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A Thesis for Master's Program

Investigation on the Performance of Train Timetable for the Case of Addis Ababa Light Rail Transit

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Abstract

Currently, the AA-LRT system operation is in its initial phase. Hence, most operations are working in their lower level such as the speed, headway time and line capacity. But still, this is reasonable in order to familiarize with the system for gaining experience in the process and to grow up step by step to its higher performance level.

One of the most decisive elements to have a good performance in a railway operation is the train timetable. With a good train timetable: the train can go faster, more frequently, more safely with efficient service to the passengers and with optimal use of the available resources. So that, investigating and studying of the current train timetable specifically for the newly operated AA-LRT timetable has a fundamental importance to design a new train timetable with better quality.

In this thesis, the main parameters which have a big influence on the design of train timetable are picked out. To mention some of them: the headway time, dwell time, trip time, speed, braking distance, synchronization of trains and other available resources. So that, these parameters are discussed in detail and their values are calculated. Based on these calculated results, comparisons between the current timetable and the obtained parameters are done. Consequently, from the comparison results the optimal values are to be taken to design the new timetable.

To check the validation of those calculated values, simulating software called Arena is used. In the Arena software parameters like headway, dwell time, speed, synchronization time, the number of trains and safety block are used as inputs. When those parameters are simulated, it runs correctly and gives valid result including visualizing animation to show the real traffic movement. So that, from the output of the simulation a decision is made for each parameter to compare with the existing timetable and to give an attention to their effect on the design of the timetable. Finally based on the calculated values and simulating results a better result for the main parameters of the timetable is found such as for the current speed a headway time of 7.5 minutes should be used and for the current available number of trains a speed of 30km/h with headway of 5.55 minutes are the optimal values.

Keywords: Train Timetable, Headway, Dwell Time, Performance, Arena Software, Animation

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Declaration

I, **Tekle Haylekiros Assefa**, hereby declare that this work entitled "**Investigation on the Performance of Train Timetable for the Case of Addis Ababa Light Rail Transit**" is the original work of mine and has not been presented for a degree in this or any other university, and all source of materials used for the thesis have been fully acknowledged.

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This Thesis has been submitted for examination with my approval as an advisor

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List of Abbreviations

AA-LRT	Addis Ababa Light Rail Transit
CASCO	Chinese-American Signal Company
DCC	Dispatcher Control Center
DONS	Design of Network Schedules
ERC	Ethiopian Railways Corporation
ERTMS	European Rail Traffic Management System
EW	East-West line
FIFO	First In First Out
NRNE	National Railway Network of Ethiopia
NS	North-South line
OCC	Operation Control Centre
OptQuest	Optimization Quest
PESP	Periodic Event Scheduling Problem
SIMAN	Simulation Model Analysis
TOC	Train Operating Companies
WIP	Work In Process

CHAPTER ONE

Introduction

1.1 Background

Transport plays an important role in supporting economic, environmental and social objectives. Among these railway transport is one best example. The development in science and technology manifests itself in railways in its present form, beginning from steam engines in early 19th century, through diesel engines, electrified railways, and high-speed trains, benefitting and significantly influencing the development of every country. Since the world's first railway journey, the railway systems have evolved hugely. Speed, comfort, costs, and high quality of service demand led engineers to continuously invent new machines and devices to develop the rail transport. Going with this development, more and more requirements appeared. Nowadays, one wants the train to go faster, more frequently, more safely, while being cheaper and environmentally friendly.

The railway transport plays a vital role in a development of a nation not only by giving a modern and efficient service but also it is environmentally friendly and modernizes the image of a city and a country as a whole.

1.2 Motivation

In railway transport, the railway timetabling is one of the main factors to have a good traffic management system. Generally speaking, a good train timetable can enable to use resources optimally (like time, human power, electric power consumption, the rail infrastructure, the trains, etc.), and it minimizes possible traffic accidents, it increases the attractiveness of railways, minimizes possible delay, announce train services to potential customers and the customers at large can be satisfied.

Having flexible and reliable train scheduling and routing is a central part of the planning process to have good traffic management, comfort, costs, and to maintain the quality of service demand for a railway company. Its design is concerned with the problem of selecting a set of lines and determining the headway, the arrival time, the traveling time and the departure time for a set of trains at a sequence of stations [2].

