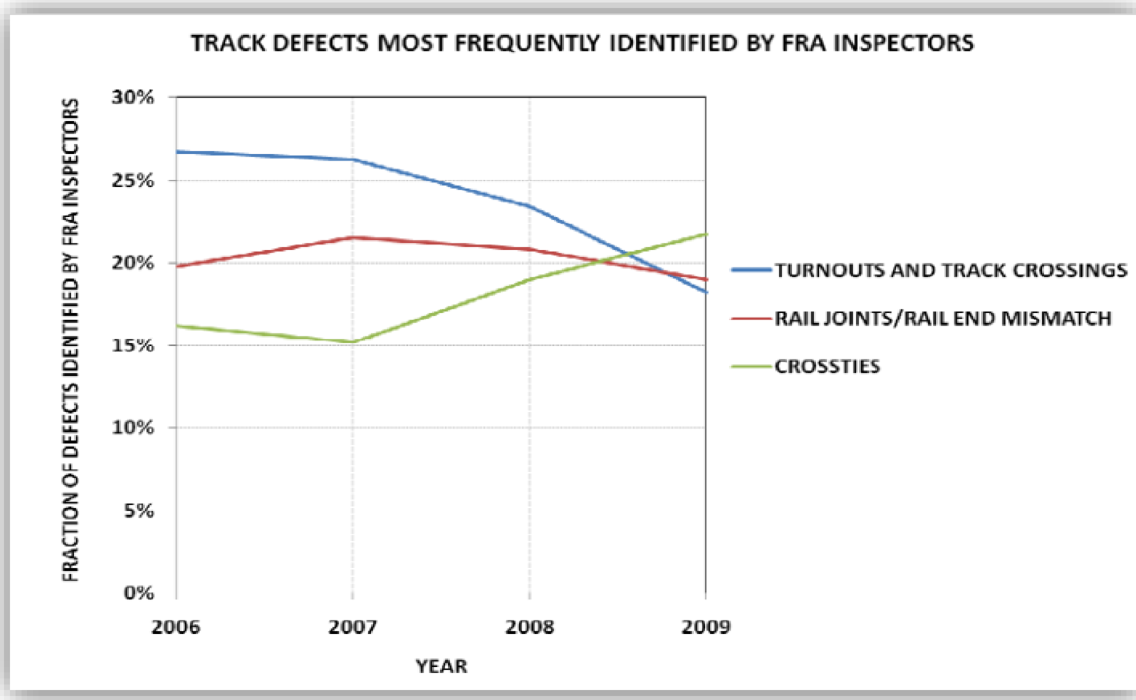


Figure 5-4 Most common track defects identified by FRA inspectors in 2010

Frequency of Rail Flaw Detection (Ultrasonic Testing)

Internal flaws develop for various reasons, and they often initiate at high-stress areas, such as the rolling contact interface between the wheel and rail. As the rail experiences repeated cyclical loading, these small initiation cracks grow in size and will eventually result in a complete rail break (also known as a service failure) if not detected and removed from the track.

A guide for scheduling rail tests to detect internal rail defects was developed (Orringer, 1990) on the basis of results produced through research activities sponsored by the Federal Railroad Administration (FRA) in the United States. The guide was designed for self-adaptation to changing track conditions, as reflected by the total rate of detected occurrences per test, the rate of service defect occurrences, and the tonnage of traffic accumulated between tests. In the present context, self-adaptation means that the frequency of rail testing is adjusted on the basis of the observed rate of detected defects and service defects.

Another factor that will influence rail inspection schedule is seasonal variation in temperature. In summer, higher temperature cause rails to expand, so broken rails may be less reliably detected In the winter, lower temperatures cause rails to contract, which increases the possibility of a broken rail, but also tends to increase the probability of detection. Defects can grow slowly with light train tonnage and warm temperatures or they can grow rapidly in extreme cold temperatures (rail under tension) with heavy trains and traffic (high forces on rail). Due to these reasons, Railroads in the United States generally tend to test rail more frequently than is required by the Code of Federal Regulations because of their high temperature variation. But since in Ethiopia is a country with no excessive seasonal variation, the effect of temperature will be relatively lower.

One of the other most important factors in determining rail testing frequencies is the rate at which rail defects can be expected to grow. The growth rate of rail defects is relatively slow at first, but increases as the defect becomes larger. As a rail defect enlarges, the chance of detecting it increases, but the load bearing capacity of the rail reduces which increases the risk of rail failure.

Taking into consideration all of the above factors, FRA's research suggests that 40 million gross tons is the maximum tonnage that should be hauled between rail tests and still allow a safer opportunity for detection of an internal rail flaw before it propagates in size to a service failure. Additionally, FRA's Accident/Incident data points to a need for inclusion of all Class 3 track in a railroad's rail testing program. The requirement states that Class 3 track, over which passenger trains operate, should be tested once a year or once every 40 million gross tons, whichever is shorter.

Geometry car inspection will supplement the weekly visual inspection of track. TGMS instrumentation generates automated signals processed online by a computer, which produces a graphical record of detailed track geometry measurements. The measurements recorded are gage, left and right rail alignment and profile, cross level, superelevation, warp, run-off, and limiting speeds. Automatic track inspection cars measure and record existing track geometry conditions and compare those measurements to ensure compliance with the standard.

The other factor to be considered during the scheduling of track inspection frequencies is accident histories in the past including their root cause. So that, the primary causes of accident are given higher priorities. This will be very helpful especially for new railway agencies like the Addis Ababa LRT. The following are primary causes of accidents in the U.S. in 2006.

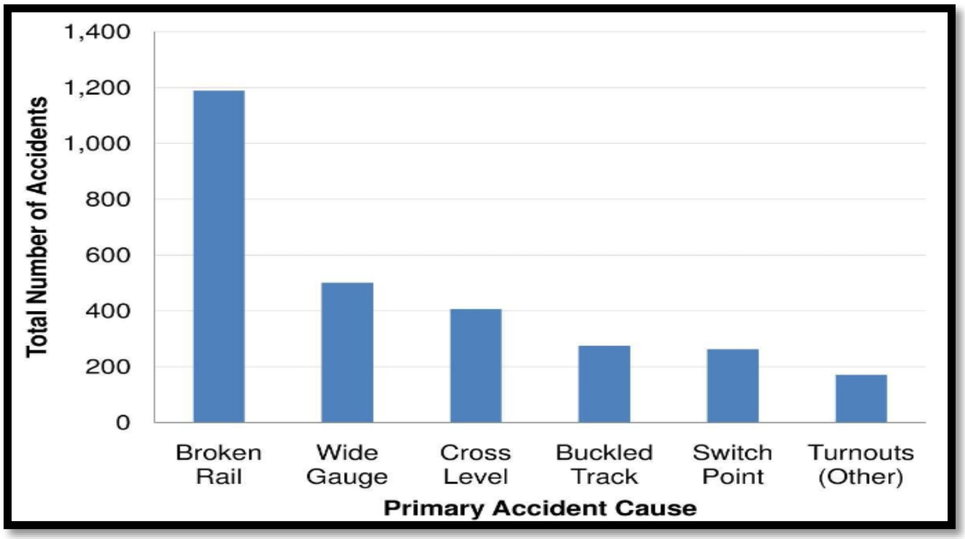


Figure 5-5 Primary causes of accident in U.S., 2006

Prioritization is made in the following order: #1 priority—Perform "must have" repairs first. These are repairs/maintenance required to meet the minimum track safety standards. #2 priority—Perform special work maintenance to keep in good state of repair. #3 priority—Perform rail maintenance such as replacement, tamping, drainage, prioritized by need.

5.5 INSPECTION METHODS

Rail testing must be performed both reliably and economically, since the cheapest and most efficient way is to catch problems before they get too large, and repair them before they cause a derailment. On the one hand the rail flaw detection system, comprising both test car and its operator, must strive to correctly identify all rail defects representing a significant risk of rail failure. This must be done at a testing speed that is compatible with train operations and at a price that is commensurate with the service.

