ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

ASSESSMENT OF THE DETERMINANT FACTORS FOR THE SELECTION OF BALLASTED TRACK VERSUS SLAB TRACK

By

Getachew Kidane

March, 2016

Addis Ababa, Ethiopia

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ASSESSMENT OF THE DETERMINANT FACTORS FOR THE SELECTION OF BALLASTED TRACK VERSUS SLAB TRACK

(a case of Addis Ababa Light Rail Transit)

A Project in Railway Engineering

By

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A thesis submitted to the School of Graduate Studies of the Addis Ababa University in partial fulfillment of the requirements for the degree of Master of Engineering in Civil Engineering

March, 2016

Addis Ababa, Ethiopia

The undersigned have examined the thesis entitled '**ASSESSMENT OF THE DETERMINANT FACTORS FOR THE SELECTION OF BALLASTED TRACK VERSUS SLAB TRACK (a case of Addis Ababa Light Rail Transit)**' presented by **Getachew Kidane**, a candidate for the degree of **Master of Engineering** and hereby certify that it is worthy of acceptance.

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DECLARATION

I declare that this research work titled "ASSESSMENT OF THE DETERMINANT FACTORS FOR THE SELECTION OF BALLASTED TRACK VERSUS SLAB TRACK (a case of Addis Ababa Light Rail Transit)" is my original work performed under the supervision of my research advisor Mequanent Mulugeta (Msc) and has not been presented as a research for a degree in any other university. All sources of materials used for this thesis have also been duly acknowledged.

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This is certifying that the above declaration made by the candidate is correct to the best of my knowledge.

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Mequanent Mulugeta *Date*

(Advisor)

ABSTRACT

The track is a fundamental part of the railway infrastructure and it is a structure consisting of parallel lines of rails with their sleepers, fittings and fastenings, ballast, etc, to provide a road for the movement of locomotives. The two types of track systems are ballasted track and slab track. Ballasted track consists of track superstructure of rails and sleepers supported on a layer of granular material (stones) and slab track consists of a continuous slab of concrete where rails are supported on the upper surface of the slab. Different scholars had studied the advantages and disadvantages of these track types in relation with different factors.

The purpose of this study is to assess and evaluate those determinant factors to select the better affordable track type for the construction of railway line for future expansion of AA-LRT project. The study mainly focuses on the ground/at-grade section of the track. The data for the study were taken from document analysis that has seen under literature review and some supportive data from observation and a few from working documents from AA-LRT project. The data were then analyzed both quantitatively and qualitatively.

During this study the construction cost, maintenance cost, ease of adjustment and maintainability in relation with construction and maintenance time with the need of accuracy and precision, track environmental impact in relation with noise and dust emission, weather conditions together with flood and dust problem, and lateral resistance were accessed from document analysis and site observation. The results revealed that slab track is more costly than the construction cost of ballasted track and less maintainability although it has better stability and durability. In addition to this from the transportation demand of the city population and addressing its facility, the study recommended that ballasted track is more affordable than slab track at ground/at-grade section.

Furthermore this study also recommended that undertaking different researches regarding these two track types in relation with the county context for both the LRT case and the national railway as well is important.

***Key Words**: Track, ballasted track, slab track, cost, Adjustment and maintainability, weather condition, and Environment*

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CHAPTER 1

1. Introduction

1.1 Background of the Study

The concept of transportation is not a contemporary phenomenon it rather has a long history even many years ago before the birth of Christ. Though it was a traditional way of transportation, the movement of people, animals and goods from one location to another had been started million years ago which could not be more far from the beginning of life on earth. Thanks to civilization, the pre-mode of transportation like the back of man and animal can't exist for a long. But it doesn't mean that, modern mode of transportation is the overnight booming occurrence (Lewis in Guy, 2001).

The second half of the nineteenth century brings a further advancement on the history of transportation that makes life more comfortable than it was before. Like any other mode of transportation railway transportation is the result of civilization. In its primitive age a kind of railway transportation were practiced by loading goods and drawn by men or animals. The first public railway in the world was opened for traffic on 27 September 1825 between Stockton and Darlington in the UK. At the same time, other countries in Europe like Germany, Italy, French and the like developed such railway system (Chandra, 2013).

The first modern railway opened from Manchester to Liverpool in 1830. Originally it was designed to transport coal and goods, but unpredictably it used for the transportation of people. It was quicker, more comfortable, and ultimately chippers than coach (Kishlansky, 2006).

In Africa, the South African railway system is the most highly developed and all major cities are connected by rail. It is the most important element of the country's transport infrastructure. The first track for steam-powered locomotives was a line of about 2 miles (3.2 km) by the Natal Railway Company, linking the town of Durban with Harbour Point, opened on 26 June 1860 (Burman, 1984).

The first Ethiopian railway was built during the regime of Minilik II in 1897. This railway was the innovation of the two French men who approached the king. The ambition was to solve the long distance trade system which may take six week mule trek from Addis Ababa to the French port city of Djibouti. The French-built railway connected the capital Addis Ababa to the Red Sea port of Djibouti. However, the old diesel railway is now being replaced by the Ethiopian railway corporation with a modern railway system. It is a grand plan that seeks to transport the country's commercial exports to its neighboring countries (Report of Africa Express Trains- Article, 2013).

The Ethiopian Government has been undertaking several transportation projects as part of a five-year growth and transformation plan (GTP), which aims to enhance the transportation network within the country by connecting to adjacent countries and ports. It will provide efficient mobility and improve the export and import activities, boosting the economic development (Ibid).

The National Railway Network of Ethiopia (NRNE) is one of the several projects constituted in the plan. The new railway line will connect northern Ethiopia with central region. It will also link the northern and eastern transportation network of Ethiopia (Ibid).

The track on a railway, also known as the permanent way, is the structure consisting of the rails, fasteners, sleepers and ballast (or slab track), plus the underlying sub-grade. It is a fundamental part of the railway infrastructure and represents the primary distinction between this form of land transportation and all others in that it provides a fixed guidance system.

Railway track classifies in to ballasted track and Slab track.

Ballasted track is a track which the ballast is the foundation of railway track and provides just below the sleepers. The loads from the wheels of trains ultimately come on the ballast through rails and sleepers.

Slab track also called ballastless track, is a modern form of track construction which has been used successfully throughout the world for high speed lines, heavy rail, light rail and tram systems.

This research was conducted on the Addis Ababa light rail transit which is the part of the five year growth and transformation plan of the Ethiopian government. The study was merely focus on the comparison of the determinant factors of track structures (ballasted track and slab track).

1.2 Statement of the Problem

The track is a fundamental part of the railway infrastructure. The two components of the track systems are the ballasted track and slab track. As stated in the literature review of this thesis, Gillet (2010), Le (2012), Proenca (2011), and other scholars stated the advantages and disadvantages of the two tracks which are the determinant factors in the choice of each track type. According to those scholars the **ballasted tracks** have the advantages of lower construction cost, better noise absorption, high maintainability, faster construction and easier sleeper replacement, and disadvantageous in terms of higher maintenance cost, higher cost for the bridge construction, limited lateral resistance, and the ballast can be churned up at high speed. As they also stated, **the slab track** have the advantages of lower maintenance cost, longer service life, more appropriate if there is strong weather condition, no emission of dust, better when there is lack of ballast materials, reduced depth of construction, and its disadvantages are higher construction cost, it needs more accuracy/precision during construction, less easily replaceable and limited/not adjusted after installation.

Generally, according to those literatures, some of the determinant factors which determine the choice of ballasted track versus slab track are construction cost, maintenance cost, ease of adjustment and maintainability, construction and maintenance time, noise, dust, weather conditions, construction precision, lateral resistance, and the like.

This study tries to contribute a possible recommendation in the choice of the two kinds of track in the development of light rail transit. The determinant factors which determine the selection of ballasted track versus slab track which stated on the advantages and disadvantages may or may not be applicable in the case of our country, Ethiopia. Since the difference in the technological, economical and other aspects is expected; the same conclusion may not do in the same way for all countries of the world. Thus, the researcher is inspired to conduct a study on the Addis Ababa light rail transit with special attention on the following points:

- The need to assess the findings of some previous studies which tries to explain the determinant factors that determine the choice of ballasted track and slab track in the context of Addis Ababa light rail transit.
- The need to check whether the findings can be relevant in the case of the newly building Addis Ababa Light Rail Transit/AA-LRT/ and are really agreed with the context of Ethiopia?

1.3 Objectives of the study

1.3.1 General Objective

The general objective of the study is to assess the determinant factors for the selection of the ballasted track versus the slab track in the case of Addis Ababa light rail transit. Meanwhile, the advantages, disadvantages, appropriateness and affordability of each track are assessed.

1.3.2 Specific Objectives

Moreover, the following points were the specific objectives of the study:

- Evaluate the determinant factors which determine the ballasted track and slab track.
- To identify more appropriate and affordable track type in the city of Addis Ababa.

1.4 Significance of the Study

Conducting this research will have the following significance

- It will shade some light to fill the research gap of the railway system in the city
- It can be an input for further studies which will be conducted in the near future
- It will suggest possible recommendation

1.5 Scope of the study

This study mainly focuses on the light railway transit system that is being built in the city of Addis Ababa. The researcher was basically focus on the determinant factors which significantly determine the two tracks (ballasted track and slab track) mainly construction cost, maintenance cost, ease of adjustment and maintainability, construction precision, and weather condition. The study cover only at grade condition/ground section of the two tracks but it did not cover factors like esthetic value, dynamic and static load condition and tracks over the bridge/elevated section and underground/ tunnel section. The non-financial aspects of costs were seen qualitatively referring the literatures in respect of the city of Addis Ababa.

1.6 Organization of the Paper

The thesis is organized with five chapters. The first chapter is the introduction which discussed the back ground of the study, the statement of the study, the objectives of the study, the significance of the study and the scope of the study. The second chapter is the review of related literature which states that what different scholars discussed about the two track forms in their findings. The third chapter is the description of the study area, research design, methods of data collection and analysis technics of the study. The fourth chapter is Data analysis and Discussion. The fifth chapter is the conclusion and recommendations.

CHAPTER 2

2. Review of Related Literature

The first and the for-most activity of the researcher were reviewing the literatures which have relation in any aspect with the study which was conducted. While reviewing the literature the researcher developed the following theoretical frame work.

2.1 Railway Transportation

In the advancement of modern mode of transportation, the innovation of railway can be considered as a fundamental invention which is the result of the industrial revolution in the second half of the 19^{th} century Europe. This mode of transport differ from the other means of transportation in its smooth metal wheel*s* running on smooth metal rail sustained by sleepers resting on a track bad of graded stone known as ballast (recently the slab track)**.** According to literatures railway has a lesser friction or rolling resistance than other types of road vehicle due to its smooth metal wheel lying over the smooth rail. This lesser amount of friction makes railway more preferable than others. In addition to such an advantage, its regular maintenance especially on the ballasted track can be seen as a disadvantage. It is believed that the cost of maintaining the ballasted railway track is several times greater than that of an equivalent length of road lane (Calla, 2003).

In this well civilized and business world, railway is a more significant mode of transportation that connects many seats to other across the world. In its very prior history, the practice of railway track comprises systems with animal (horse) power and other system. But latter, in the first decades of the 19^{th}c the traditional practices replaced by the modern land transportation system (Daoud, 2012)

> Mass motorization after World War II expressed by the growing prosperity brought about many problems, especially in densely populated areas: lack of space, congestion, lack of safety, emission of harmful substances and noise pollution. Exactly in these cases railways can be advantageous as they are characterized by the following factors: Limited use of space compared to large transport capacity; Reliability and safety; High degree of automation and management; Moderate environmental impact (Esveld, 2001).

2.2 Railway Track Structure

> Track is defined as an assemblage of rails, ties and fastenings over which cars, locomotives and trains are moved. Ballast may or may not be a part of the track, depending on the type of the track in question (AREMA, 2010).

According to Mundrey (2010), the railroad track is the structure that contains parallel lines of steel rails, fastening systems, sleepers, ballast and sub ballast to make available the path for the movement of locomotives and cars or wagons for transportation of freight and passengers.

The concept of track in railway transportation is the organization or structure of materials starting from the top of the rail up to the bottom of the subgrade for ballasted track or from the top of the rail to the bottom of the rail support device (fastener, block tie) for non-ballasted or slab track (Daniels, 2008; Suwanda ,2007).

From the railway infrastructure and its constituents, railway track is the central portion, and it has two main classifications, substructure and the superstructure. From these classes, the substructure of the track system includes ballast, sub-ballast, and sub-grade while the superstructure includes rails, rail pads, sleepers and the fastening system. Although the railway track structure has the substructure and the superstructure, both of these structures are equally significant in guarantying the safety and comfort of passengers and quality of trip (Remennikov, 2008 cited in Yeserah, 2012; Dahlberg, 2004)

The main function of the railway track structure in the railway transportation is to provide safe, smooth, economical and comfortable railway transportation for the society. To achieve this objective, the railway track should have stable guide with suitable horizontal and vertical alignment. Due to this reason, each part or element of the track structure should achieve their respective functions adequately in reply to the traffic loads and environmental factors levied on the system. They also serve to sustain the loads imposed to track structure mainly as a result of trains passages and temperature changes (Ionescu, 2004 cited in Yeserah, 2012; Selig and Waters, 1994 cited in Kennedy, 2011; Sadeghim, 2010).

2.3 Types of Track Forms

Railway track substructure is a very important component of the railway structure and it must be designed, built and maintained according to strong geotechnical principles and economically feasible approaches. Nowadays there are two types of railway track in the railway transportation system such as ballasted track and slab track. Although, from the beginning of railway history, conventionally ballasted track is the most common, nowadays some high speed railway systems have employed rigid concrete foundations which can be more cost -effective in some examples when life-cycle and maintenance costs are considered called slab track (Khabbaz, ---).

There are two main classifications of track types: ballasted track & slab tracks. Both technologies have advantages & disadvantages for the operation (Le, 2012)."

2.3.1 Ballasted Track

Before the beginning of the modern track system, ballastless track, the ballasted track functioned as the best solution for more than two centuries of existence and has been used in a vast number of high speed tracks. It is a traditional railway track form and placed on a bed of ballast material. The track components of this ballasted track can be grouped into two main components: the substructure and superstructure. In the railway track construction the substructure contains granular ballast, subballast and subgrade materials while the superstructure includes steel rails, various types of fastening system and sleepers (Selig and Waters, 1994 cited in Kennedy, 2011; Sadeghim, 2010; Proenca, 2011; Lihtberger, 2011).

In the history of railway transportation ballasted track have been used for a long period of time and still it is functional by upgraded continuously. For this developed time which the high speed line have emerged the ballasted track have been used for this purpose like the Tokaido Shinkansen in Japan and are still used in other countries such as France. In this track form the rails connected together by concrete sleeper and are laid in a layer of crushed rocks or gravel, called ballast. The imposed load that comes from the train is distributed to the ballast by the help of sleepers and these sleepers have a capacity of keeping the arrangement of the rail by avoiding lateral movement (Levinson, 1997 cited in Le, 2012).

> Ballasted railway track consists of track superstructure of rails and sleepers supported on a layer of granular material (stones) called ballast. Ballast provides a 'firm but elastic' support to the track superstructure and distributes stresses from the sleepers to the subgrade. Ballast also provides for immediate drainage of rainwater from the track but arguably the most important function of ballast is to allow maintenance of track, required to keep the track geometry within certain tolerances for safe and efficient running of trains. Ballast by weight and by volume is the largest component of the track and cost of buying and distributing ballast forms a significant part of the entire Civil Engineering budget of the railways (Cope 1993, p314). In spite of the fact that ballast is the most important component of the permanent way most attention has been focused on the track super structure of rails, fasteners and sleepers, not much consideration has been given to understand the behaviour of ballast in detail (Selig and Waters, 1994 cited in Calla, 2003).

According to Esveld (2001), in the railway track structure, the ballasted track structure have not significantly changed its principles from the beginning of railway but it has significant growth after second world war such as use of concrete sleepers, introduction of continuous welded rail, heavier rail profiles, modernize elastic fastening, modernization or mechanization of maintenance, introduction of innovative and advanced maintenance and maintenance management system. Thus the traditional ballasted track superstructure can still fulfill the great demand, as demonstrated by the TGV-tracks in France.

The construction of ballasted track has many advantages such as faster in construction and easier to change sleeper. But one of the drawback of this this track form is it needs a bulky rock materials which leads to highly expensive during ballast transporting. Whatever it is, the ballasted track is less expensive to construct, whereas to replace the ballast it require regular maintenance which leads to higher maintenance cost. On the other side the ballasted track has an advantage a better noise absorption, high elasticity, and high maintainability at relatively low costs than ballastless tracks (Esveld, 1997 cited in Gillet, 2010; Le, 2012).

Traditional ballasted tracks also have several disadvantages. Because of the non-linear and irreversible behavior of the materials, the tracks tend to float in longitudinal and lateral directions over time. In addition due to the wear of the ballast by abrasion, it requires periodic maintenance. It also offers limited lateral resistance, implying limited non-compensated lateral acceleration in curves occurring. The ballast can be churned up at high speeds, which may cause serious damages to rails and wheels. Ballast is heavy, which may lead to higher costs for the construction of bridges (Gillet, 2010).