Hence, due to those main requirements, it motivates to deal with the train timetable. Another motivation is that the AA-LRT system starts service in September 2015. That means it has a new timetable for giving its predefined services. Since the operation is in its initial stage most parameters like speed, headway time, line capacity, traveling time, etc. are used in their lower level. In general, to design a train timetable, basically, it is modified from previous year's train timetable. Hence to modify that timetable, it critically requires studying and analyzing the performance of current available timetable to get a new and enhanced one. Specifically, for the case of AA-LRT since it is in its initial stages, this time, is the exact time to make investigations on the performance of the current timetable which helps to design a new well-performed timetable. Hence investigating the performance of the current timetable will have a fundamental importance in designing a better timetable.

1.2.1 What is Train Timetable

The word 'timetable' is a chart showing the departure and arrival times of trains, buses, or aircraft. Or in other words, it's to mean schedule (something to take place at a particular time) [5]. Additionally, a timetable, (North American English schedule) is a document setting out information on service times, to assist passengers with planning a trip.

Railway schedules are necessary for the coordination of resources in different planning and production stages in order to match transport demand and capacity and to inform stakeholders and customers. Timetables must assure that the expected transport demand can be realized according to the requirements of passengers, shippers, train operating companies, infrastructure manager, and public authorities effectively and efficiently. Effectively means a high quantity and quality of available infrastructure, rolling stock, personnel, transport and traffic services; while efficiently requires a maximum output with the least possible input [6].

1.2.2 Ethiopian Railway System

The Ethiopian railway system consists national (which includes passenger and freight trains) as well as the AA-LRT system. Furthermore all are electrified systems. The AA-LRT system already starts its service since September 2015 and the Addis Ababa-Djibouti port line is in its final stage and it is expected to start its service in late 2016 according to ERC officials. Many other lines of the NRNE are under construction in phase I (see the solid lines in the map below) and some others are in plan to be constructed in phase II (again see the dotted lines in the map below). Further, the small circles on the map indicate the residents of each city (for detail see figure 1 below).