By increasing the reliability of rail flaw detection, through improvements and technology enhancements, a reduction in inspection costs and derailments can be achieved. The resulting annual savings has been estimated to be approximately $40 million (USD) in United States alone.

Inspection Program priorities and inspection methods preference involve primarily:

- Inspector observations, regarding deteriorating or noncomplying track geometry, associated with structural conditions, e.g., crossties, ballast, etc.
- A railroad's compliance history, exception repeatability, degradation rate, and track quality.
- Duration between last inspections
- Passenger operation

Each railroad track inspection method has its own advantage and drawbacks. The cost-benefit for each method will be covered as follows.

VISUAL/MANUAL INSPECTIONS

ADVANTAGES

- Saves the cost of expensive inspection machines and vehicles,
- Don't need significant skill and training to analyze the results,
- Flexible in its approach.

DISADVANTAGES

- Labor intensive.
- Lack the ability to easily record and compare data needed for trend analysis.
- Are subject to variability and subjectivity in different inspectors' interpretations of what they observe.
- Cannot measure track geometry under dynamic loading conditions.
- Risky and disturbing for the track inspector under frequent traffic like the AA LRT.

AUTOMATED INSPECTION SYSTEMS

1. INTERNAL RAIL INSPECTION SYSTEMS

Internal flaws develop for various reasons, and they often initiate at high-stress areas, such as the rolling contact interface between the wheel and rail. As the rail experiences repeated cyclical loading, these small initiation cracks grow in size and will eventually result in a complete rail break (also known as a service failure) if not detected and removed from the track.

ULTRASONICS

Ultrasonic systems produce ultrasonic waves that are transmitted into the rail. Discontinuities in the material alter the wave paths and a transducer is used to detect these reflected waves to find flaws or boundaries in the material.

ADVANTAGES

- Is the most common, efficient and effective technology
- Has deeper scanning depth than other NDT methods
- Accuracy in determining the position, size, and shape of defects

DISADVANTAGE

- Need for significant skill and training to analyze the results.
- Great difficulty associated with inspecting non-homogeneous materials.
- Defects beneath another defect closer to the surface may be difficult to detect, because the waves are reflected by the closer defect.
- Defects oriented parallel to the path of the waves are difficult to detect

2. TRACK GEOMETRY MEASURING SYSTEMS

Measures the vertical and lateral deviations of each of the rails as well as the gage and cross-level. It must be noted that the manual verification by track inspectors may result in slightly different geometry exception values. This is because the FRA track geometry cars are designed to measure track geometry under dynamic loading conditions similar to those induced by revenue trains. Certain track conditions felt by track geometry cars are difficult, if not impossible, to duplicate manually. As a result, in some isolated cases, certain geometry exceptions from the track geometry cars cannot be verifiable by track inspectors, that is, the track geometry deviation may not exceed the Track Safety Standards when measured manually.

Track Geometry Car

Test several geometric parameters of the track without obstructing normal railroad operations. Parameters generally measured include position, curvature, alignment of the track, smoothness, and the crosslevel of the two rails. Some advantages of track geometry cars are;

- Time and labor is saved when compared to doing manual inspections of track.

- Are designed to measure track geometry under dynamic loading conditions similar to those induced by revenue trains. Because track geometry cars are full-sized rail cars, they provide a better picture of the geometry of the track under loading.
- Track geometry data is stored and can be used to track trends in the degradation of track.

REMOTE INSPECTION

ADVANTAGES

- For a very busy track, Gaining access to check for defects is increasingly difficult and risky. Remote inspection equipment can solve this because it can be installed on an operating light rail vehicle, without affecting passenger schedules.
- A significant increase in inspection frequency and a significant reduction in operating costs.
- Data is available as often as the host vehicle runs over the track. Frequent operation over dedicated routes, and the resulting regular flow of measurement information, ensures that managers and engineers are supplied continuously with up-to-date condition reports.
- Provides warnings of sudden changes in the infrastructure and allows the rate of deterioration at any location to be monitored, enabling a more accurate prediction of when track components will need replacing. Taken a stage further, it becomes possible to calculate the different rates of deterioration for various types of asset, setting the stage for a move from corrective to predictive maintenance.
- Keeps the Safety of walking inspectors and reduce the man-made errors during inspection.
- Immediate feedback is obtained about the quality of track maintenance work.

DISADVANTAGE

- Remote inspection poses the problem of handling huge amounts of data.
- It cannot present accurate data for internal rail flaw detection.

Figure 5-6 Remote Inspection Box fitted on a regular train.

6 DISCUSSION, CONCLUSION and RECOMMENDATION

6.1 DISCUSSION

Ethiopia is currently constructing the first Light Rail Transit (LRT), in the history of the country. Our new experience demands other developed countries' huge experience on LRT track inspection and maintenance. Rail failures generally occur from fatigue cracks that form and grow in the rail steel as a result of cyclic forces caused by the repeated passage of train over the rails which may cause a train to derail. There are many sources that influence Track defects and failure. These effects include bending and shear stresses, wheel/rail contact stresses, thermal stresses, residual stresses and dynamic effects.

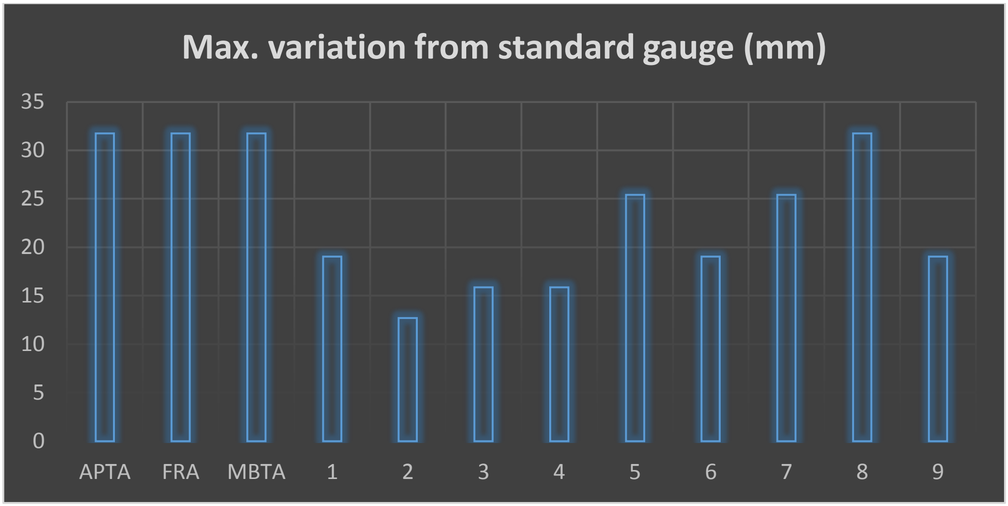
Track reacts to the forces imposed by passing traffic with damage to, or rail flaws, loosening of fastenings, erosion of the underside of the sleepers, fouling of ballast, inadequate drainage systems or an insufficient ballast bed also reduce the carrying capacity of the track system. All these faults can be eliminated by special planning and scheduling inspection and maintenance. A rail defect that goes undetected and results in a train derailment, also can cause additional costs such as excessive service interruption, extensive traffic re-routing, environmental damage, and even potential injury and death.