Figure 2-1: Ballasted HSL track of KORAIL (Esveld, 2010)

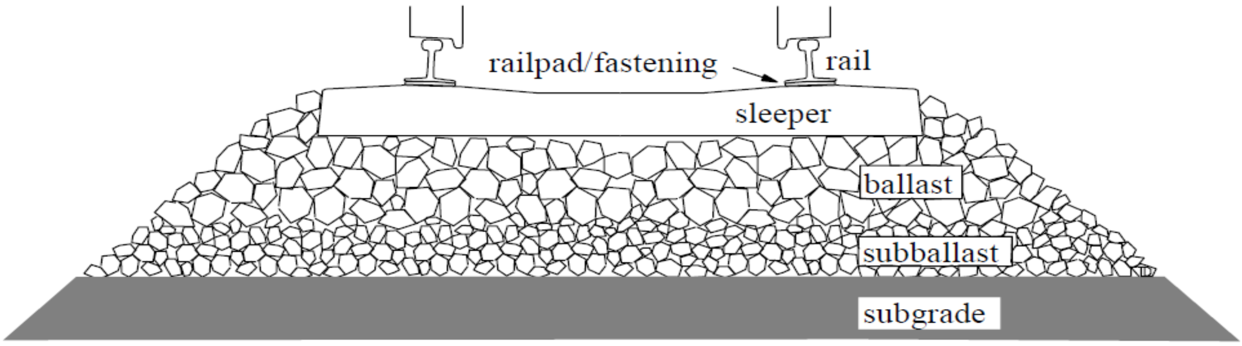


Figure 2-2: Track with its different components: rails, rail pads and fastenings, sleepers, ballast, sub-ballast, and subgrade (Dahlberg, 2004)

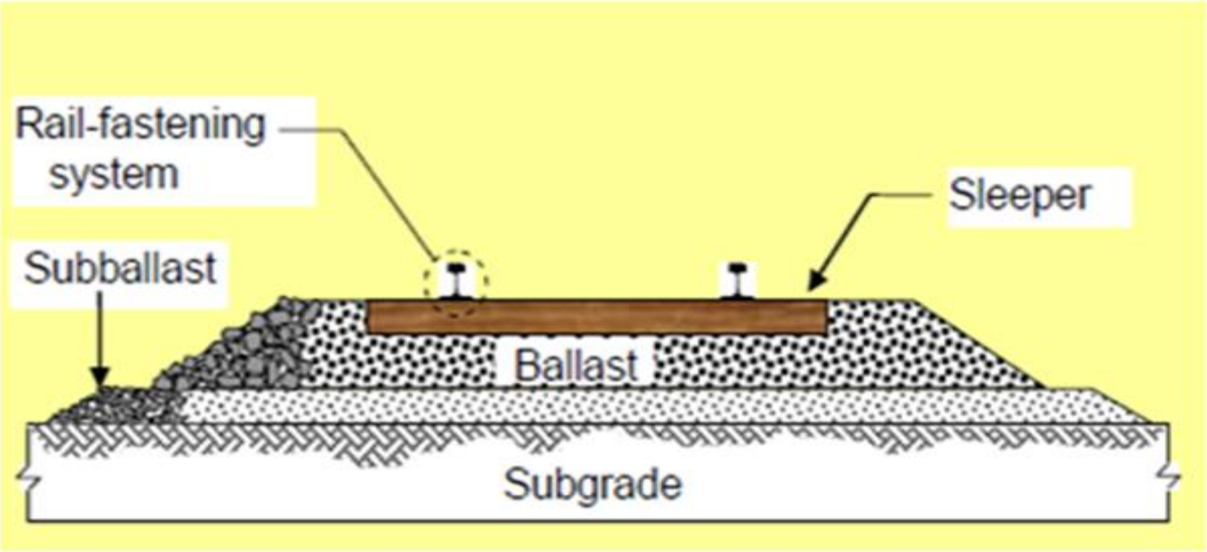


Figure 2-3: The cross section of Atypical ballasted railway track indicating main components of railway structure (Khabbaz, ---)

Generally, different scholars (Esveld (2001); Michas (2012; Gillet (2010); Lihtberger (2011); Le, (2012); and other scholars) stated the advantages and disadvantages of ballasted track from the different point of view, according to those scholars it has the following advantages and disadvantages.

Advantages of Ballasted Track:

- Low construction cost
- faster in construction and easier to change sleeper
- High elasticity and high maintainability at relatively low cost
- High noise absorption
- The longer years' experience with ballasted tracks makes the engineers more confident to deal with ballasted track problems and avoid the higher risk of dealing with problems concerning a relatively new design.
- Many recent advances in ballasted track construction make them even more competitive against slab track. Few examples of these advances are the following :
  - ✓ Introduction of reinforced concrete or steel sleepers.
  - ✓ Optimization of the rail geometry improves the wheel-rail contact condition offering a better load bearing capacity.

- ✓ Optimized rail pads and fastening providing better attenuation of the wheel-rail contact forces and of noise.
- ✓ Stone blowing and tamping machines provide more accurate corrections and faster maintenance.
- ✓ Better track resilience and resistance to settlements through the use of under sleeper mats as well as geo-grids and geo-synthetics between the different layers.
- ✓ The use of geotechnical retro-fitting techniques (e.g. lime cement columns), improving the bearing capacity of the subgrade, minimizing the possibility of settlements.

Disadvantages of Ballasted Track:

- Higher maintenance cost because it needs periodic maintenance due to wear of the ballast by abrasion
- The ballasted track does not provide good lateral or longitudinal resistance with result to have “floating” track effects.
- Limited lateral resistance of the ballasted track, resulting to lower speeds in curves.
- The deterioration of the ballast creates particles which are damaging the rail and the wheels.
- The wear of the ballast plus the intrusion of the fine particles from the subgrade, contaminate the structure making it impermeable.
- Ballasted track is heavier and higher structure demanding stronger structures and larger foundations in case of viaducts and bridges.
- The track elements and the way they are put together during construction will highly influence the rate of the track deterioration.
- In bridges and tunnels where continuous ballast bed is the case, extra elasticity must be supplied by application of ballast mats, rail fastenings with increased elasticity. Nonetheless the usual maintenance must be provided at regular basis.

2.3.2 Slab Track

Different systems of ballasted tracks have been developed in the past decades and it is the traditional kind of track. However, efficient and safe solutions that do not use ballasts have been developed in the past 40 years, called ballastless tracks, fixed tracks, slab tracks or simply non-ballasted tracks. The simplest form of slab track consists of a continuous slab of concrete where rails are supported on the upper surface of the slab, using a resilient pad. Several designs were developed, depending on which use they were planned for: on earthwork, on railway bridges, in tunnels (Gillet, 2010).

The application of slab tracks on high-speed railway lines is even more recent and is increasing. By 1993, Japan had built 1000 km of slab track (double track) for the Shinkansen. In Germany, Deutsche Bahn started to use slab tracks for high speed lines in 1995 [Ibid].

Slab track has been developed as an alternative to ballasted track and is widely used in tunnels. In the slab track the rails are supported by a continuous foundation as opposed to discrete support by sleepers in the conventional ballasted track. On slab track the change in track profile is very small and thus the slab track is superior to the ballasted track in this regard. The slab track contributes to a small cross-section of a tunnel and thus it is economical in tunnels (Watanabe, 1984; Eisenmann, 1995; Profillidis, 1995 cited in Calla, 2003).

According to Le (2012), in slab tracks rails are not rested on the ballast rather it fixed firmly or fastened on a concrete sleeper embedded in a concrete slab. The vibration is fascinated by rail pad between the fastening and the sleeper due to the reason where no ballast is used by the slab track.

Both the slab track and ballasted track have their own advantage and disadvantage one over the other. According to Proenca (2011), the slab track is now at front position of the railway engineering compared to ballasted track, for it can present a wide range of advantage than ballasted track. In addition to this, for the high demand of high speed railway traffic, it needs providing a new kind of track form having a better performance level.

In the railway transportation system challenges such as an increase in train speed, axle load and others that happen on the conventional ballasted track structure in the previous 40 years around the world, bringing an alternative track structure called slab track structure becomes vital. Due to the increased railway speeds, nowadays the slab track idea become more good-looking than previous and the concept is being attractive than ever before. Most industrialized and many unindustrialized nations in the world have high speed lines, and they are making to bring up-to-date their existing lines along with generating new high speed railway paths (Michas, 2012).

Talampekos (1999) and Esveld (2001) cited in Mihcas (2012) stated that this slab track is a concrete or asphalt surface that is substituting traditional ballasted track and the material that made of slab track structure is inflexible and inelastic materials. Therefore to attain the required elasticity, elastic components should be inserted below the rail and/or the sleeper. According to him, concrete is the dominant material in slab track application all over the world and only in very special occasions, asphalt has been used as materials for slab track construction. Slab track designs can be found mostly in civil structures in high-speed lines and light rail. The entire components of this track structure has five layers such as sub-grade or subsoil, frost protective layer, hydraulically bonded bearing layer, concrete/Asphalt bearing layer, and the rail.

Gillet (2010) stated that the emergence of the slab track is for evading all the entire disadvantage of traditional ballasted track. In addition to this, the other reasons for using slab track instead of ballasted track are lack of ballast materials, the need to make the track accessible to road vehicles, and no emission of dust to the environment due to the ballast. These track forms has higher availability of the track and lower costs of maintenance, and an increased service life. On the other side, the slab track forms have the disadvantage of higher construction cost for the building of new track than ballasted.

According to Proenca (2011), slab track is a new innovative type of railway track and has an advantage of maintenance cost reduction when it compare with ballasted track. It prevents the cost of ballast tamping, ballast cleaning and has a long service life that makes it more economical and competitive solution. This track form has a great benefit especially for high speed railway line. In contrast to ballasted track, slab track needs high investment cost for the initial construction.

Le (2012) also discussed about the advantage of the slab track. If there is strong weather condition like heavy rains and snow slab track is more appropriate than ballasted track. For example, the risk of flying ballast increases due to snow, in addition if there is other severe weather conditions the ballast deterioration will increase. Slab track has also an advantage in the case of a poor soil quality due to its lighter weight. This track forms help to reduce the wear and tear on the wheels and rail by electromagnetic breaks can be used to provide a better deceleration. Once the slab track constructed, it is not as easy as ballasted track to replace so it needs more care and more accuracy during the construction time. If the quality of the concrete is good enough as required, the slab track will have a long life time.

Figure 2-4: Flood problems on railway track

Figure 2-5: Snow problem on the railway track

Certain feasibility studies have proved that the slab track is profitable only if the construction process will not cost 30% more than the construction cost for the ballasted track. The RHEDA design is the most used slab track design nowadays in Germany and it costs approximately 1.5 times more than the ballasted track design. Despite that it is widely used due to the long-term experience with this type Taking into consideration the experience of the German network, the total costs in average is 20% to 40% more expensive than the cost of that of the ballasted track, and due to the almost zero need for maintenance it tends to be lower in the future (Lichtberger (2005) and Giannakos (2004) cited in Michas, 2012).

Figure 2-6: Continuously Reinforced Concrete Pavement for ballastless tracks (Lechner, 2011)

Advantages of Slab Track:

According to the bibliography of different scholars (Esveld5, Lichtberger, Darr & Fiebig, sited in Michas 2012; Esveld, 2001; Lihtberger. 2011; and other scholars) stated the advantages and dis advantages of slab or ballastless track by comparing construction of a slab track system instead a ballasted track.

Advantages of slab track:

- Lower maintenance need during its life cycle. No need for tamping, ballast cleaning and track lining results to a reduced cost approximately 20-30% for repairs comparing to that in ballasted track.
- Lower traffic hindrance costs.
- Higher life cycle, around 50-60 years compared to ballasted track (30-40 years) and possibility of almost full replacement at the end of the service life.
- More cost effective line positioning (as narrower curves at high super elevation and super elevation deficiency can be applied)
- No ballast or solid particles are whirled up on slab track.
- Higher safety against lateral forces and accommodation of higher axle loads.
- The eddy current brake can be applied without problems any time. (This is an advantage against ballasted track only in certain places such as signals or at station entrances. It cannot be seen as an advantage on plain line track.)

- Emergency vehicles and fire brigade vehicles can drive on the slab track in tunnels easily.
- Cost of vegetation control is either excluded or very reduced.
- Near maximum availability of the line and barely causes disturbances to the residents for maintenance during night shifts.
- Optimum design for high speed trains since it does not experience any problems such as drag forces at ballast.
- The slab track can compensate any excess in super elevation and in cant deficiency with freight trains or passenger trains without fears for dislocation of the track.
- Reduced height and weight of the structure.
- The lack of suitable aggregates for a ballasted track in a certain area can also lead to a slab track design.
- Slab track maybe also more suitable in cases where the noise emissions and the vibration nuisance do not cause problems and are acceptable.
- In places where the release of dust from the ballast bed must be prevented for environmental reasons the slab track is a good solution.
- Excellent riding comfort at high speed (VOSSLOH43).
- Better load distribution, hence reduced dynamic load of subsoil (VOSSLOH43).
- Excellent load distribution, thereby reducing the pressure on unconfined soil layers and the subgrade (Miodrag24).
- Lower wear of vehicle running gear through good retention of track geometry (Nigel & Franz26).
- The higher braking forces enable for shorter braking distances (Franz29).
- Slab tracks allow for steeper route gradients (Franz29).
- The rail can be laid in lower temperatures since buckling is less of a concern comparing to ballasted track (Kucera, Bilow & Ball44).
- Lower construction costs in case track and rolling stock are adjusted to one another (Franz29).

Disadvantages of Slab Track:

- higher investment costs combined with the longer manufacture and installation time needed for its construction
- limited options in adjustments after construction

- the higher air-borne vibration emissions
- The deterioration of the track geometry in case the operational strength of the concrete slab track has been reached, can occur very suddenly and unforeseeably. Thus the operational strength of the slab track might be compared to the occurrence of rail fracture.
- Small adaptability to large displacements in the embankment. Large displacements in track can be compensated only by significant amounts of work.
- Slab track has an estimated life cycle of 50-60 years. Of course this is valid only if the presupposition that the expected acceptable settlements will occur. In case of a derailment or any other unforeseeable events which could cause greater damage than the expected one (damage in sensitive fastening elements) can result to long term and expensive track closures. Unfortunately due to the short age of slab track there is not enough information on the actual performance during its life time in order to assess and examine this issue with high validity.
- Slab track by its rigid structure it is ensured that its life time will be at least 50-60 years. The nature of the slab track does not allow for easy adjustments and repairs after its construction. That means that its quality during the construction must be checked and reassured carefully because any defect on its quality would either remain for the entire life cycle either high costly measures should be taken in order to eliminate it.
- Not many possibilities to apply any innovation or future updates after construction.
- Slab track cannot be built in soft clays, earthquake areas or embankments on soft peat layers.
- Ballastless track requires homogeneous sub layers which are capable to carry the imposed loads with minor or no settlements. This means that in many cases and especially in earth structures special attention should be given in the foundation preparations. The high costs which are associated with the above mentioned fact is the main reason for the limited use of the slab track.
- Higher noise emissions. To handle the increased noise, extra treatment is needed which result to higher construction costs.
- Very expensive repair concepts and long term closures due to the curing and hardening procedures of the concrete.

- The frost protective layer in earth structures must be applied in any case and it is much thicker comparing to the ballasted one. This is a prerequisite in order to reassure a lengthy life cycle.
- The cost of the reconstruction (after it has reached the end of its life cycle) of the slab track is not considered. One or two standardized types of slab track seem to be optimal solutions.
- Transitions between ballasted track and ballastless track require special attention.
- In many cases new mechanisms needed for production and repair.

2.4 Component of Track Forms

"A railway track normally consists of rails, sleepers, railpads, fastenings, ballast, sub-ballast, and subgrade. Sometimes, for example in tunnels, the ballast bed is omitted and the rails are fastened to concrete slabs resting on the track foundation (Dahlberg, 2004)."

2.4.1 Component of Ballasted Track

In the railway track structure, the ballasted rack has two main components: the substructure and superstructure. From these track components, the substructure of the track system includes the ballast, the sub-ballast and the sub-grade whereas the superstructure of the track system includes the rail, the fastening system and the sleepers. Although the ballasted track is divided in to two main groups, both of these track components, superstructure and sub structure, are equally important in safeguarding the safety and comfort of passengers and a suitable quality of trip for traveler and cargo trains (Kaewunruen and Remennikov, 2008; Ionescu, 2004; Selig (2004) cited inYeserah; 2012*;* Dahlberg, 2004; Daoud, 2012).

According to Esveld (2001), the classical railroad track component includes a structure made up of rails and sleepers which are connected by fastening systems and are rested on ballast. The ballast bed is supported by the sub-ballast whereas the sub-ballast is supported by the subgrade. Other structures such as switches and crossings together with rails, fastening, and sleepers are considered as part of the track.

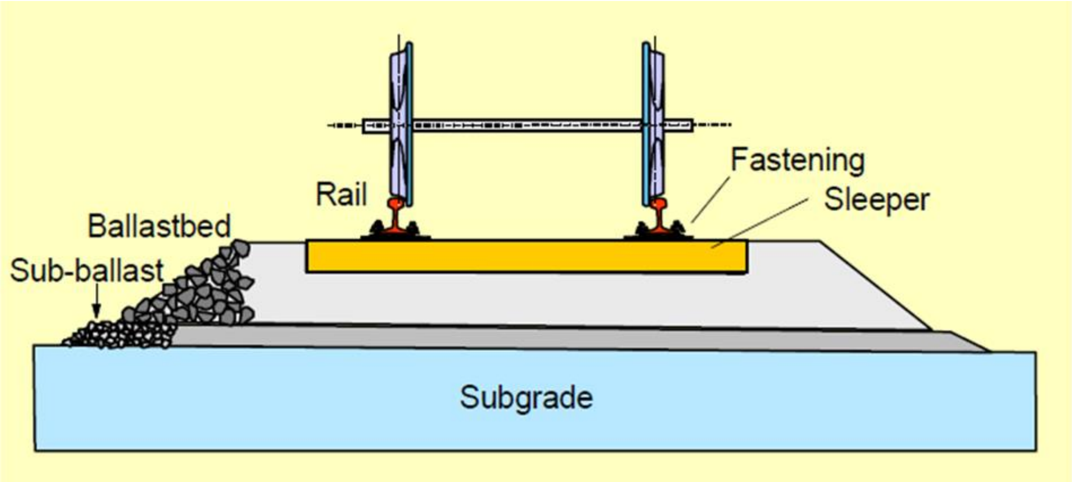


Figure 2-7: principle of track structure: cross section (Esveld, 2001)

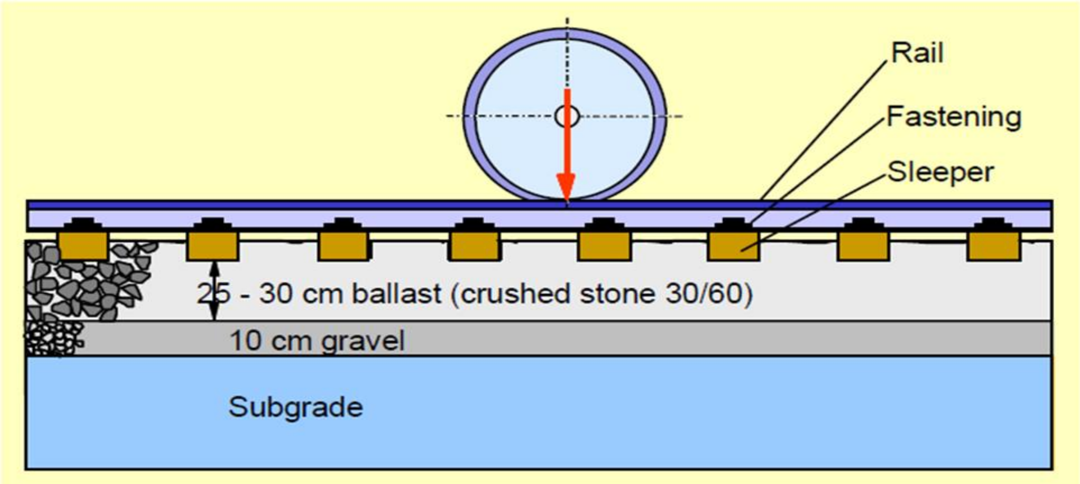


Figure 2-8: principle of track structure: longitudinal section (Esveld, 2001).

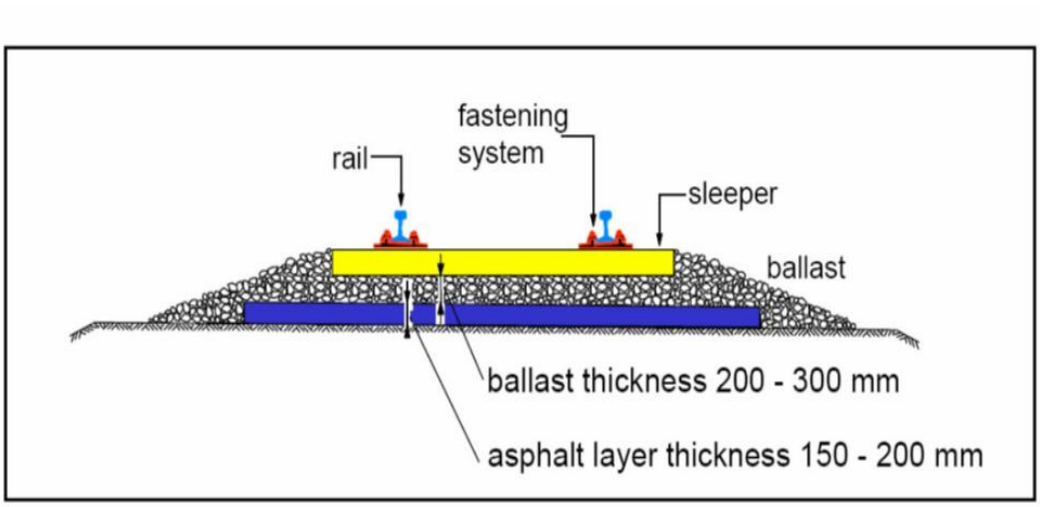
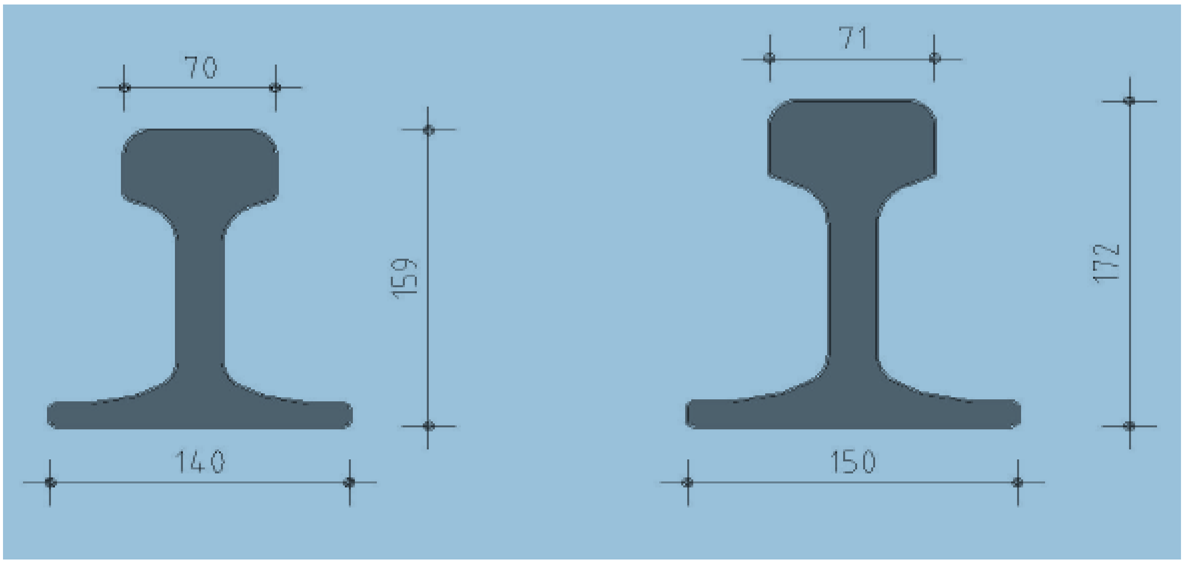


Figure 2-9: Typical cross sections of tracks with sub-ballast (Mittal, ---)

- **Rails**

Rails are made of steel which constructed longitudinally for the first element in contact with the vehicle wheels. Its main function is for the transmission of the imposed loads that come from the wheel. This loads that comes from the wheel is transmit to the sleeper with the help of the rail. The rail transmits not only the vertical load but also distribute the horizontal force to the sleeper. The other function of the rail is it is a guidance of the vehicle wheel (Daoud , 2012; Proenca 2011).

In the railway track structure the rail is one of the important track elements. It has a direct contact with the rolling stock and its main purpose is to support and guide the wheels of the vehicle. It addition to this it is an important component to withstand the wheel loads that applied in vertical, lateral, and longitudinal direction and then transmit this load to the next support of the track. Therefore from the safety point of view, the rail is a very important and needs ensuring its proper function in the track (Selig and Waters, 1994 cited in Kennedy, 2011; Calla, 2003; Sadeghim, 2010).



(a) (b)

Figure 2-10: (a) UIC 54 profile (b) UIC 60 profile (unit in mm) (Suwanda, 2007)

- **Rail Pads**

The rail pads are one of the most important elements of railway track, and it is located in between the sleeper and the rail for the purpose to reduce dynamic wheel/rail interaction force that protect the entire structure from unbalance stresses (Daoud, 2012).

In addition to the above, Selig and Waters (1994) cited in Kennedy (2011) explains that rail pads are found between the sleeper and rail and they are used as a fastening system to keep the rail against the sleeper and keep the exact track gauge. And it has an ability to withstand the vertical, lateral, longitudinal and overturning movement of the rail by attaching the superstructure to the ballast.

- **Fastening System**

Daoud (2012) stated that fastening system is the structural connection of the three components: rail, rail pads and sleepers and its purpose is to provide elasticity transmitted the imposed load that comes from rail and rail pads to sleeper. In addition, the fastening system provides electrical insulation for concrete sleepers and it withstands various movement of rail.

In the rail way track structure rails and sleepers need to be fixing each other to protect the rail from longitudinal, lateral and vertical movement. For this purpose the important components are the fastening system. In addition to this the fastening systems are important for protecting rail overturning and used as a tool for gauge restraining, reduction of wheel load impact and increasing track elasticity (Sadeghim, 2010).

- **Sleepers**

The sleepers play important roles in railway track system. It is one of the components of railway track that used to transfer the vertical and horizontal wheel load that comes from rails and fastening system to ballast and used as function of controlling the movement of rails. It also used as ties and maintain the line, level and the gauge of the rails and resist action of those forces tending to alter the line and level of the rails (Daoud, 2012; Proenca, 2011; Rolt 1968 cited in Calla, 2003; Bonnett, 1996).

Sleeper is one of the basic elements in the railway track component and has a function of transferring the vertical, lateral and longitudinal rail seat loads to the ballast, subballast and subgrade layers. Sleepers may be wooden or pre-stressed / reinforced concrete. They also serve to maintain the track gauge and alignment by providing a stable support for the rail fasteners (Fair, 2003 cited in Kennedy, 2011; Sadeghim, 2010).

Figure 2-11: Rails, fastenings, and sleepers (http://www.railway-tecnical.com cited in Suwanda, 2007)

- **Ballast**

In the railway track structure, the ballast layer is often made of angular, crushed, hard stones and rocks of ballasted railway track. It is placed on the upper layer of substructure and to the sides, in the middle of sleepers, outside the rail to form the shoulders and ends down to form a ballast layer. Its fundamental function is to withstand longitudinal force, to keep stability and elasticity of the track, to limit sleeper movement by resisting vertical, transverse and longitudinal forces from the trains, to distributes the load from the sleepers to protect the subgrade from high stresses, thereby limiting permanent settlement of the track, to provides necessary resilience to absorb shock from dynamic loading, to facilitates maintenance surfacing and lining operations, to provide immediate water drainage from the track structure, to help alleviate frost problems, and to retard the growth of vegetation and resist the effects of fouling from surface-deposited materials (Selig and Waters, 1994 cited in Kennedy, 2011; Dahlberg, 2004; Wee Loon Lim, 2004 cited in Daoud, 2012).

In the railway ballast track structure the ballast is the top layer of the substructure and it is the vital element in the railway track structure which supports the rail and sleepers. It is designed to guarantee the capacity of spreading and transmitting the loads that comes from the upper structure to the bottom supporting structure. Its main significant purposes are to distribute the load from the sleepers, to absorb impact, noise and vibration induced from the wheels, to damp dynamic loads, and to provide lateral resistance, to reduce the stress intensity to the level to be tolerable for subgrade layer, to facilitate track maintenance operations, especially those related to the correction of track geometry defects and to provide adequate drainage for the track structure. It is the preferable choice for substructure material over other alternatives such as concrete slabs or asphalt because ballast provides less stiff support (which is an important factor in case of differential settlement or subgrade failure), is more economical, and produces less noise (Aursudkij, 2007 cited in Yeserah, 2012; Sadeghim, 2010; Proenca, 2011).

- **Sub ballast**

Sub ballast in the railway track structure is the stratum located between the ballast layer and the subgrade layer to separate these two layers. The function of the sub ballast is to distribute and decrease stress from ballast to subgrade and to avoid interpenetration between ballast and subgrade. This layer is also used to act as a filter layer which prevents ballast and subgrade materials from mixed together (Dahlberg, 2004; Sadeghim, 2010; Daoud, 2012).

Kennedy (2011) and Boras, 2004 cited in Yeserah, (2012) discussed that the sub-ballast is the layer that present next to ballast at the top of subgrade layer. It is a granular material and has many functions. From these functions, the fundamental once is to distribute stress that comes from ballast layer to sub-grade layer. In addition to this, it has other important functions in the railway construction such as, helping the ballast to decrease the stress on subgrade, maintaining separations between the ballast and sub-grade particles and retaining the upward migration of fine material coming from the subgrade penetrating up into the ballast while wet and under pressure. It also plays a vital role in track drainage.

- **Subgrade Soil**

In the railway track structure, the subgrade layer is the foundation and the load-bearing layer of a track structure that supports the loads comes from the upper layer of the track structure and this layer is either a selected materials that is transported from other area or the compacted existing natural ground. During the operation time the loads comes from the upper layer need to have a stable foundation to protect them from different problems. Due to this reason the subgrade has a great advantage in the track performance and maintenance; it limits progressive settlement from repeated traffic loading; limit consolidation settlement; prevent massive slope failure; and restrict swelling or shrinking from water content change (Radampola, 2006; Selig, 2004 cited in Yeserah, 2012; Dahlberg, 2004; Kennedy, 2011; Bonnett, 1996).

2.4.2 Component of Slab Track

Mihcas (2012) stated that this slab track is a concrete or asphalt surface that is substituting traditional ballasted track and the material made up of this track structure is inflexible and hard or inelastic materials. Therefore to attain the required elasticity, introduce elastic components below the rail and/or the sleeper. Concrete is the dominant material in slab track application all over the world and only in very special occasions asphalt has been used as materials for slab track construction, and this is as a result of high construction demands. This slab track designs can be found mostly in civil structures in high-speed lines and light rail. The entire components of this track structure have five layers: sub-grade or subsoil, frost protective layer, hydraulically bonded bearing layer, concrete/Asphalt bearing layer, and the rail.

Typical slab track construction has the following parts from top to bottom:

- Rails
- Sleepers - optional
- Concrete slab
- Ballast concrete layer
- Anti –frost layer
- Subgrade

Non- ballasted or slab track uses a series of successive layers in order to reduce gradually stresses from rail till subgrade.

2.5 Application Area of each Track (at earth work/ground level/ at-grade condition, in tunnel and on bridge/elevated)

Slab track has been developed as an alternative to ballasted track and is widely used in tunnels. In the slab track the rails are supported by a continuous foundation as opposed to discrete support by sleepers in the conventional ballasted track. On slab track, the change in track profile is very small and thus the slab track is superior to the ballasted track in this regard. The slab track contributes to a small cross-section of a tunnel and thus it is economical in tunnels (Calla, 2003).

Most slab track constructions take place in tunnels where the ground is stiff and stable. The application of slab track in tunnels is very efficient in terms of construction, durability, strength and economy. The slab track can be built directly on the tunnel base and the thickness of the slab in many cases can be reduced compared to the slab track in earth structures. In addition when slab track is applied in tunnels the drainage requirements, as well as vehicle access in case of calamities and safety issues, must be guaranteed. The available free space of the tunnel may influence the decision of the most appropriate slab track system (Lichtberger 2005 cited in Michas, 2012).

In the railway construction, bridges are usually needed when a railway line crosses a river or an existing road. Bridges need special attention when it comes to designing since loads are no longer carried by earth works. During the construction of Railway Bridge in the area where they are need and demand of the construction raw material get higher and higher, finding solutions to design bridges that are less expensive are required. Ballasted tracks have the drawback that they need periodic maintenance, which lead to increase its maintenance cost and slab track structures have been developed, among other things, in order to avoid this drawback. In addition to this, ballast is heavy which may lead to higher costs for the construction of bridges (Gillet, 2010).

The weaknesses of the ballasted track structure which may lead the decision-makers to choose a slab track construction are that ballasted track is heavier and higher structure demanding stronger structures and larger foundations in case of viaducts and bridges and in bridges and tunnels where continuous ballast bed is the case, extra elasticity must be supplied by application of ballast mats, rail fastenings with increased elasticity (Esveld 2001 in Michas, 2012).

2.6 Railway Infrastructure Cost

Infrastructure refers to the important structures, arrangements, and facilities serving a country, city, or area, including the services and facilities necessary for its economy to function. Infrastructure cost is large portion of the infrastructure expenses is associated to the construction, renewal and maintenance of infrastructure assets with an estimated lifetime of more than 1 year (ECORYS Transport, 2005).

According to ECORYS Transport (2005), the overall classification of used for railroads

- **Investment costs**: costs aimed at new structure or improving the quality or functionality of existing structure over and above its original functionality.
- **Renewal costs**: costs aimed at substituting existing structure that has reached the end of its designated useful life.

- **Maintenance costs**: costs aimed at structure actually reaching its designed useful lifetime.

The track on a railway is the structure consisting of the rails, fasteners, sleepers and ballast (or slab track). The cost study for this structure includes construction cost, maintenance cost and life cycle cost.

2.6.1 Construction Cost

Construction cost means expense incurred by a contractor for labor, material, equipment, financing, services, utilities, etc., plus overheads and contractor's profit.