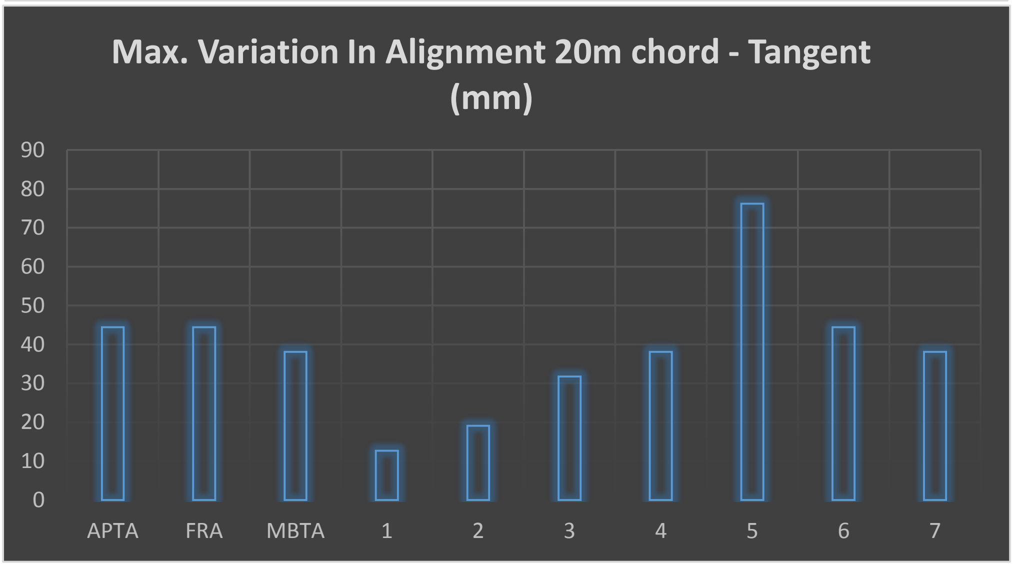
Effective planning, scheduling and staffing of inspection and maintenance for the railway track, has a great influence upon the service life of the whole track and the safety of the passengers. Generally, it's important to schedule track inspections such that the potential defects are captured as much as possible within minimum times to increase safety to the maximum.

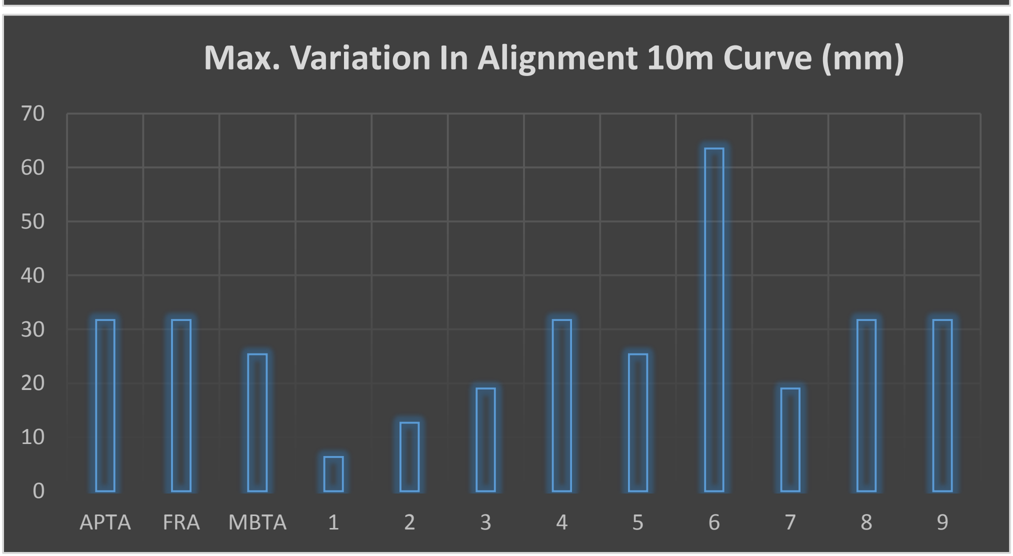
Since the Addis Ababa LRT is new for inspection and maintenance, the need to revise and refer other standards is very important. Consequently, different track safety standards are referred to see their maintenance threshold limits and inspection frequency, thereby analyzing the parameters and conditions considered.

The railway agencies are selected taking into consideration their design speed (class-III railroads), gauge width (standard gauge), material specification (ballasted tracks, concrete sleepers), and headway time of 4-12minutes. A total of 12 standards and manuals are referred, and their threshold limits are presented in a tabular form with the inspection parameters they considered. It was found that, different railway agencies has different track maintenance tolerance limits and frequencies of inspection based on factors like track class, track material properties, service defect rate, defect experience and defect growth rate.

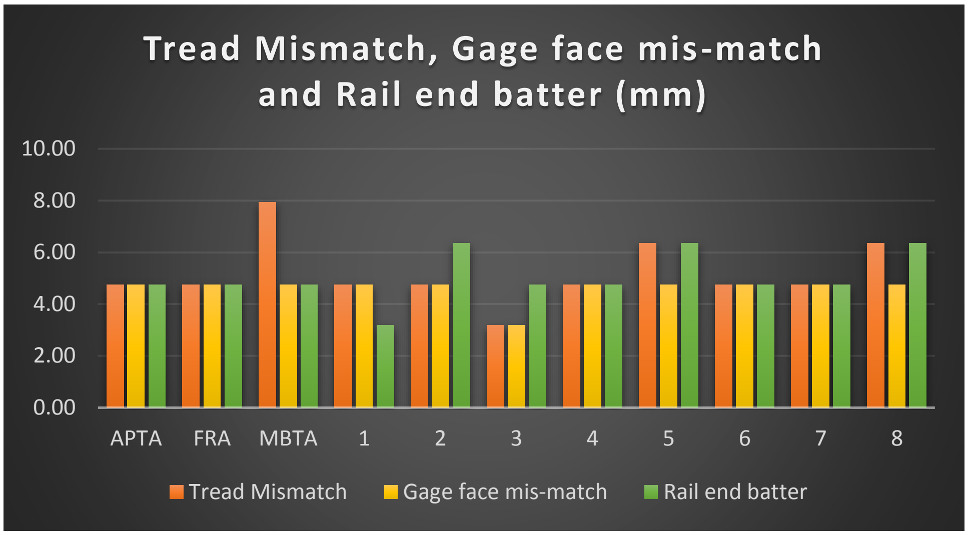
From the bar charts developed from the selected standards' tolerance limits, it can be seen that agencies with high design speed (with in class-III) and those with lots of sharp horizontal curves tend to have lower acceptable tolerance limits for variations in gauge, surface and alignment. Thus, it can be seen that Addis Ababa LRT should be limited to have a relatively low tolerance limit.

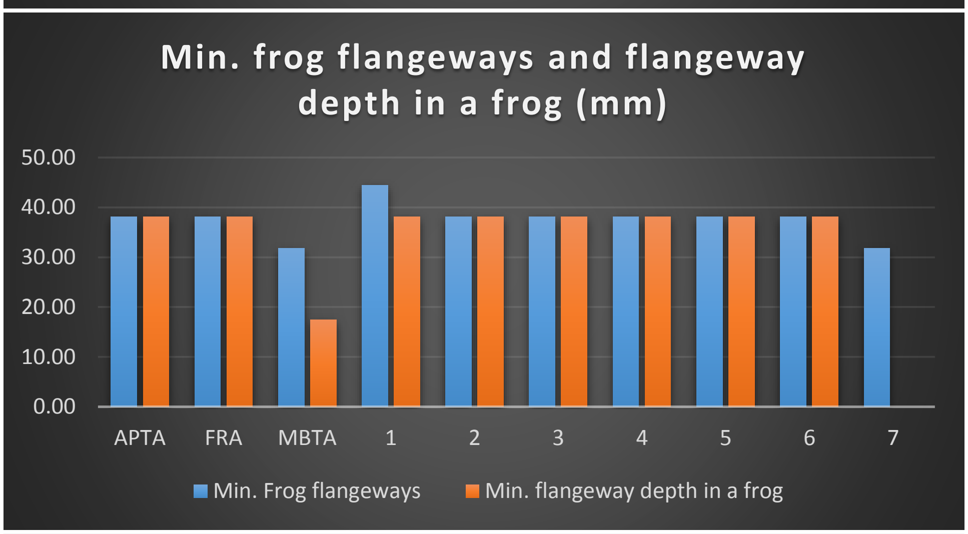

Max. variation from standard gauge (mm)
35
30
25
20
15
10
5
0
APTA
FRA
MBTA
1
2
3
4
5
6
7
8
9