2.6.2 Maintainance Cost

According to Patra, A P; Söderholm, P and Kumar, U (2008), maintenance costs are the most complex cost component of an asset during its life since maintenance is a long continuous process throughout the asset life. While the cost of any specified maintenance work on an asset can be comfortably estimated using engineering costing methodologies, estimating maintenance costs throughout the asset life is a much more sophisticated process. This is because the types of maintenance are dependent on many factors, of which the most important are asset deterioration rates, maintenance policy, and budget constraint. Maintenance schedules therefore need to be planned to enable maintenance costs to be estimated. Maintenance costs of track must include:

- materials, equipment, and labour;
- condition monitoring and inspection;
- track possession time.

The track maintainace actions that includes under maintaince cost are Rail grinding cost, Track tamping cost, Rail lubrication cost, Ballast cleaning cost, Track inspection cost, Rail renewal cost, Ballast renewal cost, Sleeper renewal cost, Fasteners renewal cost, Rail replacement cost and Downtime cost

a. Rail Grinding Cost

Grinding is the maintenance action done on the railto control rolling contact fatigue defects. Rail grinding consists of grinding machines travelling along the track withgrinding stones, which are rotating stones or stones oscillating longitudinally, to abradethe rail’s surface. It is conducted to correct rail corrugations, fatigue and metal flow and to re-profile the rail. Cost due to rail grinding primarily depends on the periodicity of grinding and the number of grinding passes and is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((T_{g_i} * C_L * L_i * n_{g_i}) + (C_{eg} * T_{g_i} * L_i * n_{g_i})) * (m/m_{g_i})}{(1+r)^j} \qquad \text{(2 - 1)}$$

b. Track Tamping Cost

Tamping is the maintenance action done on the track to correct its alignment. It is conducted to correct longitudinal profile, cross level and alignment of track. A number of sleepers at a time are lifted to the correct level with vibrating tamping tines inserted into the ballast. Cost due to track tamping depends on the interval of tamping and is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((T_{ta_i} * C_L * L_i) + (C_{eta} * T_{ta_i} * L_i)) * (m/m_{ta_i})}{(1+r)^j} \qquad \text{(2 - 2)}$$

c. Rail Lubrication Cost

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

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{(T_{clu} * C_L * n_{l_i})}{(1+r)^j} \qquad \text{(2 - 3)}$$

d. Ballast cleaning cost

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

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((T_{b_i} * C_L * L_i) + (C_{eb} * T_{b_i} * L_i)) * (m/m_{b_i})}{(1+r)^j} \qquad \text{(2 - 3)}$$

e. Track inspection cost

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

$$\sum_{j=1}^{N-1}\frac{((T_t * C_L * L) + (C_{et} * T_t * L)) * (m/m_t)}{(1+r)^j} \qquad \text{(2 - 4)}$$

f. Rail Renewal cost

Rail renewal is done when the rail deterioration reaches maintenance or safety limits. The cost due to rail renewal is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((C_r * L_i) + (T_{rr_i} * C_L * L_i) + (C_{err} * T_{rr_i} * L_i)) * (m/m_{rr_i})}{(1+r)^j} \quad \text{-------------------------} \quad (2-5)$$

g. Ballast Renewal Cost

Ballast renewal is done when ballast deterioration reaches maintenance or safety limits. The cost due to ballast renewal is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((C_b * L_i) + (T_{br_i} * C_L * L_i) + (C_{ebr} * T_{br_i} * L_i)) * (m/m_{br_i})}{(1+r)^j} \quad \text{------------------------------} \quad (2-6)$$

h. Sleeper Renewal Cost

Sleeper renewal is done when the sleeper deterioration reaches maintenance or safety limits. it is a sleeper replacement process in almost all types of sleeper defects, remedial action is not possible and the sleeper requires replacement. Defective sleepers can result in the rail losing the correct gauge, which can cause rollingstock derailments. The cost due to sleeper renewal is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((C_s * L_i) + (T_{sr_i} * C_L * L_i) + (C_{esr} * T_{sr_i} * L_i)) * (m/m_{sr_i})}{(1+r)^j} \quad \text{----------------------} \quad (2-7)$$

i. Fastener Renewal Cost

Fastener renewal is done when the fastener deterioration reaches maintenance or safety limits. The cost due to fastener renewal is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((C_f * L_i) + (T_{fr_i} * C_L * L_i) + (C_{efr} * T_{fr_i} * L_i)) * (m/m_{fr_i})}{(1+r)^j} \quad \text{----------------------} \quad (2-8)$$

j. Rail Replacement Cost

Rail replacement is done when rail breaks occur on the track. It may be conducted to upgrade the track to a higher gauge rail or to replace the same gauge rail due to defects, wear or derailment damage. Cost due to rail break primarily depends on the probability of rail breaks and is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((C_r * L_r) + (T_{rb_i} * C_L) + (C_{er} * T_{rb_i})) * (m/m_{rb_i})}{(1+r)^j}$$ -------------------------------- (2 – 9)

k. Track Downtime Cost

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

$$\frac{\sum_i f_{rb_i} * T_{rb_i}}{\sum_i f_{rb_i}}$$ --- (2 - 10)

2.6.3 Life Cycle Cost

Life cycle cost (LCC) is used as a cost-effective decision support for maintenance of railway track infrastructure. It takes into account all costs related with the lifetime of the structure, such as operating costs, maintenance costs, energy costs, and taxes apart from capital costs. For many complex assets, the cost of maintenance plays an important role in the LCC analysis, especially for assets like track infrastructure, where the operation and maintenance phase comprises a major share of the system's life cycle (Patra, A P; Söderholm, P and Kumar, U, 2008).

Life-cycle costs are the sum of all costs of a specified track throughout its economic life, from first installation through removal or replacement. These costs include the material purchase and initial track construction, routine track inspections, and periodic maintenance to the end of its economic life, as well as disposal or recycle costs.

To quantify Life-cycle Cost of the Railway Infrastructure, from the perspective of an Infrastructure manager Zoeteman proposes a model:

$$LCC = \sum_{y=0}^{n}\frac{TC(y)}{(1+r)^y} = \sum_{y=0}^{n}\frac{CC(y) + MC(y) + RC(y) + DC(y) + OC(y)}{(1+r)^y}$$ ------- (2-11)

This model includes construction costs (CC), spot maintenance costs (MC), periodic maintenance and renewal costs (RC), delay costs (DC) and organizational costs (OC). Every single cost is estimated for a specific year (y) and discounted to the base year considering a constant discount rate(r) , throughout the lifecycle (Ramos, 2008). From this it is understand that without knowing all this parameters, it is difficult to estimate the life cycle cos of both the ballasted track and slab track.

From the below figure, it can understand that the advantages of slab track are started after 20 years of service. This measns after some years the two tracks reach at breakeven point and the advantages of ballasted track is reduced and the slab tack is increased. This is known by carefully study and estimates each types of maintenance and renewal cost to reach the lifecycle decision.

Figure 2-12: Time depending value, ballasted track and slab track (Rudolf & Dirk cited in Michas, 2012)

CHAPTER 3

3. Description of the Study area, Methods of Data Collection and Methods of Data Analysis for the study

3.1 General Description of the Study area

This study focused on AA-LRT covers a total of 34.37 km (The east-west line starts from Ayat and ends at Torhailoch which has a total length of 17.4 km and North –South from Menelik II Square to Kaliti which has a total length of 16.97km). As stated on China Railway Group Limited (2009), Addis Ababa is the capital of Ethiopia and has the altitude of 2,400m. The population of the city is over 3.4 million. The total area coverage of the city reaches 530.14 km^2 and the density of the population per square kilometer is 5,607.96. During this time there is a transportation problem in the city and to overcome this problem the government of Ethiopia decides to construct the railway transportation system. The Addis Ababa light rail transit system planned to build in two directions, the east-west direction and the south-north direction.

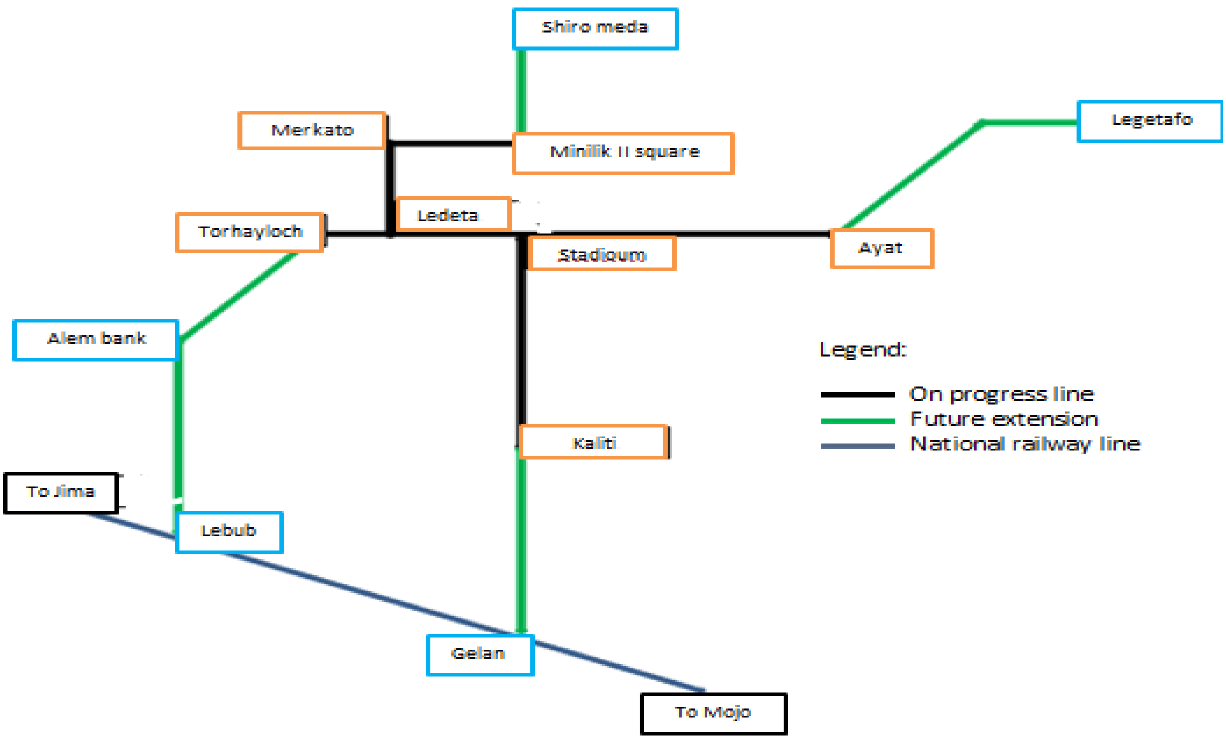


Figure 3-1: Schematic Diagram of Station locations (ERC, 2009).

According to China Railway Group Limited (2009), some of the data stated for the Addis Ababa Light Rail Transit projects are:

- **Passenger Flow Forecast**
  - ✓ Forecasting year is proposed to be that initial stage is 2014, short-term is 2021 and long-term is 2036.
  - ✓ Based on the passenger transport survey the passenger flow of Line E-W and N-S in Addis Ababa LRT is forecasted as 734.4 thousands and 536.9 thousands persons/day respectively.
- **Tramcar Size**
  - ✓ The outside dimension of the tramcar should conform to the metro gauge requirements.
  - ✓ Tramcar Length: 28400mm
  - ✓ Tramcar Width: 2650mm
- **Marshaling Scheme:**
  - ✓ Initial Stage: one unit of the tramcar is arranged to be operated with a capacity of 286 persons with 64 seats and 6 standing persons per m^2.
  - ✓ Long-term: two units are coupled together to form one train has a capacity of 572 Passengers with 128 seats and 6 standing persons per $m^{2.}$
- **Tramcar Performance**
  - ✓ The Highest Speed: 80km/h
  - ✓ Weight of Tramcar: 43t
  - ✓ Weight of Axis (axle): ≤11t
- **Criteria for Noise Control**
  - ✓ when the tramcar is operated on the flat-straight rail at the speed of 60Km/h, the noise of the area where passenger compartment center is 1.5m away from floor should be ≤75 dB (A）
  - ✓ when the tramcar is operated on the flat-straight rail at the speed of 60Km/h, the noise of the area 7.5m away from train center should be ≤82 dB （A）
- **Vibration and Impact**
  - ✓ Vibration: The longitudinal, transverse and vertical vibrations of the tramcar should all conform to IEC60077 standard. If the vibration is sine wave, the frequency of the vibration should be within 1Hz-50Hz:

- **Route plan**
  - ✓ Number of Mainlines: two lines
  - ✓ The Highest Speed of Travelling: 80km/h
  - ✓ Average Travelling Speed: 18km/h
  - ✓ Gauge of Track: 1435mm
  - ✓ Minimum Curve Radius: The Mainline Interval 50 meters in general, 30 meters in difficult sections.
  - ✓ the gradient algebraic difference between two adjacent slopes is not less than 2‰
  - ✓ Load: axis(axle) weight of the tramcar is not more than 11 tons
  - ✓ The surface of ballast bed should be 30-40mm lower than the supporting rail surface of the sleepers
- Rail: 50kg/m
- **Ballast Bed**
  - ✓ Ballast Bed for Underground Track

Underground mainlines adopt monolithic track bed with reinforced concrete short sleepers. The solid track bed with reinforced concrete short sleepers maintains the characteristics of mature techniques, simple structure, long duration, simple construction and can ensure good quality, convenient operation and maintenance.

✓ Ballast Bed for Grade Track

Ballast bed with pre-stressed reinforced concrete sleeper will be adopted for grade track. The double-layered gravel ballast bed has a thickness of 450mm.

a

b

Figure 3-2: AA-LRT a) Switch and Crossing Picture at Ayat b) Switch & Crossing and Station Picture on Elevated section at Estephansos

Figure 3-3: AA-LRT Track Level Crossing Picture around CMC

Figure 3-4: AA-LRT Station Picture around Torhayloch

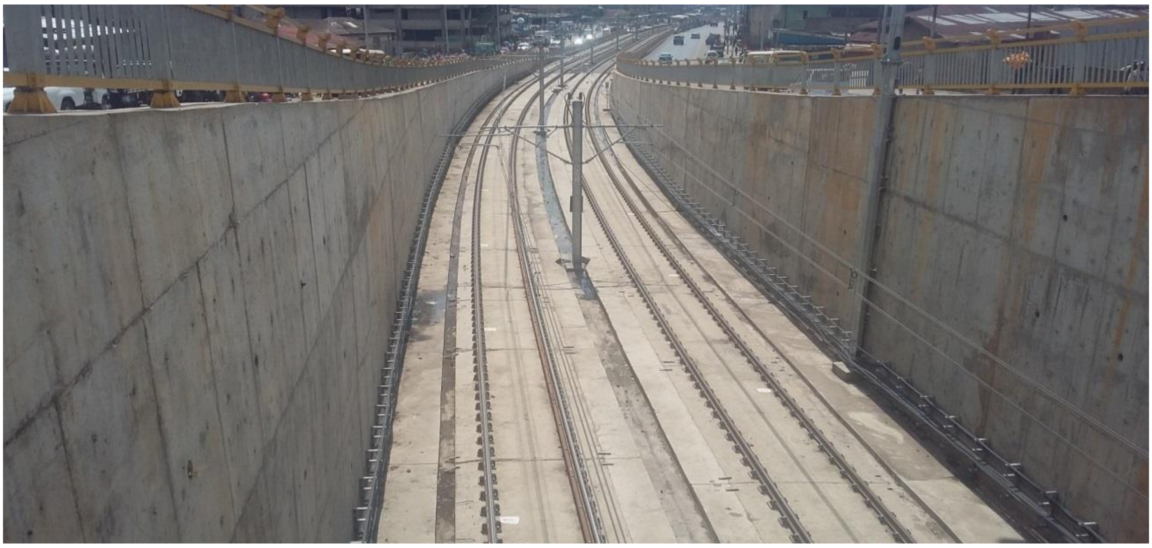


Figure 3-5: AA-LRT Transition Section Track Picture at Atikilt tera

Figure 3-6: AA-LRT Track Picture around at Kality

- **Geographical Location of Addis Ababa.**

Addis Ababa lies 9°1′48″N latitude and 38°44′24″E longitude. The city is located at the heart of the country, at an altitude ranging from 2,100 meters at Akaki in the south to 3,000(9,800 ft) meters at Entoto Hill in the North. This makes Addis Ababa the third highest city in the world, after La Paz and Quito in Latin America. Its time zon**e** is categorized in East Africa Time (UTC+3). The city occupies a total area of 540 Sq.Km2 (City Government of Addis Ababa Bureau of Finance and Economic Development, 2013).

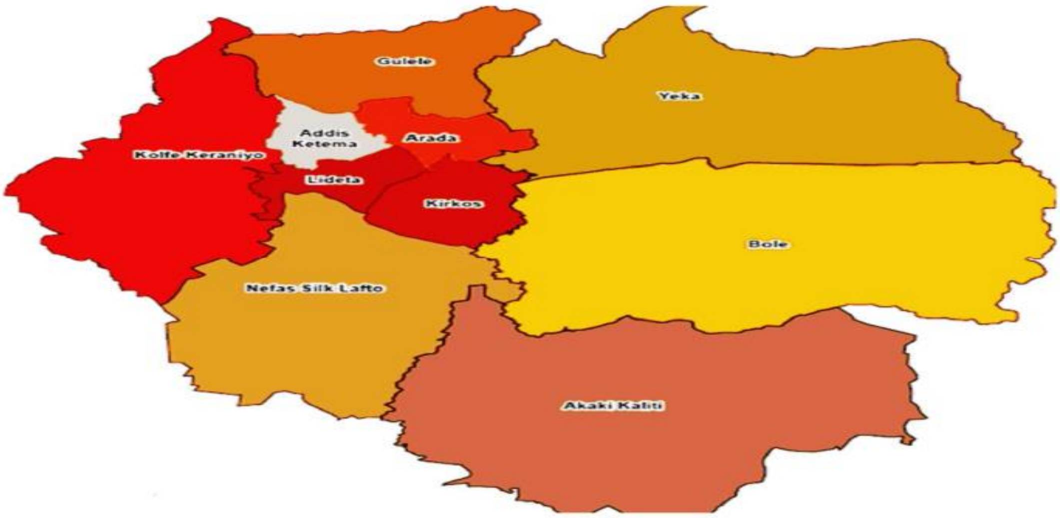


Figure 3-7**:** Administrative Map of Addis Ababa (City Government of Addis Ababa Bureau of Finance and Economic Development, 2013)

❖ **Climate of the City**

Addis Ababa has a Sub-tropical highland climate .The city has a complex mix of highland climate zones, with average temperature differences of up to 12.2°C, depending on elevation and prevailing wind patterns. The high elevation moderates temperatures year-round, and the city's position near the equator means that temperatures are very constant from month to month (www.climatezone.com cited in City Government of Addis Ababa Bureau of Finance and Economic Development, 2013).

Table 3-1: Climate Data of Addis Ababa for the year 2004 E.C (City Government of Addis Ababa Bureau of Finance and Economic Development, 2013)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Average High Temp °c	23.0	24.3	24.8	24.2	24.4	20.0	17.9	20.0	21.3	22.3	22.6	22.8	22.8
Average low Temp °c	6.0	9.0	11.6	12.0	12.3	11.2	11.3	11.2	11.0	9.9	8.7	8.1	10.6
Rainfall in mm	16.8	36	68.2	88.8	76	123.5	259.4	278	174.1	41.1	8.3	10.2	1,180.4
Average rainy days	5	3	7	10	10	20	27	26	18	4	1	1	132

As shown in the above table the months from June to mid-September is the main rainy season during which days and nights are cool by local standards. Average annual rainfall is 1,184mm, of which about 80% falls between June and September, the months of July and August being the wettest. The hottest and driest months are usually April and May. The short rains fall during March to mid-April, characterized by relatively cool nights and warm days (City Government of Addis Ababa Bureau of Finance and Economic Development, 2013).

According to Dr. Tamiru Alemayehu *et.al* (2003), the mean monthly and annual mean rainfall of National Meteorological Services Agency (NMSA) stations at Addis Ababa Bole, Addis Ababa Observatory (Tekelehaimanot) and Akaki Mission are shown in the below table and the three stations are located at different latitude and longitudes. Monthly total rainfall records of three stations for the year between 1964 and 1998.

Table 3-2: Mean Monthly station in three sections

Station	J	F	M	A	M	J	J	A	S	O	N	D	Ann. mean
Akaki (mm)	13.71	43.12	60.04	95.05	66.47	128.77	271.1	303.79	140.99	23.96	4.31	3.41	1154.72
AA Obse. (mm)	17.19	43.6	65.01	93.67	86.44	128.98	257.89	279.66	176.5	38.97	8.44	8.84	1205.19
AA Bole (mm)	15.38	40.13	68.73	92.8	79.5	116.64	234.83	244.14	150.32	34.25	10.08	4.48	1091.28

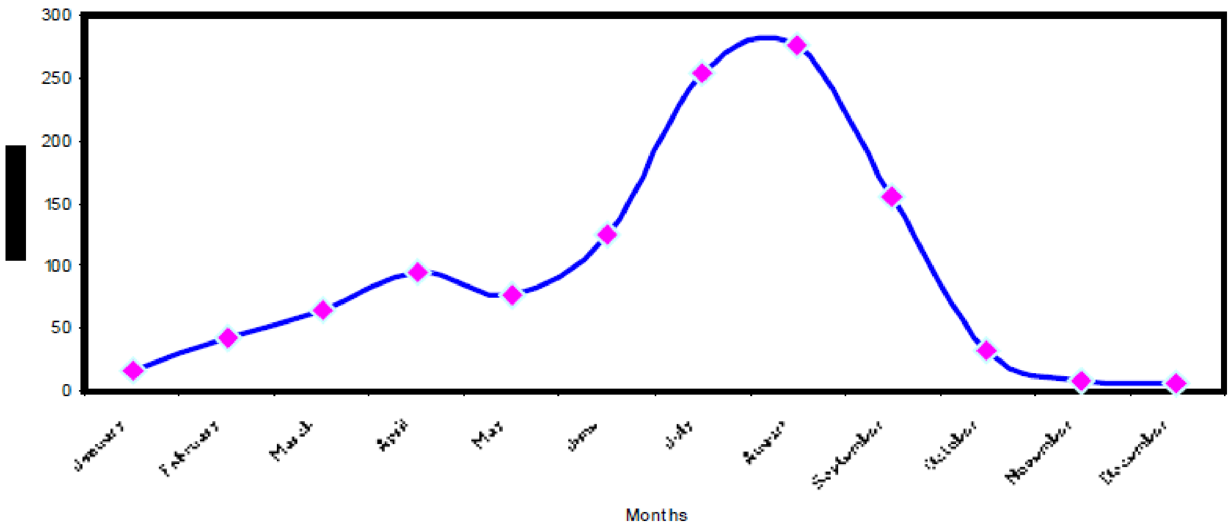


Figure 3-8**: Mean monthly rainfall at Addis Ababa Observatory.**

The monthly mean records of rainfall for thirty-five years shows that the mean annual rainfall at Addis Ababa Observatory (at an elevation of 2408m a.s.l.) Bole (at an elevation of 2324m a.s.l.), and Akaki Mission (at an elevation of 2120m a.s.l.) are 1205.19mm, 1091.8mm and 1154.2mm respectively. Thus, the city receives annual average rainfall of about 1150mm.

3.2 Method of Data Collection

The general purpose of this study was to assess and evaluate the determinant factors that affect the selection of ballasted track versus slab track based on the aspects of construction cost, maintenance cost, ease of adjustment and maintainability, construction precision, and weather condition. The attainment of this study needs collection of a necessary data from the actual site, from the concerned bodies that actively participate in the construction process, and secondary data from selected literatures.

- **Document Analysis** (Reviewing previous studies, Working Documents)

Previous studies which have important findings for this study were reviewed. These literatures should contain findings on the cost aspect of tracks, the adjustment and maintainability of the tracks, construction precision that should be considered while constructing the tracks, weather condition that affect the tracks, and in general the advantages and disadvantages of the two track types.

- **Observation**

As stated above, observation was one important method to gather the necessary data for the study. While conducting observation, the researcher used measuring tapes and camera in collecting the information which is needed for the study. And while observation some important photos and measurements were taken as a supplementary tool in data collection.

3.3 Methods of Data Analysis

The data collected through observation and document analysis was analyzed based on the objective of the study and the usefulness of the data. The selected representative data were then analyzed both quantitatively and qualitatively. Percentage tables and graphs were employed to analyze the quantitative data. The qualitative data was also evaluated in relation with the study area.

CHAPTER 4

4. Data analysis and discussion

4.1 Data and data source

For this data analysis and discussion, more of the data comes from document analysis that has seen under literature review and some supportive data taken from observation and a few from working documents from AA-LRT project. Using these data the analysis and discussion comes to meet the objective of this work and evaluate those determinant factors in terms of the study area conditions. Therefore, some of the determinant factors for the selection of ballasted track versus slab track were analyzed and discussed below.

4.2 Factors for the selection of the two tracks (ballasted and slab tracks)

4.2.1 Cost

Under this topic, the analysis and discussion mainly focus on the railway track construction and maintenance cost. This discussion and analysis is about the ballasted and slab track on at -grade /ground section in that it excludes the costs of elevated and underground sections of the track. The data for this analysis was derived from the total construction cost of AA-LRT project which is obtained in the working document and further clarification were obtained by consulting track professionals who work on the project. Furthermore, the data was also supplemented with the literatures studied by different scholars.

But during calculation, the track parts which are included on the cost calculation are:

- For the ballasted track:

The ballast layer and the super structure above the ballast includes rails, sleepers, fastening systems, rail joints, rail pads, rubber panels etc. and all the costs (labor cost, material cost, machinery cost, transportation cost, installation cost and the like) which are needed for this part.

- For slab track:

The concrete pedestal and the super structure above the pedestal includes rails, rail joints, fastening systems, welding, short sleepers etc. and including all costs (labor cost, material cost, machinery cost, transportation cost, installation cost and the like) which are needed for this part.

- Assumption:
  - ✓ The track is only at grade or ground section not included elevated section and underground section as stated on the scope of the project.
  - ✓ The track alignment taken is straight and no curve to calculate the volume.
  - ✓ For both track type all the structures below the ballast and concrete pedestal is the same and stable

4.2.1.1 Construction Cost

Construction cost means expense incurred by a contractor for labor, material, equipment, financing, services, utilities, etc., plus overheads and contractor's profit.

- ❖ From current AA-LRT Project lump sum cost

Let;

Construction cost of ballasted track = X
Construction cost of slab track = Y

- ❖ From Literatures

According to Lichtberger (2005) cited in Mickas (2012) stated that certain feasibility studies have proved that the slab track is profitable only if the construction process will not cost 30% more than the construction cost for the ballasted track.

According to K. Giannakos (2004) cited in Michas (2012) stated that the experience of the German network, the total costs in average is 20% to 40% more expensive than the cost of that of the ballasted track which means:

Construction cost of Slab track = construction cost of ballasted track + (20% - 40% of construction cost of ballasted track) ------------------ (4-1)

.

Analysis:

From AA-LRT project lump sum cost estimation per km

Table 4-1: Track work unit rate per kilo meter (Amount and Percentage of Executed Work Addis Ababa E-W & N-S (Phase I) Light Rail Transit Project May, 2014)

Item No.	**Work Items Description**	**Unit**	**Qty**	**Unit Price (USD)**	**Remark**
1	Track work				
1.1	Design				
1.2	Track laying				
1.2.1	Track laying on ballastless track of Elevated Section	km	1	495,683.09	
1.2.2	Track laying on Ground Section	km	1	384,786.23	It is a ballasted track part which includes rails, sleepers, fastening systems, rail joints, rail pads; rubber panels and include all costs (labor cost, material cost, machinery cost, transportation cost, installation cost and the like)
1.2.3	Track laying on Underground and transition Section	km	1	511,753.60	It is a slab track part which includes rails, rail joints, fastening systems, welding, short sleepers except concrete pedestals and including all costs (labor cost, material cost, machinery cost, transportation cost, installation cost and the like)
1.2.4	Track laying in Depot	km	1	170,079.88	
2	**Track-bed laying**				
2.1	Ballastless track	m^3	1	516.26	including all costs (labor cost, material cost, machinery cost, transportation cost, installation cost and the like)
2.2	Ballast track	m^3	1	21.07	include all costs (labor cost, material cost, machinery cost, transportation cost, installation cost and the like

The cost of ballasted track (X) per km is:

X= 384,786.23 USD + [(7m*0.45m*1000m)* 21.07 USD] ----------- (4-2)

Where:

Width of the track = 7m (from the site observation 6.9m at the station location and 7m out of the station)

Depth of the ballast = 0.45m (from AA-LRT study report)

Length of the track = 1000m (assumption for 1km)

X = 384,786.23 USD + 66,370.5USD = **451,156.73**USD per km

Figure 4-1**: Ballasted track at grade/ground section AA-LRT project**

The cost of slab track (Y) per km is estimated:

Y= 511,753.60 USD + [(6.4m*0.15m*1000m)* 516.26 USD] -------------- (4-3)

Where:

Width of the track pedestal = 6.4m (from site at the transition section)

Depth of concrete pedestal = 0.15m (average depth from site at the transition section)

Length of the track = 1000m (assumption for 1km)

Y = 511,753.60 USD + 495,609.6USD = **1,007,363.20** USD per km

Figure 4-2**: Slab track at transition section AA-LRT project**

But to check the cost of slab track using the information that taken from the **Literatures:**

Y' = X + (20% *X) -- (4-4)
= 451,156.73+ (0.2* 451,156.73) = **541,388.08USD for 20%**

Y' = X + (40%)*X -- (4-5)
= 451,156.73+ (0.4*451,156.73) **= 631,619.42USD for 40%**

Slab track is profitable only if the construction process will not cost 30% more than the construction cost for the ballasted track.

Y'' = 451,156.73 + (0.3*451,156.73) = **586,503.75USD** for 30% ----------- (4-6)

To know the percentage of slab track cost for AA-LRT project how much is more than ballasted track cost:

% slab track = [(Y-X)/X]*100 --- (4-7)

$\% \, slab \, track = \left[\frac{1{,}007{,}363.20 - 451{,}156.73}{451{,}156.73}\right] * 100$ = 123% more than the construction cost of ballasted track.

Discussion:

From the above analysis using the literature and the data from AA-LRT Project for the construction cost of ballasted track, the minimum cost of slab track is 541,388.08USD for 20% and the maximum cost of slab track is 631,619.42USD for 40% by comparing with the construction cost of ballasted track.

As it can be seen from the above calculation, the construction cost of slab track at the transition section at AA-LRT project is 1,007,363.20 USD which is greater than the maximum cost of slab track is 631,619.42USD for 40%. Using the data that taken from the literatures by adding 30% of ballasted track on the cost of ballasted track, the slab track construction cost be 586,503.75USD per Km. But the slab track construction cost that calculated using the transition section unit rate, 1,007,363.20 USD, is more than 30% additional cost beyond the ballasted track construction which is 123%. This 123% indicates that the construction cost of slab track is more than double from the construction cost of ballasted track. Therefore, according to the data which stated in researches, it is not profitable. This may happen in different reason, because the data which is obtained from the above table is taken from the lump sum pricing system of the EPC turnkey contract unit rate. For the previous first phase AA-LRT project, there is no detailed studied cost break down for each item on the client side. This may lead to the contractor increase the items unit rate. In other time may be present less unit rate for other contract. Therefore this study recommended that for the future it needs detail cost break down study on the client side for each item to get each item unit rate for track construction on ground section. And by do so, it may minimize this gap and may reach to the possible profitable margin.

4.2.1.2 Maintenance Cost

According to Patra, A P; Söderholm, P and Kumar, U (2008), maintenance costs are the most difficult cost element of an asset throughout its lifetime since maintenance is a lengthy continuous process during the asset lifetime. While the cost of any stated maintenance work on an asset can be estimated using engineering costing procedures, estimating maintenance costs throughout the asset lifetime is a much more sophisticated process. This is because the kinds of maintenance are reliant on various factors, of which the most important are asset deterioration rates, maintenance policy, and budget constraint. Maintenance schedules therefore need to be planned to enable maintenance costs to be estimated. Maintenance costs of track must include:

- materials, equipment, and labour;
- condition monitoring and inspection;
- Track possession time.

The costs included under track maintenance actions are:

- Rail grinding cost

- Track tamping cost
- Rail lubrication cost
- Ballast cleaning cost
- Track inspection cost
- Rail renewal cost
- Ballast renewal cost
- Sleeper renewal cost
- Fasteners renewal cost
- Rail replacement cost
- Downtime cost

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

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

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

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

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

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

Ballast renewal cost: Ballast renewal is done when ballast deterioration reaches

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

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

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

Track downtime cost: Downtime on the track occurs due to track possession for maintenance actions on the track.

All the above and related costs should be known to calculate the track maintenance cost using the models indicated under each parameter in the literature review; however, all these costs are not yet studied on the case of newly built AA-LRT Project. Due this reason to estimate the maintenance costs and compare each track type, the data which obtained from the literatures is used. Therefore by taking the ratios and percentages that has got from the result, the estimation of the maintenance costs of the two tracks as follows:

Let;

Maintenance cost of ballasted track = W

Maintenance cost of slab track = Z

- From literatures

Annual maintenance cost of slab track is 8% of its construction cost and Annual cost of ballasted track is 11% of its construction cost (Esveld, 2003 sited in Michas, 2012)

Maintenance cost of slab track = Maintenance cost of ballasted track – (20%-30% of maintenance cost of ballasted track) (Michas, 2012) ----------- (4-8)

Analysis:

The annual maintenance cost of the track for AA-LRT using the information obtained from the literatures is calculated as follows:

From the previous construction cost calculation

Ballasted track:

- Construction cost of ballasted track (X) = 451,156.73 USD per km

Slab Track: to calculate the maintenance cost of the slab track, the study seen in two cases;

Case 1: using direct construction cost of slab track which obtained from the cost at the transition section which stated as not profitable (123% more than the construction cost of ballasted track), that is:

- Construction cost of slab track (Y) = 1,007,363.20 USD per km (not profitable)

Case 2: using the profit margin which stated in the literatures; Slab track is profitable only if the construction process will not cost 30% more than the construction cost for the ballasted track, which is:

Y’’ = 451,156.73 + (0.3*451,156.73) = 586,503.75USD for 30%

The annual maintained cost:

For ballasted track

W= X*11% -- (4-9)

= 451,156.73*.11 = **49,627.2403USD** per km/year

For slab track

Case 1:

Z = Y*8% -- (4-10)

= 1,007,363.20*.08 = **80,589.056 USD** per km/year

Case 2:

Z = Y’’*8% --- (4-11)

= 586,503.75*.08 = **46,920.30 USD** per km/year

But to check the annual maintenance cost of slab track using the information that taken from the **Literatures** that says:

Maintenance cost of slab track = Maintenance cost of ballasted track – (20% - 30% of maintenance cost of ballasted track) (Michas, 2012)

Z' = W - (20% *W) -- (4-12)

= 49,627.24- (0.2* 49,627.24) = **39,701.79USD** for 20%

Z' = W- (40%*W) -- (4-13)

= 49,627.24 - (0.3*49,627.24) = **34,739.07USD** for 30%

Discussion:

From the above analysis using the literatures and the data from AA-LRT project for the annual maintenance cost estimation of slab track, the maximum annual maintenance cost of slab track is 39.701.79USD USD for 20% deduction and the minimum annual maintenance cost is 34,739.07USD for 30% reduction. According to the first case calculation of annual maintenance cost of slab track using the actual construction cost at transition section in AA-LRT project which multiply by 8% is 80,589.056 USD per km/year. According to the statement which stated on the literatures, this results should it be in between the reduction of 20% and 30% from the maintenance cost of ballasted track. But the reality is far from the statement, 80,589.056 USD per km/year is above the maximum one. However, if consider the second case it is somewhat reduced and approach to 20% deduction.