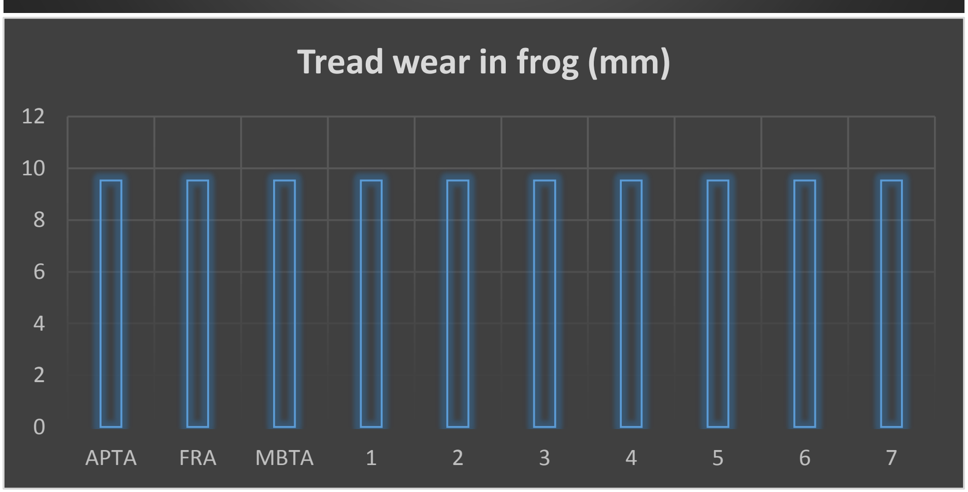

Max. Variation In Alignment 20m chord - Tangent (mm)
90
80
70
60
50
40
30
20
10
0
APTA
FRA
MBTA
1
2
3
4
5
6
7


Max. Variation In Alignment 10m Curve (mm)
70
60
50
40
30
20
10
0
APTA
FRA
MBTA
1
2
3
4
5
6
7
8
9

Most of the reviewed standards also have almost similar limits for tread mismatch, gauge face mismatch, rail end batter, minimum frog flangeways, flangeway depth and tread wear in frog. Flange way dimension requirements are a function of the wheel profile and curve radius used. The flangeway depth must be sufficient to accommodate dirt and debris without causing wheel lift.







The frequencies at which rail tests are conducted tend to vary from one railroad to another, but are mostly based on either time (i.e., a certain number of times per year) or traffic tonnage (e.g., every 20 million gross tons). But usually, traffic tonnage is not considered in light rail transit agencies. Railroads have evolved their rail testing schedules empirically, based on decades of field experience.

The standards of FTA and APTA consider various railroads' track defect compliance history, exception repeatability, degradation rate, and track quality, when selecting their governing frequency of inspection. But in the case of AA LRT, since it is a new railway line we cannot consider defect experience and defect growth rate to calculate optimum frequency of inspection, accordingly, fixed schedule is preferable based on the most common standards.

At present there is no up-to-date information available on the true state of components between inspections, which is another reason for scheduling inspections at fixed intervals for Addis Ababa LRT. However, if information about actual wear would always be available, at least for the critical components, the time between complete inspections could be extended and adapted to the actual need. Foot inspections in the UK depends on speed and equivalent tonnage. Inspections in certain track categories of CWR may be relaxed after risk assessment.

The inspection frequency requirements stated in the APTA manual also considers the service defect rate between tests can be controlled by scheduling rail tests in accordance with actual track usage, defect experience, and detection equipment performance. For Class 3 track over which passenger trains operate, the date of the most recent inspection will define the beginning of a new inspection cycle, and before the expiration of time, an inspection for internal rail defects must be conducted. The growth rate of rail defects is relatively slow at first, but increases as the defect becomes larger. As a rail defect enlarges, the chance of detecting it increases, but the load bearing capacity of the rail reduces which increases the risk of rail failure.

The new Addis Ababa LRT has totally 87 curved sections, 41 in the E-W line (5.53km or 31.8% of the line) and 46 in the N-S line (6.59km or 39.8% of the line). According to other countries experience on railway and urban rail transit, it is fatigue rather than wear that control the life of normal rails in Straight lines and large-radius curve sections. While in small-radius curve sections, it is wear.

It is also known that it takes a very long time for rail to wear out in the LRT environment, significant wear will usually be observed only in sharp curves or at locations where heavy braking occurs. Thus, the track inspection frequencies for Addis Ababa LRT are taken by taking into consideration its typical lots of curves which relatively needs frequent rail flaw and geometry inspection. There are also several stations in our LRT (44 stations, 22 in both sections of the E-W and N-S line). Since these stations are locations of accelerated top-of-head rail wear due to occasional use of track brakes, it increases the track inspection frequency.

Another factor that will influence rail inspection schedule is seasonal variation in temperature. Defects can grow slowly with light train tonnage and warm temperatures or they can grow rapidly in extreme cold temperatures (rail under tension) with heavy trains and traffic (high forces on rail). In summer, higher temperature cause rails to expand, so broken rails may be less reliably detected In the winter, lower temperatures cause rails to contract, which increases the possibility of a broken rail, but also tends to increase the probability of detection.

Due to these reasons, Railroads in the United States generally tend to test rail more frequently than is required by the Code of Federal Regulations because of their high temperature variation. But since in Ethiopia is a country with no excessive seasonal variation, the effect of temperature is relatively lower and consequently,

In the Addis Ababa Light Rail Transit system, there are total of 12 highway-rail grade crossings, 7 in the East-West (at ayat, summit roundabout, cmc, salitemihret roundabout and gurdshola) and 5 in the North-South Direction. (At kaliti, saris, adey abeba and meshualekia round about). At these sections there is a huge highway traffic loading in addition to the train loading. Providing a solid subgrade beneath railway/roadway crossings is extremely important due to the double loadings and impact of railway and roadway traffic.

According to (FRA 2010), turnout and crossings are the most common defective parts of the track. Therefore, it is of prime importance to give special consideration for turnouts and track crossing sections, by frequently inspecting those section for small defects before it propagates into larger and difficult ones. Consequently, this paper proposes a monthly detail inspection for each Turnout and Track crossings.

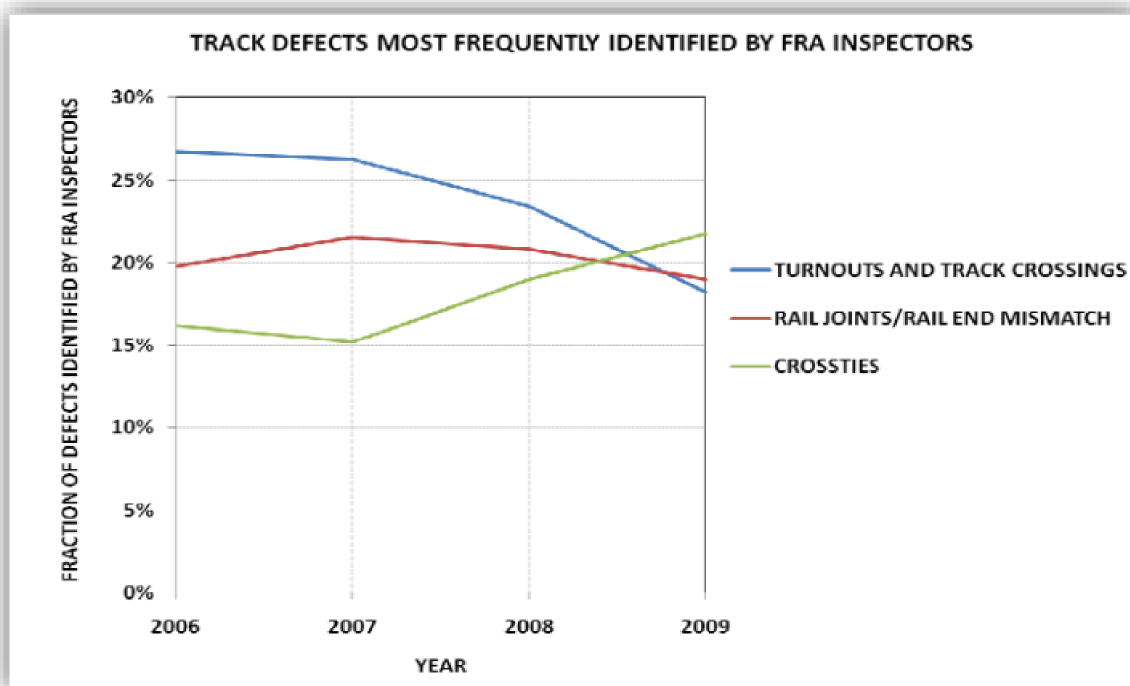


Figure 6-1 Most common track defects identified by FRA inspectors in 2010

The other factor considered during the scheduling of track inspection frequencies is accident histories in the past including their root cause. So that, the primary causes of accident, like broken rails, gauge and crosslevel variations, are given higher priorities. This is very helpful to prioritize defects, especially for new railway agencies like the Addis Ababa LRT.

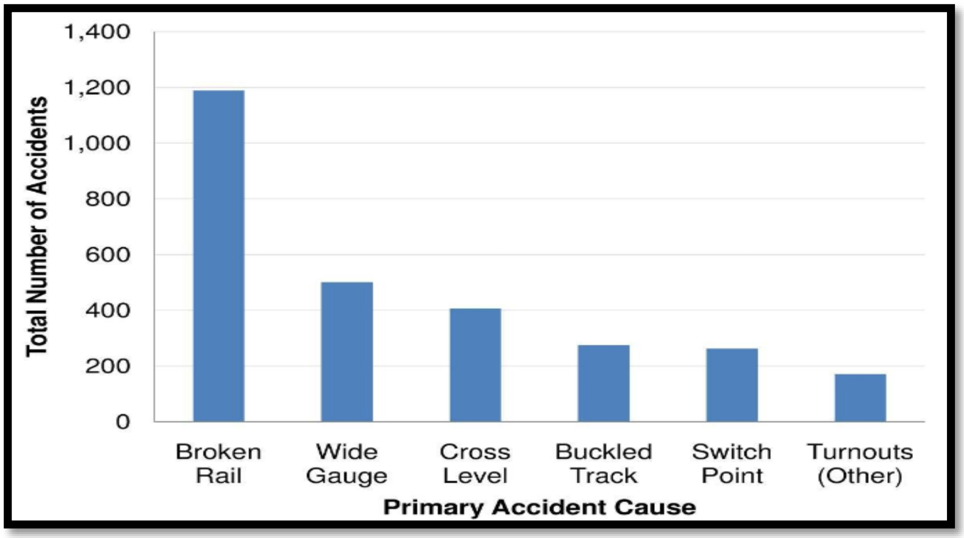


Figure 6-2 Primary causes of accident in U.S., 2006

Current track inspection methods, techniques and best practices in the railroad industry are covered in detail, including visual inspections, several automated and remote inspection options, so that the best inspection technology that suits the Addis Ababa LRT can be chosen to maintain a safe railway network. The cheapest and most efficient way is to catch problems before they get too large, and repair them before they cause a derailment. Inspection methods are chosen considering cost, efficiency, and availability with the specific conditions of the Addis Ababa LRT.

Addis Ababa LRT has a design headway of 6 minutes, so gaining access to check for defects is increasingly difficult and risky. Remote inspection equipment can solve this because it can be installed on an operating light rail vehicle, without affecting passenger schedules.

The vehicles for Addis Ababa LRT are 6-axle double-articulated 70% low-floor Light Rail tramcar. The Distance between Tramcar Floor and Track Top is, Low-Floor Area: 365mm, High-Floor Area: 865mm. The use of 70% low-floor Light Rail tramcar somehow restricts the extended usage of remote inspection or camera system inspection, as it is installed on bogey of an operating light rail vehicle. But since the tramcar also contains a 30% high-floor area at the front and back of the trains, it is possible to install the remote inspection system on this high floor area. Ultrasonic method for the inspection of internal rail flaw should also be used, since the remote inspection alone cannot present accurate data for internal rail flaw detection.

Generally, Scheduling inspection and maintenance operations should always be properly planned and be aimed at keeping high quality of track, at lowering track deterioration rate and, thus, at extending the service life of the track.

6.2 CONCLUSIONS

From FRA's accident data statistics, it can be clearly seen that the most common cause of railway accident is derailment. The cheapest and most efficient way is to catch problems before they get too large, and repair them before they cause a derailment. So the most important role of inspecting and maintaining track is to prevent derailments. When a transit system begins to fail, it could be because of two main factors, lack of proper planning and lack of adequate maintenance.

Different track safety standards are referred to see their maintenance threshold limits and inspection frequency, thereby analyzing the parameters and conditions considered. The agencies are selected taking into consideration their design speed, gauge width (standard gauge), material specification (ballasted tracks, concrete sleepers), and headway time of 4-12minutes. A total of 12 standards and manuals are referred, and their threshold limits are presented in a tabular form with the inspection parameters they considered. It was found that, different railway agencies has different track maintenance tolerance limits and frequencies of inspection based on factors like track class, track material properties, service defect rate, defect experience and defect growth rate.

From the bar charts developed by comparing the selected standards' tolerance limits, it can be seen that agencies with high design speed and those with lots of sharp horizontal curves tend to have lower tolerance limits for variations in gauge, surface and alignment. Thus, it can be seen that Addis Ababa LRT should be limited to have a relatively low tolerance limit.

Most of the reviewed standards also have almost similar limits for tread mismatch, gauge face mismatch, rail end batter, minimum frog flangeways, flange way depth and tread wear in frog. Flange way dimension requirements are a function of the wheel profile and curve radius used. The flangeway depth must be sufficient to accommodate dirt and debris without causing wheel lift.

The Addis Ababa LRT has a total of 40 stations (22 in the E-W line and 22 in the N-S line) and curved sections (86 curved sections). The effect of tractive efforts and braking forces is even higher with small wheel diameters, like the case of the AA LRT having a small tramcar wheel diameter of 600mm. Reduction of wheel/rail wear can be achieved by optimization of wheel/rail profiles, properly designed truck primary suspension, improvement of track maintenance, and application of lubrication.

The standards of FTA and APTA consider various railroads' track defect compliance history, exception repeatability, degradation rate, and track quality, when selecting their governing frequency of inspection. Inspection frequency for the AA LRT is scheduled at fixed time intervals, since the AA LRT has no specific maintenance history, we cannot put the factors like, service defect rate, defect experience/growth rate, and the date of most recent maintenance. The recommended minimum frequency of inspection is shown in table 6.1 below.

Table 6-1 Proposed inspection frequency

ITEM	Description	Frequency
1	Frequency of hi-rail or walking inspection or Remote inspection	**Twice Weekly**
2	Frequency of Geometry car testing on mainline	**Twice per year**
3	Switch, and track crossing detail inspections	**Monthly**
4	Frequency of Gauge Restraint (GRMS) test on mainline	**Annually**
5	Frequency of rail flaw detection (ultrasonic test)	**Twice per year**

In addition, it is known that significant wear is usually observed in sharp curves or at locations where heavy braking occurs. Typical lots of curves in the AA LRT (87 curved sections, 41 in the E-W line and 46 in the N-S line) and several stations (44 stations, 22 in both sections of the E-W and N-S line) relatively needs special rail flaw and geometry inspection, since these stations are locations of high lateral load and accelerated top-of-head rail wear due to occasional use of track brakes.

By increasing the reliability of rail flaw detection, through improvements and technology enhancements, a reduction in inspection costs and derailments can be achieved. Addis Ababa LRT is a busy track, with design headway of 6 minutes, so gaining access to check for defects is increasingly difficult and risky. Remote inspection equipment can solve this because it can be installed on an operating light rail vehicle, without affecting passenger schedules.

The vehicles for Addis Ababa LRT are operated in two directions, and are 6-axle double-articulated 70% low-floor Light Rail tramcar. The Distance between Tramcar Floor and Track Top is, Low-Floor Area: 365mm, High-Floor Area: 865mm. The use of 70% low-floor Light Rail tramcar somehow restricts the extended usage of remote inspection or camera system inspection, as it is installed on bogey of an operating light rail vehicle. But since the tramcar also contains a 30% high-floor area at the front and back of the trains, it is possible to install the remote inspection system on this high floor area. Ultrasonic method for the inspection of internal rail flaw should also be used, since the remote inspection alone cannot present accurate data for internal rail flaw detection.