From this analysis, case 1, the annual maintenance cost of slab track is more than the annual maintenance cost of ballasted track even if the percentage rate (8%) annual maintenance cost of slab track is less than the rate (11%) of ballasted track. But as it seen in the second case the annual maintenance cost of slab track (46,920.30 USD per km/year) is lower ballasted track (49,627.2403USD per km/year) if the construction cost of slab track is more than 30% of the construction cost of ballasted track.

From this it can understand that, the initial construction cost of the slab track is more costly and as discussed in the above it is 123% greater than the construction cost of ballasted track which is unprofitable. Therefore, due to this reason for ground/at grade section ballasted track is more preferable and preferable.

On the other hand, as calculated in the above maintanance cost estimation, the annual maintenance cost of slab track may be higher due to the higher of construction cost, whereas as it can see from the below figure (Figure 4-3) after successive years the slab track annual maintenance cost may not be increase like ballasted track. If the construction works precision is correct and accurate, the slab track maintenance cost will be lower than ballasted track because in the slab track there is now a problem of ballast degradation and rail is not affected by ballast which means this type of track is out of ballast tamping, ballast cleaning cost and in addition to that sleeper and rail replacement is not much higher like ballasted track. But in the case of ballasted track, after some time, ballast tamping cost, ballast cleaning cost, sleeper replacement cost will faced and regular maintenance needed.

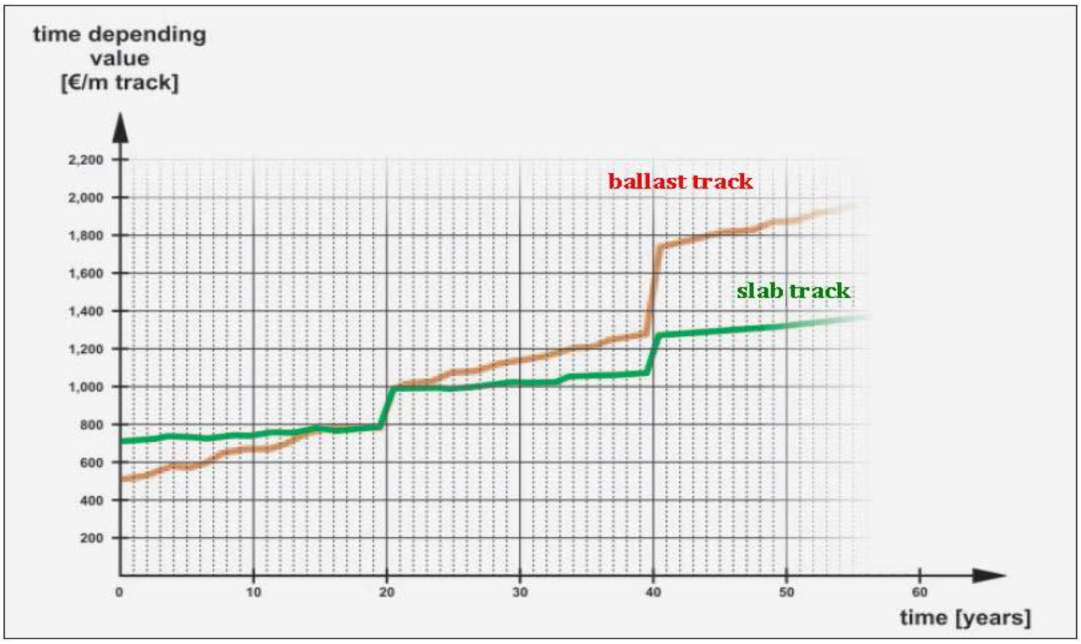


Figure 4-3: Time depending value, ballasted track and slab track

From this figure, the advantages of slab track are started after 20 years of service. Now is the final recommendation which type of track will be more preferable for the Addis Ababa city future expansion LRT project. To give recommendation, we need to assess our country actual condition in terms of financial capacity, trained professional, technological advancement in relation with the demand of the transportation by city population and also the need higher construction cost, construction precision and accuracy and less easily maintainability of the slab track.

From the transportation demand of the city, the population is highly in need of transportation and lost much working time by waiting transportation service. Due to this reason and highly construction cost needed by slab track, ballasted track is preferable than slab track for the city at current condition.

4.2.2 Ease of Adjustment and Maintainability, Accuracy or Precision, and Construction Time

In addition to low construction cost, ballasted track has high maintainability with relatively low cost. From the very long year experience, ballasted track construction makes the engineers more confident to deal with problems and avoid risks related with new designs. Many recent advances in ballasted track construction make them even more competitive against slab track. From these advances, stone blowing and tamping machines provide more accurate corrections and faster maintenance. If somewhere defects happen, it can make correction within a short period of time and low correction cost in comparison with slab track.

On the other hand even if slab track has low maintenance cost and long life time, it is a new technology type of track structure and needs high accuracy and precision during design and construction time as it has seen in the literature review above. That means, if a silly mistake happen during construction, it is not easy to maintain. It has to be totally changed so that it needs much time and cost to reconstruct the track. During this much time needed readjustment, another cost added by leading delay of operation in addition to readjustment cost.

Due to these less ease of adjustment and maintainability, needing more accuracy or precision, and taking more readjustment construction time and other related reasons slab track is lease preferable than ballasted track.

4.2.3 Weather Condition, Flood and Dust Problem

The railway engineers and practitioners agree on the fact that slab track is more suitable for strong weather condition such as snow and heavy rain. For instance, snow increase the risk of flaying ballast, while other severe weather conditions increase the ballast deterioration (Le, 2012)

In the study area, Addis Ababa, the weather condition is not much stronger that lead to creation of snow because as we can see Table 3. 1, the temperature range of the city is 5 – 30 degree Celsius which can't lead to creation of snow because Snow forms when the atmospheric temperature is at or below freezing (0 degrees Celsius) and there is a minimum amount of moisture in the air. Therefore snow is not a problem of the city and due to this reason ballasted track is not affected by snow problem.

On the other hand, to see which track type is more affected by flood problem, briefly knowing how it happen is important.

Flooding occurs when a river's discharge exceeds its channel's volume causing the river to overflow onto the area surrounding the channel known as the floodplain. The increase in discharge can be caused by several events. The most common cause of flooding is lengthy rainfall. If it rains for a long time, the ground will become saturated and the soil will no longer be able to store water leading to increased surface runoff. Rainwater will enter the river much faster than it would if the ground wasn't saturated leading to higher discharge levels and floods.

As it can see from the metrological data, monthly rainfall range is 4mm-305mm and the city receives annual average rainfall of about 1150mm which is smaller than that annual rainfall recorded in other countries. For instance, average annual rainfall, the wettest place is Mawsynram, Meghalaya, India, with 11,873 mm (467 in) of rain per annum. However, this data may not indicated it creates flood, because as stated before floods occurs because of different events that is flooding occurs in known floodplains when lengthy rainfall over several days, intense rainfall over a short period of time, or a debris jam causes a river or stream to overflow and flood the surrounding area.

In the study area, flood was happen in 2014 and damage different properties and in addition to this different times, the rain water is overflow on the road out of the drainage system. This reason is not only because of the volume and intensity of the rain but most of the drainage systems which build at the sides of the roads are blocked by debris and garbage. As a result flooding is happen out of the drainage pipe and covers the surface of the road. The following figure (Figure 4-4) shows the flood that happen in Addis Ababa city in 2014.

Figure 4-4: Flooding in Addis Ababa

Now to compare the two types of track and to recommend which one is appropriate for the city in relation with this condition, it needs to discuss some points regarding the flooding problem and the situation of the new railway line at ground section and the below figure (figure 4-5) shows that the railway line that built at the center of the two road lane. As stated in the above, the flood is overflow out of the drainage system due to the problem of the drainage system itself and other additional reasons and it may has a probability entered to the railway line. If the flood enter in to the railway line, the ballasted track has got series problem of filled with silts and the ballast may also washed away. During the rainy time, floods comes with a lot of unwanted particles and silts that fill the ballast space that lost its friction and makes the ballast flying over. This leads regular maintenance for ballast cleaning and other related maintenance work that makes the ballasted track high maintenance cost. Therefore, due to this reason slab track is more preferable than ballasted track. However, to avoid such problem the track needs secured drainage system and if the flood problem due to the drainage system is avoided, it can minimize the maintenance cost that comes from this reason and can increase the lifetime of the ballasted track.

Figure 4-5: Sample Pictures from AA-LRT Track Line

On the other hand, in Addis Ababa city new build infrastructures are ongoing and make this more dust and on some area the garbage is near to the line that the wind carries the dusts and plastic materials to the railway line. This makes the track is affected by those unwanted materials and regular maintenance needed. This regular maintenance makes the ballasted track higher maintenance cost. Therefore, for the area where this dust particle is much higher and unwanted materials affected the track, slab track is more preferable than ballasted track. But it can minimize the dust by clearing the unwonted material from the area to protect the ballasted track from the problem.

4.2.4 Environment/ Noise, Vibration, and Dust emission/

Noise is the unwanted sound because of its volume and can be harmful. Sound responding is not equal for every people and therefore, there is no fixed value at which a sound is perceived as noise. Railway noise is sound emissions arising from the operation of trains and trams and there are different sources and causes of railway noise, such as locomotives accelerating, vibration from rail corrugation, the types of tracks constructed and the pantographs of high-speed trains.

> If sound emission is louder than 120 dB (A), there is a risk of injury. Noise is regarded as particularly critical when its exposure during sleep such as night flight. So night noise causes health hazards already at individual levels below 45 dB (A), if the difference between the individual level and the background noise is more than 3dB. Noise above 55 dB (A) is considered as noise pollution. If noise above this level lasts for an extended period of time, the efficiency and well-being of a person will be reduced. Noise in the range 65 to 75 dB (A) causes stress to the body. This can lead to arterial hypertension (high blood pressure), cardiovascular disease and myocardial infarction (heart attack). Noise can also provide for a reduction of gastric secretion and be the cause of stomach ulcers [WHO JRC 2011]. A recent survey [Schreckenberg et al. 2011] showed that 45% of the inhabitants along the middle Rhine region are highly annoyed by rail noise, compared to only 13% by road noise. WHO recommends environmental noise limits between 32 and 42 dB (A) at night to avoid risks for health (Clausen, *et.al*, 2012).

Studies of noise and vibrations caused by traffic operations on tracks, as a part of analysis of rail traffic impact on the environment, are often considered as one and the same discipline because both phenomena have many common physical characteristics. They are both analyzed as a wave phenomenon: noise is defined as sound waves propagating through the air, while vibrations travel through the ground also in the form of waves. They are both result of oscillations (vibrations) of wheels and rails during vehicles rolling on track.

If the speed is up to 120km/h, the vibration is weaker because the vibration is increase for high speed cases. Therefore above 120km/h, the vibration is increase rapidly as the speed increase. In this case the maximum speed of the AA-LRT is 80km, either of the track types has not a problem of vibration.

As stated in Lichtberger (2005) cited in Mickas (2012) the slab track produces significantly higher noise pollution compared to the ballasted track which is recorded +5dB (A) more than ballasted track. The reason why this happen is due to the nature of the slab track structure, the uncoupling of the rail fastening and lack of noise absorption of the bed. Hence the higher noise emissions are solely produced due to the nature of the slab track structure.

From the above noise and noise problem discussion statement “night noise causes health hazards already at individual levels below 45 dB (A), if the difference between the individual level and the background noise is more than 3dB”, which help to understand what the noise emission of slab track +5dB (A) more than ballasted track means. Around the study area, there are residential buildings and schools. Aaccording to (Le, 2012), Gillet (2010) and Esveld (2001), the ballast track provides a high and better noise absorption capacity, and the noise level is 5dB lower than slab track. Minimizing +5dB (A) by constructing ballasted track has high advantages and therefore ballasted track is better choice in this regard.

On the other side, to minimize or resolve the noise and vibration problem, many solutions have been explored and investigated like noise absorbing material, noise protective barriers, acoustically innovative slab tracks are some of the proposals, which deal satisfactorily with the noise reduction but all of them lack either in serviceability lifetime either appear to be very expensive or both.

As it see from the above the slab track has a problem of high noise emission and to avoid this problem it needs different mechanism and solutions which add more costs. Initially the slab track, without addition these solutions, has high construction cost and also adding these solutions means adding more cost on the slab track construction. Whereas ballasted track has a capacity of noise and vibration absorption without incurring additional cost to solve such problems because the ballast has a capacity of damping noise and vibration. In this regard also ballasted track is more advantageous than slab track.

Figure 4-6: AA-LRT Track Line around Nifas Silk

From the dust emission point of view, in places where the release of dust from the ballast bed must be prevented for environmental reasons the slab track is a good solution.

4.2.5 Soil Condition & Settlement

According to different research's proved that the slab track requires stable subsoil basically free of settlements in order to perform adequately. This is why most times slab track is found in tunnels and bridges because in tunnel the subgrade is very stable and free of settlement and on bridge the concrete pedestals rests on rigid structure which not a problem of settlement .

Whereas on ground/at grade section it is a fact that the adjustments to the track geometry after construction are very limited, hence special preparation of the subsoil before construction is essential. Due to this reason the substructure requirements are the following:

- The substructure of slab track must be secured down to a depth of 2.5m below the bearing plate by special earthwork treatments
- In case of embankments the lower bearing layer should not be less than 1.80m thick and it should be made up of the top layer of the filling, for cuttings – of the soil below, or the soil has to be exchanged, if the bearing capacity of the existing soil is insufficient .
- In case of soft cohesive or organic soils the safer solution is to exchange them at a depth not less than 4m from the upper edge of the track

From this, it can understand that the slab track need more cost for the special treatment which make the slab track is costlier. In addition to this, to avoid track settlement the design, the treatment and the construction need more accuracy and precision because if some errors happen the rework of the slab track is required long time and higher cost which makes delay lead to addition cost.

Slab track is difficult to repair in case of poor subgrade failure or inaccuracy realization. It needs to be on very good soil foundation, which must be stable during all the construction life time. Differential settlement and other failures are hard to repair for reasonable price without traffic closure.

On the case of ballasted track, it is not that much need special substructure treatment for the substructure even if it need correct installation work during construction and has a tolerance for settlement. And even if settlement happen, it can possible to make adjustment easily and the cost of readjustment is not much more like slab track because ballasted track has high maintainability at relatively low cost.

4.2.6 Stability and Lateral Resistance

The ability of ballast to allow track realignment is one of its most serious weaknesses. Limited lateral resistance of the ballasted track, resulting to lower speeds in curves .The lateral movement caused by passing trains on curved track is one of the major causes of maintenance costs added to which is the crushing caused by axle weight and damage due to weather and water. Ballast damage leads to tracks pumping as a train passes and, eventually, rail or sleeper damage will occur, to say nothing of the reduced comfort inside the train and the additional wear on rolling stock. Apart from regular repacking or tamping, ballast will have to be cleaned or replaced every few years. In addition to this to make a solution for the lateral movement caused by passing trains on curved track, make the width of the ballasted track wider than the straight one and this makes additional cost on the construction cost as well as on the maintenance cost.

Where as in case of slab track, the lateral movement of passing the train is stable and it is not a problem and this makes the slab track low maintenance cost in comparison with ballasted track and it has high lateral track resistance which allows future speed increases in combination with tilting technology and no problems with churning up of ballast particles at high-speed.

In many cases slab track systems seem to have the capabilities to serve these high speed routes more efficiently than the ballasted tracks mainly due to their higher structural stability, significantly lower need of maintenance, and longer life cycle. The slab track can ensure very good geometrical stability of the track comparing to the ballasted track, on the other side it produces higher noise emissions.

The slab track design can be found mainly in civil structures in high-speed lines and light rail. It gains more and more popularity in railway projects as the railway speed increases. There are many newly updated designs constructed recently around the world and much more to be built in the near future. This fact alone show that in the following years the knowledge about the slab track systems will increase rapidly allowing for much more accurate comparisons with the ballasted systems. Slab tracks may be proved to be the dominant design in the future high-speed railways.

The high speed operation of railway line slab track is more preferable than ballasted track because ballasted track need more regular maintenance due to the high speed that leads to fast ballast degradation and ballast fouling and churned up. Even if slab track is preferable for high speed line, ballasted track also used for high speed operation and now a day also different researches are on progress to improve the capacity of the ballasted track to be used in high speed operation.

Whereas for low speed operation, ballast degradation and churned up is not a series problem as compared to high speed operation. When this study case, AA-LRT, the maximum design speed is 80km/h and average speed is 18km/h which is low speed operation which is fast ballast degradation is not a problem and as compared to high speed it needs lower maintain ace cost. Therefore lateral resistance is not much a problem and ballasted track is not that much affected like high speed line.

4.3 Summary of the Discussion

The overall purpose of this study is to assess the determines factors for the selection of ballasted track versus slab track to recommend the better types of track that affordable for the future expansion of LRT project in Addis Ababa and to be an input for further studies which will be conducted in the near future.

The study discussed in review literature on advantages and disadvantage ballasted track and slab track in terms of construction and maintenance, ease of adjustment and maintainability, weather condition and flood problem, environment/noise, vibration and dust emission/, soil condition and settlement, stability and lateral resistance, and analyzed and discussed them in relation with Addis Ababa city condition and the newly built LRT in the city.

The summary of the discussion is presented in the below table in the form of advantages and disadvantages of the two track forms.

Table 4-2: Advantages and disadvantages of Ballasted track versus Slab track

S.N.	Description	Ballasted Track	Slab Track
1	Cosstruction cost	Low construction cost	High construction cost
2	Maintainanc e cost	High maintenance cost during its service life	Low maintenance cost during its service life
3	Ease of ajustment	-Easily adjustable if defects happen during construction and easily maintainable and sleeper is easily replaced during maintained time	Not easily ajustable and costy to replaceplce if defects happen
4	Wether condition	Affected by heavy rain and snow	Preferable in heavy rain and snow
5	Noise and vibration emmision	Relatively low noise and vibration emission	High noise and vibration emission
6	Dust pollution.	Release of dust from the ballast into the environment thus causing environmental Pollution.	Less environment pollution.
7	Maintenance Input	Frequent maintenance for	No frequent maintenance

		geometry.	for geometry.
8	Elasticity.	High elasticity due to ballast.	Elasticity is achieved through use of rubber pads and other artificial materials.
9	Stability.	Over time, the track tends to float, in both longitudinal and lateral directions, as a result of non-linear, irreversible behaviour of the materials.	No such problem.
10	Lateral resistance.	Limited non compensated lateral acceleration in curves, due to the limited lateral resistance offered by the ballast.	High lateral resistance to the track which allows future increase in speeds in combination with tilting coach technology.
11	Churning up of Ballast.	Ballast can be churned up at high speeds, causing serious damage to rails and wheels.	No such damage to rails and wheels.
12	Permeability.	Reduced permeability due to contamination, grinding-down of the ballast and transfer of fine particles, from the sub grade.	High impermeability.
13	Construction cost of Bridges/Tunnels/ etc.	Ballast is relatively heavy, leading to an increase in the costs of construction bridge and viaducts if they are to carry a continuous ballasted track.	Less cost of construction of bridges and viaducts due to lower dead weight of the ballast-less track.
14	Construction Depth	Depth of Ballasted track is relatively high, and this has direct consequences for tunnel diameters and for access points.	Reduced height.
15	Availability of Material.	Limited availability of suitable ballast material.	No problem of material.

16	Accessibility to road vehicles. .	Ballasted Track is not accessible to road vehicles	Slab the track can be accessible to road vehicles if it is embeded slab track
17	Suitability on the basis of requirement of maintenance input.	Less suitable due to limited availability of traffic block in the present scenario of high traffic growth.	Highly suitable in the present and future scenario due to very less maintenance requirement.

CHAPTER 5

5. Conclusion and Recommendations

5.1 Conclusion

The general purpose of the study is to assess the determinant factors for the selection of the ballasted track versus the slab track with advantages, disadvantages, affordability and appropriateness of each track in the case of Addis Ababa light rail transit.

In Addis Ababa Light Rail Transit (AA-LRT) project, there are sections of track structures such as at grade/ground section, underground section and elevated section. This work is mainly focused on at-grade/ground section because in the underground and elevated section mainly slab track is more preferable.

As many research works proved that in the underground or tunnel section the subgrade is very stable and stiff and can resist the imposed load without additional treatment and the slab can also rest directly to the subgrade. The construction of slab track in the underground section has less thickness so that the construction cost of it in this section is not much more like that of ground section.

On the other hand, on the elevated section, slab track is preferable because as indicated on different researches and proved that if ballasted track is constructed on the elevated section, the thickness of the ballast could be large and it adds heavy load to the elevated or the bridge section. If this load is huge, all the structures has to be designed and constructed to sustain this heavy load of the ballast which means increase the construction cost of the section. As a result, slab thickness is small and need less construction cost than that of ballast.

Therefore, this study focuses on at-grade/ ground section to assess and evaluate the determinant factors for the selection of the ballasted track and slab track and give possible recommendation on more affordable form of track for future expansion of line in the city of Addis Ababa.

On the study point of view, as it can see from the analysis and discussion part, in many respects like construction cost, ease of adjustment and maintainability, weather condition of the city, soil condition and settlement, speed of AA-LRT, ballasted track is preferable than slab track. Because, if we can see the construction cost of slab track is more than double the construction cost of ballasted track which means it can build more than double km ballasted track instead of 1km slab track and this result forced us to analyze and compare the city population demand of transportation and supplying the transportation facility to satisfy the demand. It should be also noted that the need of high precision and accuracy for slab track construction in relation with less maintainability together with more time need of slab track make it less preferable than ballast track. Whereas ballasted track is easily maintainable relatively with low cost if defects happen. In addition, low speed of the current train operation resulted in less ballast degradation so that it needs low maintenance cost than high speed train operation. .

Finally, from over all analysis result, discussion and conclusion, the study selected ballasted track is more preferable and affordable than slab tracks for AA-LRT future expansion project.

5.2 Recommendations

This study will shade some light to fill the research gap of the railway system in the city it can be an input for further studies which will be conducted in the near future.

But now a day conducting the research on both the ballasted as well as slab track system is being done. The slab track is a modern type of track type and different researches are ongoing to increase its usefulness and to minimize its draw back like noise emission and other. On the other side on the ballasted track also different researches are on ongoing to increase its performance and to use for the high speed line.

Therefore, in our country, Ethiopia, also need undertaking different researches regarding these two track types in relation with the county context for both the LRT case and the national railway as well. In addition, study needed also to get the exact unit rate for each item and secure drainage system to protect the track from flood.

For this study, from over all analysis result, discussion and conclusion, ballasted track is more preferable than slab tracks for AA-LRT future expansion project due to low construction cost in relation with addressing transportation facility to satisfy the demand of the population, and easily maintainability.

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Appendixes:

Appendix A: Terminology

Ballast cleaning is the maintenance action done to eliminate trapped water inside the ballast in order to restore the track quality and stiffness.

Ballast Degradation can cause significant changes in ballast grain size distributions and particle shape properties when compared to the corresponding properties of the original new ballast material.

Ballast is the top layer of the substructure which made of angular, crushed, hard stones and rocks and it supports the rail and sleepers to guarantee the capacity of spreading and transmitting the loads that comes from the upper structure to the bottom supporting structure.

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

Ballasted track is a track which the ballast is the foundation of railway track and provides just below the sleepers.

Construction cost means expense incurred by a contractor for labor, material, equipment, financing, services, utilities, etc., plus overheads and contractor's profit.

Elevated railway is a railway built on supports over city streets.

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

Fastening system is the structural connection of the three components: rail, rail pads and sleepers and its purpose is to provide elasticity transmitted the imposed load that comes from rail and rail pads to sleeper.

Gauge is the width between the inner faces of the rails

Grinding is the maintenance action done on the rail to control rolling contact fatigue defects**.**

Infrastructure cost is large portion of the infrastructure expenses is associated to the construction, renewal and maintenance of infrastructure assets with an estimated lifetime of more than 1 year.

Infrastructure is refers to the important structures, arrangements, and facilities serving a country, city, or area, including the services and facilities necessary for its economy to function.

Investment costs are costs aimed at new structure or improving the quality or functionality of existing structure over and above its original functionality.

Life Cycle Cost si the sum of all costs of a specified track throughout its economic life, from first installation through removal or replacement and a process of economic analysis to assess the total cost of acquisition, ownership and disposal of a product .

Lubrication is done on the rail to control rail wear.

Maintainance is activity aiming to maintain something in good working order, prevent operational disturbance and/or uphold a given technical standard.

Maintenance costs are costs aimed at structure actually reaching its designed useful lifetime.

Noise is sound that is unwelcome, because of its volume or structure, and can be harmful.

Rail noise is sound emissions arising from the operation of trains and trams.

Rail pads are one of the most important elements of railway track, and it is located in between the sleeper and the rail for the purpose to reduce dynamic wheel/rail interaction force that protect the entire structure from unbalance stresses.

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

Rail replacement is done when rail breaks occur on the track.

Rails are made of steel which constructed longitudinally for the first element in contact with the vehicle wheels and its main function is for the transmission of the imposed loads that come from the wheel.

Renewal costs are costs aimed at substituting existing structure that has reached the end of its designated useful life.

Slab track is a modern form of track construction which has been used successfully throughout the world for high speed lines, heavy rail, light rail and tram systems.

Sleeper is wooden or pre-stressed / reinforced concrete and has a function of transferring the vertical, lateral and longitudinal rail seat loads to the ballast, sub-ballast and subgrade layers.

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

Sub ballast is the stratum located between the ballast layer and the subgrade layer to separate these two layers and to distribute and decrease stress from ballast to subgrade and to avoid interpenetration between ballast and subgrade.

Tamping is the maintenance action done on the track to correct its alignment.

Track inspection is done to detect flaws on the track that can lead to failures.
Track is the structure consisting of the rails, fasteners, sleepers and ballast (or slab track), plus the underlying sub-grade over which cars, locomotives and trains are moved.

Appendix B: Abbreviation

GTP	Growth and Transformation Plan
NRNE	National Railway Network of Ethiopia
HSL	High Speed Line
E-W	East Waste
N-S	North West
NRNE	National Railway Network of Ethiopia
AA-LRT	Addis Ababa Light Rail Transit
LCC	Life Cycle Cost
RAMS	Reliability, Availability, Maintainability and Safety
UIC	International Union of Railway
USD	US Dollar or United States, Dollar
AREMA	American Railway Engineering Maintenance of Way Association
LRT	Light Rail Transit
CC	Construction Costs
MC	Maintenance Costs
RC	Renewal Costs
DC	Delay Costs
OC	Organizational Costs

Appendix C: Notation

$\mathbf{C_b}$ cost of ballast in SEK/km

$\mathbf{C_{eb}}$ equipment cost for ballast cleaning in SEK/h

$\mathbf{C_{ebr}}$ equipment cost for ballast renewal in SEK/h

$\mathbf{C_{efr}}$ equipment cost for fastener renewal in SEK/h

$\mathbf{C_{eg}}$ equipment cost for grinding in SEK/h

C_{er} equipment cost to repair rail breaks in SEK/h

C_{err} equipment cost for rail renewal in SEK/h

C_{esr} equipment cost for sleeper renewal in SEK/h

C_{et} equipment cost for track inspection in SEK/h

C_{eta} equipment cost for tamping in SEK/h

C_f cost of fasteners in SEK/km

C_L average labour cost in Swedish Kroner (SEK)/h

C_{lu} cost of lubrication material for each lubricator per year in SEK

C_r cost of rail in SEK/km

C_s cost of sleeper in SEK/km

f_{rbi} failure rate of rail (breaks) in the ith curve

K class of curve radii

L total length of track section in km

L_i length of ith curve in km

L_r average length of rail replacement due to rail break

m_{bi} interval for ballast cleaning for ith curve in MGT

m_{bri} interval for ballast renewal for ith curve in MGT

m_{fri} interval for fastener renewal for ith curve in MGT

m_{gi} interval for grinding for ith curve in MGT

m_{rbi} mean time to rail breaks in ith curve in MGT

m_{rri} interval for rail renewal for ith curve in MGT

m_{sri} interval for sleeper renewal for ith curve in MGT

m_t interval for track inspection in MGT

m_{tai} interval for tamping for ith curve in MG

M gross tonnage per year in MGT

M life period of track in MGT

n_{gi} number of grinding passes on ith curve

n_{li} number of wayside lubricators in ith curve

N life period of track (equivalent toM) in years

r discount rate

T_{bi} mean time to clean ballast for ith curve in h/km

T_{bri} mean time for ballast renewal for ith curve in h/km

T_{fri} mean time for fastener renewal for ith curve in h/km

T_{gi} mean time to grind for ith curve in h/km

T_{lu} mean time to refill lubrication material for each lubricator in hour

T_{rbi} mean TTR rail break in ith curve in hour

T_{rri} mean time for rail renewal for ith curve in h/km

T_{sri} mean time for sleeper renewal for ith curve in h/km

T_t mean time to inspect track in h/km

T_{tai} mean time to tamp for ith curve in h/km

Appendix D: Cost Calculation

D.1. Track Construction cost

Table D-5-1: Amount and Percentage of Executed Work on AA-LRT project (CREC, 2014)

AMOUNT and PERCENTAGE OF EXECUTED WORK

Project:	Addis Ababa E-W & N-S (Phase I) Light Rail Transit Proj	IPC No.: CREC/LRT-0028
Employer:	Ethiopian Railways Corporation (ERC)	Month: May, 2014
Consultant:	Swedish National Road Consulting AB (SWEROAD)	Period: May 1-May 31, 2014
Contractor:	China Railway Group Limited (CREC)	

Item No.	Work Items Description	Unit	Design Quantity	Unit Price (USD)	Contract Amount (in USD)	Executed Quantity			Percentage of Executed Quantity in Work			Amount (USD) of work		
						Previous Months	This Month	To date	Previous Months	This Month	Total to Date	Previous Months	This Month	Total to Date
1	Temporay facilities construction				12,591,943.98									
1.1	Contractor's camp	set	1.00	4,056,072.84	4,056,072.84	100%		100%	4,056,072.84		4,056,072.84			
1.2	Batching plant	set	1.00	1,449,487.55	1,449,487.55	100%		100%	1,449,487.55		1,449,487.55			
1.3	Prefabricated beam plant	set	1.00	1,288,433.38	1,288,433.38	100%		100%	1,288,433.38		1,288,433.38			
1.4	Quarry plant	set	1.00	2,415,812.59	2,415,812.59	100%		100%	2,415,812.59		2,415,812.59			
1.5	Asphalt-aggregate Mixing Plant	set	1.00	644,216.69	644,216.69	100%		100%	644,216.69		644,216.69			
1.6	Temporay access road	set	1.00	161,054.17	161,054.17	100%		100%	161,054.17		161,054.17			
1.7	Base for Prefabricating and assembling Track panels	set	1.00	2,576,866.76	2,576,866.76	100%		100%	2,576,866.76		2,576,866.76			
Sub total									12,591,943.98		12,591,943.98	100.0%		100.0%
2	Station				30,339,884.51									
2.1	Design				3,669,313.39	100%		100%	3,669,313.39		3,669,313.39			
2.2	Underground Station													
2.2.1	Building envelope													
2.2.1.1	C20 shotcrete	m^3	283.80	736.98	209,154.92	28380%		283.80	209,154.92		209,154.92			
2.2.1.2	C30 Reinforced Concrete	m^3	1,618.96	543.15	879,338.12	1,346.58		1,346.58	731,394.93	0.00	731,394.93			
2.2.2	Top beam													
2.2.2.1	Top beam concrete	m^3	194.40	746.24	145,069.06	194.40		194.40	145,069.06		145,069.06			
2.2.3	Open cutting earthwork and stonework													
2.2.3.1	Excavation	m^3	46,250.85	5.09	235,416.83	37,041.48		37,041.48	188,541.13		188,541.13			
2.2.3.2	Backfilling	m^3	32,522.70	4.43	144,075.58									
2.2.4	Main structure													
2.2.4.1	Base slab concrete	m^3	4,414.64	506.89	2,237,736.87	4,234.63	152.43	4,387.06	2,146,491.60	77,265.24	2,223,756.84			
2.2.5	Platform slab													
2.2.5.1	Concrete	m^3	299.29	365.28	109,324.65									
2.2.6	Water proofing works													
2.2.6.1	Water proofing works	m^2	4,317.89	33.96	146,635.54	3,454.31		3,454.31	117,308.37		117,308.37			
2.3	Ground Station													
2.3.1	Earth work													
2.3.1.1	Excavation	m^3	44,280.00	4.91	217,414.80	434.00		434.00	2,130.94		2,130.94			
2.3.1.2	Backfilling	m^3	29,700.00	3.14	93,258.00									
2.3.1.3	Breakstone backfilling	m^3	7,371.00	19.50	143,734.50									
2.3.2	Platform	m^3	7,236.00	520	3,762,720.00	150.30	294.31	444.61	78,156.00	153,041.20	231,197.20			
2.3.3	Rainshed	Set	27	203,656.14	5,498,715.78									
2.4	Elevated Station													
2.4.1	Concrete of Platform slab	m^3	12,420.90	622.30	7,729,526.07									
2.4.2	Rainshed	Set	9.00	203,656.16	1,832,905.44									
2.5	Overpass	Set	9.00	365,060.55	3,285,544.95									