Most railroad agencies, as reviewed earlier, have almost same documentation and record keeping cultures. Thus, the APTA documentation system can be adopted which suggests to maintain track defect records for a minimum of **two years** after inspection and **one year** after corrective action. An auditable System must exist for all actionable defects from detection/ notification to investigation, assessment, repair programming, and repair action. The 'System' must include, as a minimum, the following details: Defect, Type, Size and Location (line, track and kilometers), Date found, source of information, action required (includes investigation, assessment, and repair) programmed action date, repair action, repair date and repair agency, review of performance.

6.3 RECOMMENDATIONS

- The Proposed minimum frequencies of inspection should be adjusted in the future by considering operational factors like, service defect rate, defect experience/growth rate, exception repeatability and the date of most recent maintenance, in order to select governing frequency of inspection because, Selecting an appropriate frequency of rail testing is a complex task involving many different factors which include, but are not limited to, temperature differential, curvature, residual stresses, rail sections, cumulative tonnage, and past rail test results. Inspection frequency also depend on Inspector observations, regarding deteriorating or noncomplying track geometry, and structural conditions. But those frequencies of inspection proposed in this paper can be taken as minimum frequencies.
- At locations where obvious deterioration occurs at higher rates due to such factors as curvature, usage, axle load or speed, more frequent inspections should be scheduled. These additional inspections may be reduced in scope to address only those parts of the inspection affected by the additional factors.
- The threshold limits compared based on design speed of the track and shown in a tabulated form, are to be applicable for the AA LRT after performing a variety of tests considering all the stresses on the track, operational and technical parameters used.
- Documentation of any track defects and accident data should be given primary importance, as it helps as a reference for future. The Addis Ababa LRT office has to improve its data management and compilation system. It is very hard to find the necessary up to-date information about the track system or any future plans for our new railway lines.
- ERC should have a new sub-section or department of research, which will guide and financially support new local and problem solving researches on Ethiopian railways. Research is necessary to solve operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the transit industry. We have to experience more from institutions, like the Transit Cooperative Research Program (TCRP) in U.S.A, which has a variety of research fields including planning, operations, equipment, facilities, human resources, maintenance, policy and administrative practices.

7 TOPICS FOR FURTHER STUDY

Based on the information in this thesis, the following general topics are suggested for future study in the Ethiopian railway system:

- Inspection time analysis,
- Track Safety and Maintenance standards,
- Staffing level (quantity and quantity of track personnel),
- Training of qualified inspection and maintenance personnel.

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APPENDIX-A- FRA RAIL DEFECTS AND DESCRIPTION

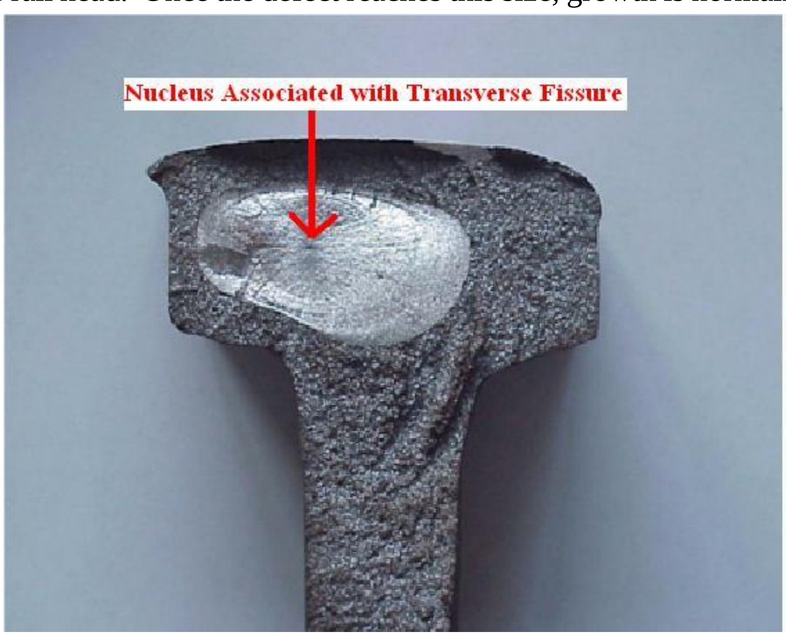
1. Transverse Defects in the Rail Head

A transverse defect is a type of fatigue that has developed in a plane transverse to the cross sectional area of the rail head. Development can be normal or in multiple stages prior to failure. The transverse defect is only identified by the nondestructive inspection process, unless the defect has progressed to the rail running surface and has cracked out.

Transverse Fissure

Transverse fissure means a progressive crosswise fracture starting from a crystalline center or nucleus inside the head from which it spreads outward as a smooth, bright, or dark, round or oval surface substantially at a right angle to the length of the rail. The distinguishing features of a transverse fissure from other types of fractures or defects are the crystalline center or nucleus and the nearly smooth surface of the development that surrounds it.

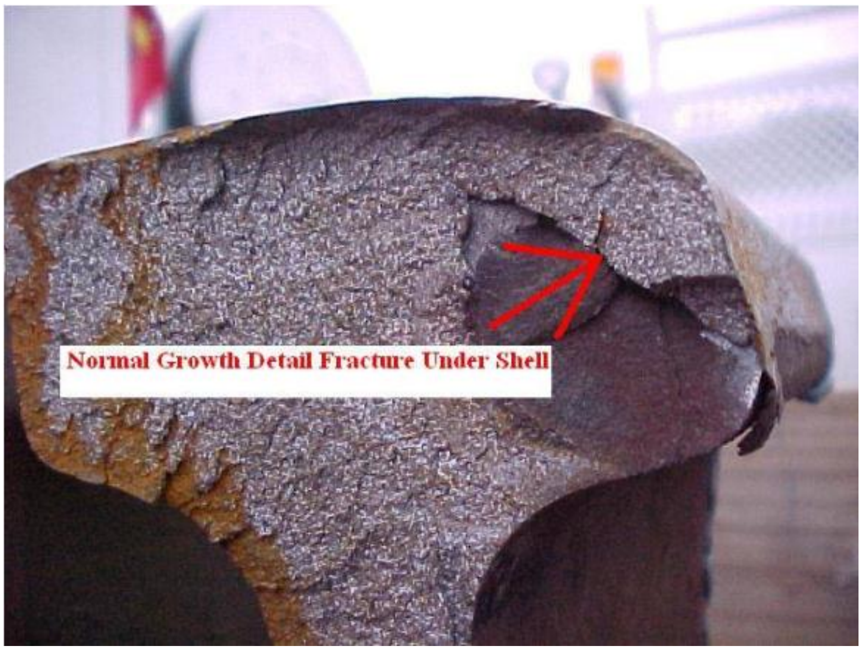
It is not uncommon for multiple fissures to be present in one rail length. Identification of this type defect is not accurately made until the rail section is broken and the size determined by the area of cross-section of the rail head affected. It is normal for a transverse fissure to remain in service for some time without further development. Development is highly influenced by wheel impact and rail bending stresses, and growth is normally slow to a size encompassing 20- to 25-percent cross-sectional area of the rail head. Once the defect reaches this size, growth is normally more accelerated.



Transverse Fissure

Compound Fissure

Compound fissure means a progressive fracture originating from a horizontal split head that turns up or down, or in both directions, in the head of the rail. Transverse development normally progresses substantially at a right angle to the length of the rail. Growth is normally slow to a size of 30–35 percent. The compound fissure can result in an oblique type failure and is considered a hazardous rail defect.

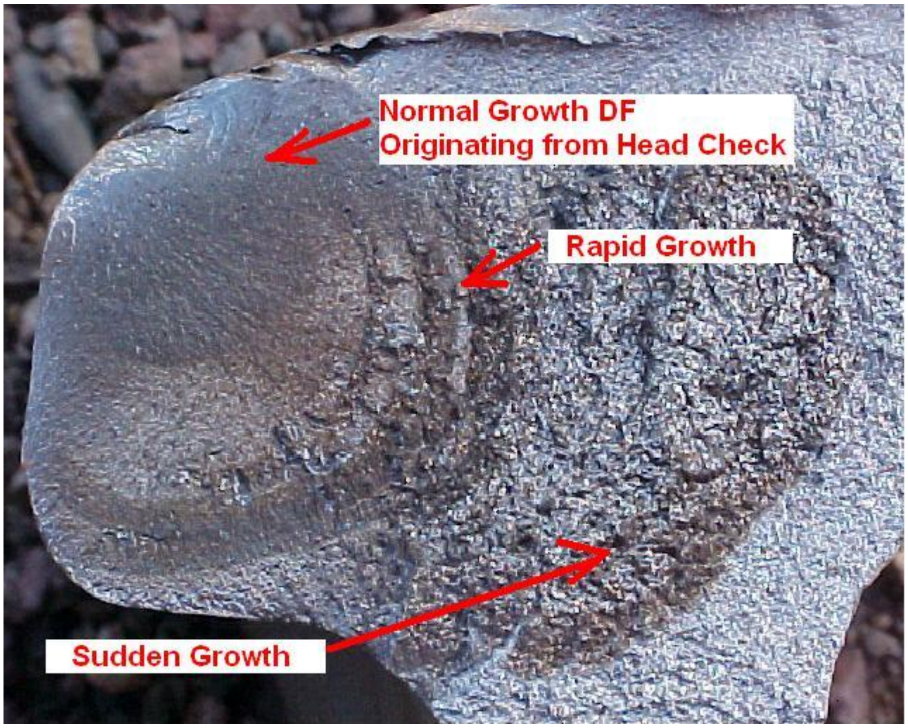


Compound fissure

Detail Fracture

Detail fracture means a progressive fracture originating at or near the surface of the rail head. These fractures should not be confused with transverse fissures, compound fissures, or other defects, which have internal origins. Detail fractures may originate from shelly spots, head checks, or flaking.

The detail fracture is usually associated with the presence of a longitudinal seam or streak near the running surface on the gage side. Unlike the transverse fissure, no nucleus will be present. Growth can be normally slow to a size of a 10- or 15-percent cross-section of the rail head. Growth can then become rapid and/or sudden, prior to complete failure. It is not uncommon for more than one detail fracture to develop in an immediate area where the conditions that initiate their development, such as shelling or head checking, are present.



Detail Facture from Head Check

The source of the detail fracture can also be reversed. The reverse detail fracture is a progressive transverse fracture normally originating at the bottom corner of the gage side of the rail head. The growth is normal to a size of 10 percent and is often rapid or sudden prior to complete failure of the rail section. It is not uncommon for complete failure at a size much less than that of a typical detail fracture type defect.

Reverse Detail Fracture

Engine Burn Fracture

Engine burn fracture means a progressive fracture originating in spots where driving wheels have slipped on top of the rail head. In developing downward, they frequently resemble the compound or even transverse fissures with which they should not be confused or classified. The defect originates when a slipping engine driver wheel heats a portion of the rail surface, and rapid cooling forms thermal cracks. Impact from wheels over the affected burned area initiates a slight horizontal separation of the burned metal from the parent rail metal and develops a flat spot. Transverse separation may start from a thermal crack in the region of the burn at any time.

It is common for more than one engine burn to be located within a short proximity. Growth is normally slow to a size of 10–15 percent. However, once transverse separation reaches a size of 10–15 percent, growth can become accelerated.

Engine Burn Fracture Showing Significant Growth

Ordinary Break

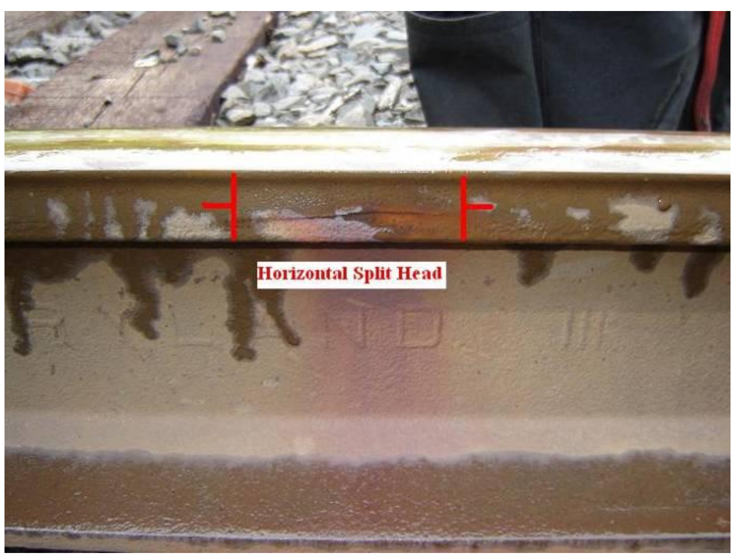
Ordinary break means a partial or complete break in which there is no sign of a fissure, and in which none of the other defects described in this section is found. This type of failure can be more susceptive to break where an unevenly supported base is present. The cause of failure cannot easily be determined.

Rail Failure Fracture Face Showing No Transverse Defect

1. <u>Longitudinal Defects in the Rail Head</u>

Horizontal Split Head

Horizontal split head means a horizontal progressive defect originating inside of the rail head, usually one-quarter inch or more below the running surface and progressing horizontally in all directions, and generally accompanied by a flat spot on the running surface. The defect appears as a crack lengthwise of the rail when it reaches the side of the rail head.



Side View of Horizontal Split Head

The horizontal split head originates from an internal longitudinal seam, segregation, or inclusion Inherent from the manufacturing process. Horizontal separation will progress longitudinally and horizontally (parallel to the running surface) and is normally rapid in development. Wheel impact can initiate transverse separation, in which case the defect should be classified as a compound fissure. The horizontal separation may be present in several locations within the same rail section.

Vertical Split Head

Vertical split head means a vertical split through or near the middle of the head, extending into or through it. A crack or rust streak may show under the head close to the web or pieces may be split off the side of the head.

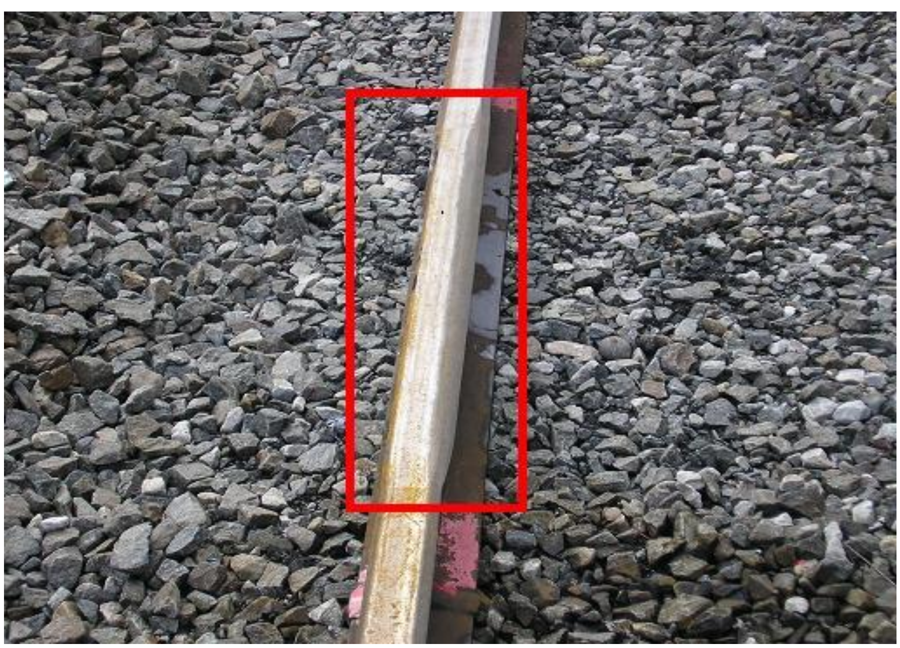
The origin is an internal longitudinal seam, segregation, or inclusion inherent from the manufacturing process. Vertical separation will progress longitudinally and vertically (parallel to side of head), and may gradually turn toward the gage or field side of the rail head. It is common for a portion of a vertical split head to develop toward the gage side of the rail head while the other end develops toward the field side. Growth is normally very rapid once the seam or separation has opened up anywhere along its length.