Item No.	Work Items Description	Unit	Design Quantity	Unit Price (USD)	Contract Amount (in USD)	Executed Quantity			Percentage of Executed Quantity in Work			Amount (USD) of work		
						Previous Months	This Month	To date	Previous Months	This Month	Total to Date	Previous Months	This Month	Total to Date
3	**Section**				**186,873,655.01**									
3.1	**Design**				**7,338,626.79**	100%		100%	7,338,626.79		7,338,626.79			
3.2	**Underground Section (Tunnel)**													
3.2.1	Excavation and protection													
3.2.1.1	Excavation	m^3	124,792.52	6.12	**763,730.22**	124,563.0		124,563.00	762,325.56		762,325.56			
3.2.1.2	Backfilling	m^3	78,395.22	4.43	**347,290.82**									
3.2.1.3	C20 shotcrete	m^3	1,315.87	736.98	**969,769.87**	1,315.87		1,315.87	969,769.87		969,769.87			
3.2.2	Main structure													
3.3.2.1	Concrete Structure	m^3	12,501.51	506.89	**6,336,890.40**	12,501.51		12,501.51	6,336,900.54	-10.14	6,336,890.40			
3.3.2.2	Water proofing works	m^2	13,531.96	34.00	**460,086.64**	12,492.22		12,492.22	424,735.48		424,735.48			
3.2.3	Road Restoration													
3.2.3.1	Road Restoration	m	340.00	441.20	**150,008.00**									
3.3	**Elevated Section**													
3.3.1	Foundation work													
3.3.1.1	Earth excavation	m^3	67,107.24	9.83	**659,664.17**	67,107.24		67,107.24	659,664.16	0.01	659,664.17			
3.3.1.2	Backfilling	m^3	45,865.53	4.38	**200,891.02**	45,865.53		45,865.53	200,891.02		200,891.02			
3.3.2	Pile Foundation and cap													
3.3.2.1	C30 reinforced concrete pile	m^3	19,861.60	861.18	**17,104,412.69**	19,861.60		19,861.60	17,104,412.69		17,104,412.69			
3.3.2.2	C30 Concrete pile cap	m^3	14,671.80	464.41	**6,813,730.64**	14,671.8		14,671.80	6,813,721.36	9.28	6,813,730.64			
3.3.3	Substructure													
3.3.3.1	Abutment													
3.3.3.1.1	C25 concrete of abutment	m^3	2,823.06	385.81	**1,089,164.78**	2823.06		2,823.06	1,089,164.78		1,089,164.78			
3.3.3.2	Piers													
3.3.3.2.1	C30 concrete	m^3	9,910.78	495.89	**4,914,656.69**	8,131.76	1,431.95	9,563.71	4,032,458.48	710,089.69	4,742,548.17			
3.3.3.2.2	C40 concrete of bent cap	m^3	3,447.14	921.26	**3,175,712.20**	3,447.14		3,447.14	3,175,712.21	-0.01	3,175,712.20			
3.3.3.2.3	C35 concrete of abutment cap	m^3	2,701.30	1,002.15	**2,707,107.80**	675.28	2.00	677.28	676,731.86	2,004.30	678,736.16			
3.3.4	Superstructure													
3.3.4.1	Type 20m of simply supported beam	Pcs	102.00	77,900.87	**7,945,888.74**	68.00	6.00	74.00	5,297,259.16	467,405.22	5,764,664.38			
3.3.4.2	Type 23m of simply supported beam	Pcs	4.00	103,928.07	**415,712.28**		4.00	4.00		415,712.28	415,712.28			
3.3.4.3	Type 25m of simply supported beam	Pcs	348.00	112,965.29	**39,311,920.92**	134.00	38.00	172.00	15,137,348.86	4,292,681.02	19,430,029.88			
3.3.4.4	Type 30m of simply supported beam	Pcs	1.00	330,135.64	**330,135.64**	1.00		1.00	330,132.92		330,132.92			
3.3.4.5	Tyoe 4*30m of Continuous beam	Team	2.00	4,115,968.25	**8,231,936.50**	1.00		1.00	4,115,968.25		4,115,968.25			
3.3.4.6	Type 29.36+26+26.75m of continuous beam	Team	1.00	2,743,963.57	**2,743,963.57**	1.00		1.00	2,743,963.57		2,743,963.57			
3.3.4.7	Type 26.75+26+26.75m of continuous beam	Team	4.00	2,813,064.00	**11,252,256.00**	2.00	2.00	4.00	5,626,128.00	5,626,128.00	11,252,256.00			
3.3.4.8	Type3*28.4m of continuous beam	Team	1.00	2,738,688.02	**2,738,688.02**									
3.3.5	Bridge deck													
3.3.5.1	Water proofing	m^2	12,927.80	29.14	**376,716.09**									
3.3.5.2	Type DTSF-60 expansion joint	Pcs	293.00	5,019.84	**1,470,813.12**									
3.3.5.3	Deck handrail	m	12,616.00	241.56	**3,047,520.96**									
3.3.5.4	Cable channel	m	7,777.40	140.00	**1,088,836.00**									
3.4	**Ground section**													
3.4.1	Earth work													
3.4.1.1	Excavation	m^3	519,166.00	4.91	**2,549,105.06**	364,766	11,850.00	376,616.00	1,790,999.35	58,183.50	1,849,182.85			
3.4.1.2	Filling	m^3	315,770.00	3.14	**991,517.80**	306,755.75		306,755.75	963,213.06		963,213.06			
3.4.2	Retaining wall (concrete)													
3.4.2.2	C30 reinforced concrete	m^3	30,989.87	516.17	**15,996,041.20**	22,294.63	1,231.22	23,525.85	11,507,819.17	635,518.83	12,143,338.00			
3.4.3	Subgrade consolidation and protection													
3.4.3.1	Filling for subgrade	m^3	23,500.00	5.64	**132,540.00**	23,500.00		23,500.00	132,540.00		132,540.00			
3.4.3.2	Waterproof bituminous concrete	m^3	8,115.78	591.42	**4,799,834.61**	2,715.16	954.00	3,669.16	1,605,799.93	564,214.68	2,170,014.61			
3.4.3.3	C25 concrete for side slope protection	m^3	16,896.00	335.20	**5,663,539.20**	4,740.06	584.50	5,324.56	1,588,868.11	195,924.40	1,784,792.51			
3.4.4	Ground drainage system													
3.4.4.1	C25 reinforced concrete ditch of Ground drainage system	m^3	22,193.36	358.95	**7,966,306.57**	16,239.03	1,451.50	17,690.53	5,828,999.84	521,015.93	6,350,015.77			
3.4.4.2	Cable tray	km	44.00	140,000.00	**6,160,000.00**	12.71		12.71	1,779,400.00		1,779,400.00			
3.4.4.3	Handrail	km	44.00	241,560.00	**10,628,640.00**									
	Sub total								**108,033,555.02**	**13,488,876.98**	**121,522,432.00**	**57.8%**	**7.2%**	**65.0%**
4	**Track work**				**39,125,294.72**									
4.1	**Design**				**4,892,417.86**	100%		100%	4,892,417.86		4,892,417.86			
4.2	**Track laying**													
4.2.1	Track laying on ballastless track of Elevated Section	km	14.40	495,683.09	**7,137,836.50**	1.39		1.390	692,964.96		692,964.96			
4.2.2	Track laying on Ground Section	km	46.00	384,786.23	**17,700,166.58**	21.17		21.17	8,145,924.50		8,145,924.50			
4.2.3	Track laying on Underground and transition Section	km	1.70	511,753.60	**869,981.12**									
4.2.4	Track laying in Depot	km	4.80	170,079.88	**816,383.42**									
4.3	**Turnout laying**	Team	76.00	23,464.49	**1,783,301.24**									
4.4	**Track-bed laying**													
4.4.1	Ballastless track	m^3	7,200.00	516.26	**3,717,072.00**	764.50		764.50	394,680.77		394,680.77			
4.4.2	Ballast track	m^3	104,800.00	21.07	**2,208,136.00**	8385.50		8,385.50	176,682.49		176,682.49			

Table D-5-2: Calculate Construction cost of Ballasted Track and Slab Track obtained from AA-LRT project and Check According to the Information obtained from Restructures

1. Data from AA-LRT Project

Item No.	Work Items Description	Unit	Quantity	Unit Price (USD)	
1.1.	Track work				
1.1.1.	Track laying on Ground Section	km	1	384,786.23	
1.1.2.	Track laying on Underground and transition Section	km	1	511,753.60	
1.2.	**Track-bed laying**				
1.2.1.	Ballast less track	m^3	1	516.26	
1.2.2.	Ballast track	m^3	1	21.07	

➢ ***Calculating each track type for 1km length of track using AA-LRT project***

	Track Type	**width**	**depth**	Length	W*d*L	Rate in USD	Total amount
1	Ballasted track	7m	0.45m	1000m	$3150m^3$	21.07	66,370.5
				1km		384,786.23	384,786.23
Estimated total construction cost of ballasted track per km (1000m)							451,156.73
2	Slab (ballast less) track	6.4m	o.15m	1000m	$960m^3$	516.26	495.609.6
				1km		511,753.60	511,753.60
Estimated total construction cost of slab track track per km (1000m)							1,007,363.20

2. Information from literature to estimate and check the construction cost of the two tracks

➢ Construction cost of Slab track = construction cost of ballasted track + (20% - 40% of construction cost of ballasted track)

	Ballasted track (X)	20%	X*20%	X+(X*20%)	Sum for 20%
Slab track (Y')	451,156.73	0.2	90231.346	541,388.08	**541,388.08**
		40%	X*40%	X+(X*40%)	Sum for 40%
		0.4	180,462.69	631,619.42	**631,619.42**

➢ Slab track is profitable only if the construction process will not cost 30% more than the construction cost for the ballasted track

Slab track (Y'')	451,156.73	30%	X*30%	X+(X*30%)	Sum for 20%
		0.3	135347.019	586,503.75	**586,503.75**

D.2. Track Maintenance and Renewal

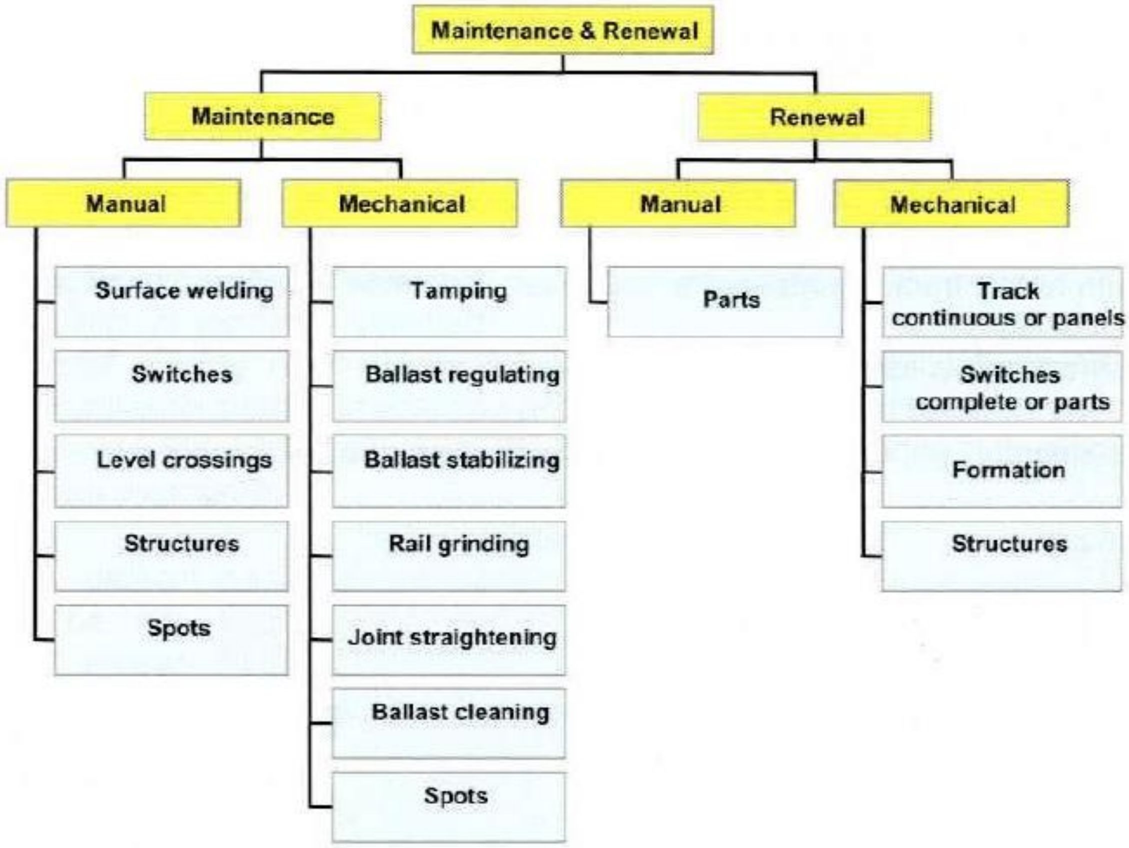

Figure D-1: Schematic survey of maintenance and renewal process, (Esveld, 2001) cited in Ramos, 2008

Table D-5-3: Track maintenance activities (Patra, 2007) cited in Ramos, 2008

Maintenance strategy	Maintenance activity	Maintenance trigger
Preventive maintenance	rail grinding	Time
	Tamping	Condition
	rail lubrication	time
	ballast cleaning	Condition
	track inspection	Time
Renewal	rail renewal	Condition
	ballast renewal	Condition
	sleeper renewal	Condition
	fasteners renewal	Condition
Corrective maintenance	rail replacement	Failure

Table D-5-4: construction and annual cost (EUR/m) for four different slab track and on ballasted track (Esveld) cited in Michas, 2012

Present cost estimate:	Construction	Annual Costs
• Slab track, ERS, NI (Not integrated)	EUR 1,200	EUR 90
• *Slab track, ERS, NI, optimized*	*EUR 860*	*EUR 70*
• Slab track, ERS, INT (Integrated)	EUR 910	EUR 80
• Rheda	EUR 1,270	EUR 100
• Ballasted track	EUR 1,000	EUR 110

Table D-5-5: Calculated Annual Maintenance cost of Ballasted Track and Slab Track for AA-LRT

1. **The data obtained from literature for the two track types**

1.1. Slab Track

	Construction cost	Annual cost	Ratio (Annual/Construction	% of annual cost
1.	1200	90	0.075	
2.	860	70	0.081	
3.	910	80	0.087	
4.	1270	100	0.078	
Sum of the ratio			0.323	
Average % ratio for the annual maintenance cost [(Sum of Ratio/4)*100]				8 %

1.2.Ballasted track

1. Ballasted track	1000	110	0.11	
Annual maintenance cost [(Ratio)*100]				11%

2. **Annual maintenance cost of AA- LRT project using these rate**

	track type	construction cost per km	annual rate from literatures	annual maintenance cost (W')	annual maintenance cost (Z')
1	ballasted (X)	451,156.73	0.11	49627.24	
2.1	slab (Y) (not profitable	1,007,363.20	0.08		80,589.056
2.2	Slab(Y'') (in profit margin)	586,503.75	0.08		46,920.30

Calculating Maintenance cost of slab track

From the literature

- Maintenance cost of slab track = Maintenance cost of ballasted track – (20% - 30% of maintenance cost of ballasted track) (Michas, 2012)

			W'*0.2	W'*.3	Slab main. Cost
		0.2	9925.44806		
Annual maintenance cost of slab track = Annual maintenance cost of ballasted track – 20% of annual maintenance cost of Ballasted track (W' – 0.2*W'					39,701.79
		0.3		14888.17	
Annual maintenance cost of slab track = Annual maintenance cost of ballasted track – 30% of annual maintenance cost of Ballasted track (W' – 0.3*W'					34,739.07

Appendix E: Noise emission

Table E-1: Rail Noise – Sources and Prevention Measures Key Findings (Clausen; *et.al,* 2012)

• **Main source** of railway noise is **rolling noise** coming from rail freight wagons.
• **Of minor importance** is engine noise (at lower speeds) and aerodynamic noise (high speed trains).
• Locally also squeal noise can be important.
• Rolling stock which is introduced from the year 2000 on is about **10 dB (A) less noisy** then rolling stock from the 1960s and 1970s.
• Against each source of noise an **enormous number of measures** have been developed in the last years.
• **Rolling noise and wheel noise** can be reduced by **composite brake blocks** (freight wagons), **resilient wheels** or **wheel dampers.**
• **Rail noise** can be reduced by rail dampers, resilient track pads and combinations with noise barriers of different heights.
• Track side or vehicle side **lubrication systems can avoid squeal noise** and are well introduced in tram way systems.
• **The most efficient measure to achieve network wide noise reduction is the retrofitting of freight cars with composite brake blocks.**

Appendix F: Different Photograph taken from the Study Area (AA-LRT Project)

1. **From East West Line (EW)**

Figure F-1: AA-LRT Track Picture around Ayat

Figure F-2: AA-LRT Level Crossing Picture around CMC

Figure F-3: AA-LRT Track Pictures around at Gurdshota

Figure F-4: AA-LRT Track Pictures around Megenagna

Figure F-5: AA-LRT Elevated Track Pictures around at Estephanos

Figure F-6: AA-LRT Track Pictures around Torhayloch

2. From North West Line (NS)

Figure F-7: AA-LRT Underground Station at Minilik II Square

Figure F-8: AA-LRT Transition Section Pictures at Atikilt Tera

Figure F-9: AA-LRT Track Piture at Gojam Berenda

Figure F-10: AA-LRT Track Pictures at Sebategna

Figure F-11: AA-LRT Track Pictures around at Mesholekia

Figure F-12: AA-LRT Track Pictures around at Lanchia

Figure F-13: AA-LRT Track Pictures around Nifas Silk

Figure F-14: AA-LRT Track Pictures around at Adey Ababa

Figure F-15: AA-LRT Track Pictures around at Kalit