The vertical split head defect can be identified by the presence of a dark streak on the running surface and widening of the head for the length of the defect development. The side of the head to which the split is offset may show signs of sagging or dropping, and a rust streak may be present in the head/web fillet area under the rail head.

Vertical Split Head Defect Breaking out in Head/Web Fillet Area

Vertical Split Head Crack Out in Head/Web Fillet Area

A shear break is a longitudinal separation of the rail head, resulting from the loss of significant rail head parent metal. The reduction of rail head parent metal results in the loss of the ability of the rail section to support loading, and is not typically associated with inherent conditions in the material. A shear break usually occurs when the rail is loaded off the center axis, causing rail head collapse, and can be associated with gaging problems, light weight rail, severely worn (vertical wear) rail, or off-center loads caused by worn rolling stock wheels.



Shear Break Showing Dark Discoloration Identifying Defect Length

Growth is usually very sudden, and more than one shear break may be present in the immediate vicinity as a result of the significant weakness of the rail head. Visual characteristics are the same as a vertical split head and it is classified as a vertical split head defect when discovered.

2. Web Defects

Head and Web Separation

Head and web separation means a progressive fracture longitudinally separating the head and web of the rail at the fillet under the head. Gravel in crossings, excessive speed on curves, or improper canting of the rail can cause eccentric loading of the rail head and initiate development. Fatigue development can appear as rust-colored "rail strain" in the head/web fillet area, or as a slight horizontal cracking under the head. This type of defect can also develop in the head fillet area at the jointed rail end as a result of extreme stress conditions often created by pumping or swinging joints.


Head and Web separation

Split Web

Split web means a lengthwise crack along the side of the web, extending into or through it. The origin can be a seam or damage to the web, mechanical damage, or the split web can sometimes develop at locations where heat numbers are stamped into the web. Split webs can also develop as a result of high residual stresses from the roller straightening process, rail welding, and joint application.

Growth can be very rapid once the crack extends through web. It can also be accelerated by heavy axle loading. The defect can be visibly identified by the presence of rust-colored bleeding along the crack development.

Split Web Defect Showing Bleeding Condition along Crack Development

Piped Rail

Piped rail means a vertical split in a rail, usually in the web, due to failure of the shrinkage cavity in the ingot to unite in rolling. The origin of a piped rail is normally from the presence of a longitudinal seam or cavity inside the web that is inherent from the manufacturing process. Once development initiates, the seam will develop vertically toward the head and base of the rail. This type of defect is relatively uncommon in modern rail manufacturing technology.

The original seam does not normally progress either vertically or horizontally. Heavy axle loading can result in the seam spreading or opening up in a crosswise direction, resulting in a bulge in the web. These internal seams are also susceptible to development when subjected to pressure butt welding.

Piped Rail Showing Significant Rail Collapse

3. Miscellaneous Defects

Broken Base/ Base Fracture

Broken base means any break in the base of the rail. Broken base is generally categorized into two types of failure—broken base and base fracture. A broken base is normally confined within the flange area of the rail base and is normally an oval-shaped break referred to as a "half-moon" break. This type of base break is commonly caused by a seam, segregation, or improper bearing on the tie plate. A base fracture is normally the result of a nick or other type damage to the base that results in an identifiable indentation.

Half-moon Shaped Broken Base

A base fracture is a progressive fracture in the base of the rail, which can develop in a transverse plane. These defects, as a rule, originate on the outer edge of the base and can result in complete transverse failure of the rail section. Base fractures are usually caused by a nick on or a blow to the edge of the base, which results in an indentation or similar damage. Damage of this nature is sometimes caused by improper rail handling.

Transverse development can be relatively slow until the defect has progressed some distance into the rail section. However, a complete and sudden transverse rupture of the rail can occur with minimal transverse progression.

Base Fracture Showing Nick with Transverse Development

Defective Weld

Defective weld means a field or plant weld containing any discontinuities or pockets, exceeding 5 percent of the rail head area individually or 10 percent in the aggregate (oriented in or near the transverse plane) due to incomplete penetration of the weld metal between the rail ends, lack of fusion between weld and rail end metal, entrainment of slag or sand, under bead or other shrinkage cracking, or fatigue cracking. Weld defects may originate in the rail head, web, or base, and in some cases, cracks may progress from the defect into either or both adjoining rail ends. If the weld defect progresses longitudinally through the weld section, the defect is considered a split web for purposes of remedial action.

Electric Flash Butt Weld Showing Oxide Entrapment and Progression

Thermite Weld with Slag Entrapment

Plant welds are identifiable as a result of the shearing processes used to remove excessive weld material. This removal will provide a finish that is more flush with the web design, as opposed to field welds that will show excess weld material along the web and base area of the rail. Both types of welds can also fail at an angular or oblique direction from an anomaly associated with the web area such as shear gouges, trapped oxides, or improper heat.

Thermite Weld Oblique Type Failure Originating in Web Area

Bolt Hole Crack

Bolt hole crack means a crack across the web, originating from a bolt hole, and progressing on a path either inclined upward toward the rail head or inclined downward toward the base. Fully developed bolt hole cracks may continue horizontally along the head/web or base/web fillet, or they may progress into and through the head or base to separate a piece of the rail end from the rail. Multiple cracks occurring in one rail end are considered to be a single defect. However, bolt hole cracks occurring in adjacent rail ends within the same joint must be reported as separate defects.

A bolt hole crack is normally the result of stresses associated with pumping or swinging joints, improper drilling, excessively worn joint bars, or abnormal rail end impacts from rolling stock. Unchamferred holes that result a drilling burr on the edge of the hole left by the drilling operation can result in defect development. Growth is normally erratic and the rail can frequently rupture from a very small defect when the rail end is subjected to unusual stresses.

Bolt Hole Crack Originating in Lower Quadrant with Significant Progression

Flattened Rail

Flattened rail means a short length of rail, not at a joint, that has flattened out across the width of the rail head to a depth of three-eighths inch or more below the rest of the rail and 8 inches or more in length. Flattened rail occurrences have no repetitive regularity and thus do not include corrugations, and have no apparent localized cause such as a weld or engine burn. Their individual lengths are relatively short, as compared to a condition such as head flow on the low rail of curves.

Flattened Rail

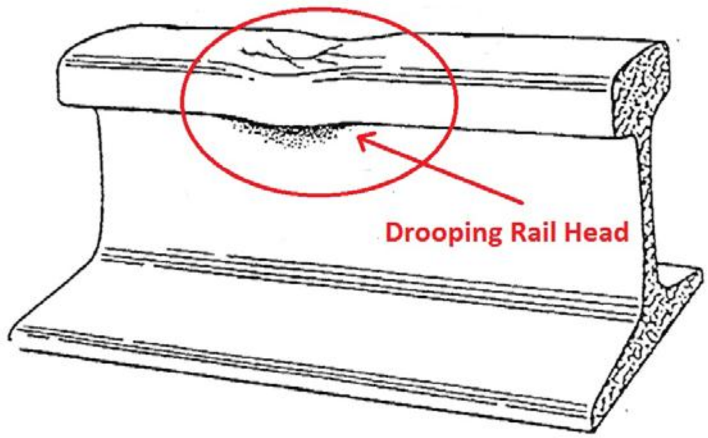
Damaged Rail

Damaged rail means any rail broken or injured by wrecks, broken, flat, or unbalanced wheel, wheel slipping, or similar causes.

Damaged Rail

Crushed Head

Crushed head means a short length of rail, not at a joint, which has drooped or sagged across the width of the rail head to a depth of three-eighths inch or more below the rest of the rail head and 8 inches or more in length. Unlike flattened rail, where the depression is visible on the rail head only, the sagging or drooping is also visible in the head/web fillet area.



Example of Drooping Rail Head