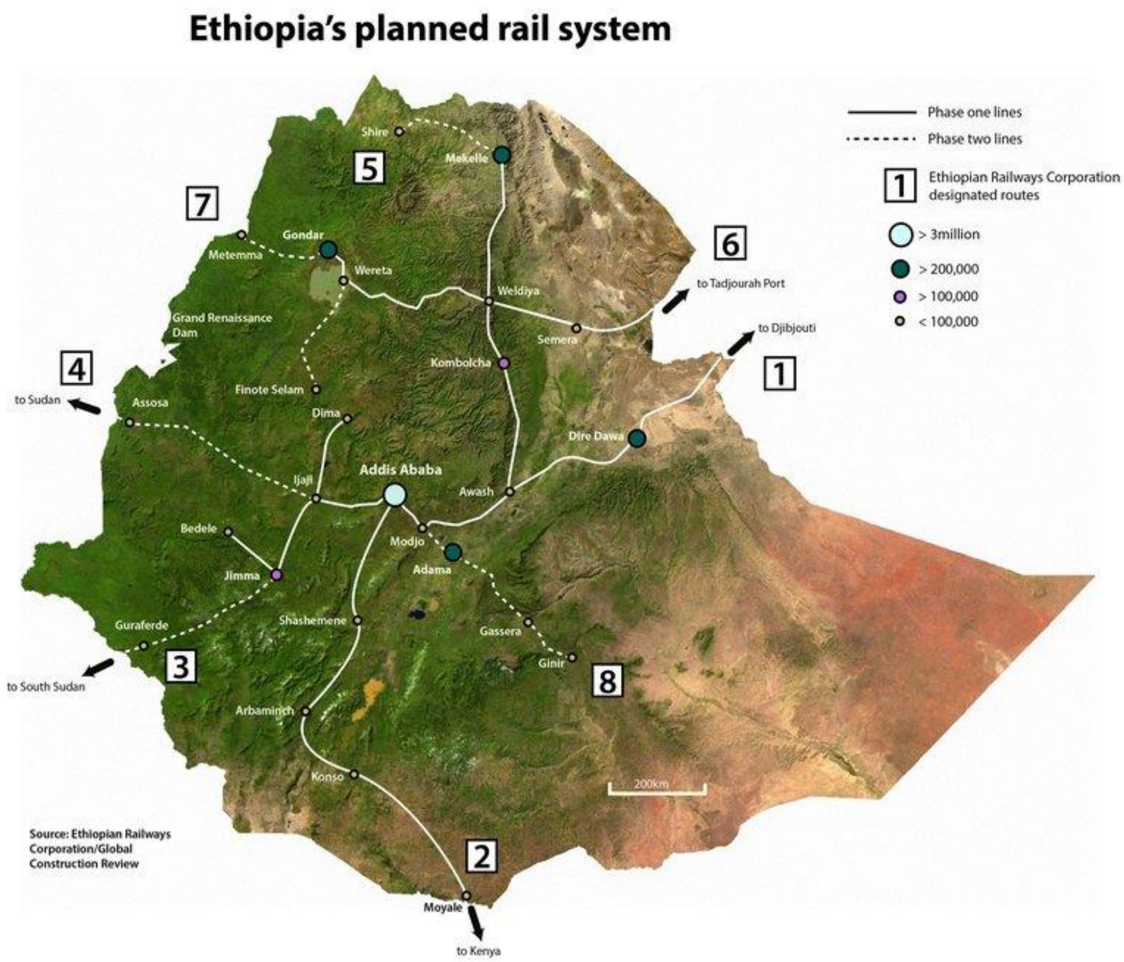

Figure 1: Map of NRNE showing lines of phase-I and phase-II

Some general properties of NRNE includes

- About 5060km of national railway line after completing both phases [7].
- Standard Gauge (1435 mm) and high capacity (25 ton/axle)
- Electric traction for all lines
- Speed of 120-160km/h for passenger and 80 -120 km/h for freight trains in the NRNE
- Concrete sleeper (160cm x 20.5cm x 22cm)

1.3 Problem Statement

Railway timetable is one of the most important parts of the many which make up a railway system. Efficient use of resources, train movement safety, control, and management of trains as well as customer satisfaction depend on it. Over the years, many railway scheduling and train control systems have been evolved in different countries so that today a highly technical and complex industry has been developed.

In this thesis, the performance of the current AA-LRT is investigated. The main necessity to make the investigation is, by analyzing the current timetable it helps as a cornerstone to design a better performed and enhanced timetable for the next times. The analysis is to be done in terms of many parameters such as time requirements (headway, dwell, travel time, speed etc.) as well as on reliability, flexibility, safety, line capacity and satisfaction of customers. Then based on the investigation result a new well-performed timetable is designed. Consequently, the following research questions are addressed.

- How does the current timetable works?
- Does the AA-LRT railway traffic system effectively work according to its timetable?
- What is the impact of the timetable on the performance of railway traffic?
- How can we use the timetable efficiently?
- How can we optimize resources related to the timetable?
- What are the main parameters of a train timetable?
- What are the optimal values of the timetable parameters for the available resources?
- How can we give efficient service for the customers?
- What is the optimal speed for the current available trains?
- How can we minimize possible accidents occurring due to scheduling mismatch?

1.4 Objective

1.4.1 General Objective

Generally, the objective of this thesis is to analyze the impact of train timetable on the traffic management system and to design the main parameters of the train timetable for safe, efficient, competitive and sustainable timetable for AA-LRT of phase-I.

1.4.2 Specific Objectives

Specifically, the aim of this thesis is to:

- Perform an in-depth investigation on the limitation of AA-LRT timetable
- Point out optimal possible values based on the available resources
- Extensively study the available railway timetable design technologies
- To determine schedule performance
- Illustrating the delay risks associated with train schedules
- Comparing the safety requirements with the results and suggesting correction

1.5 Scope

The scope of this thesis is to analyze the existing train timetable of the Addis Ababa's Light Rail Transit of the first phase (phase I). Then, based on the analyzing result, some possible suggestions to modify the existing timetable for the purpose of increasing the performance of the train traffic system are given. Additionally, it will be helpful to familiarize with the different methods of timetabling design strategies.

1.6 Thesis Methodology

Data Needed for the Study

In this thesis work, updated data are collected from ERC offices, Specifically from Kality depot of AA-LRT (from both OCC, and DCC centers). Hence based on the available information the possible requirements have been calculated to design a timetable. Further, some observations of the train transport of AA-LRT as how it takes place on the ground have been made. On the process, some necessary information is collected through email, mobile calls and direct interviews from individuals who have some experience and knowledge on the AA-LRT system.

Modeling System

Currently, the AA-LRT uses lower levels of some parameters and it has some predefined designed parameters such as headway of 6 minutes. Hence, the investigating of the performance of the train timetable will be done by comparing the current timetable and the expected (future plan) timetable. Based on these comparison results, the parameter values of a new timetable can be designed.

To design a new timetable first, the necessary parameters using the standard and available methods are calculated. Then using those calculated parameters Arena simulation software is used to check whether the system is working well or not. Furthermore, we can visualize the train movement using the animations through the zigzag line in the Arena software for a matter of checking of their expected movement.

1.7 Thesis Organization

This thesis has 6 chapters. The first chapter discusses on introduction part, the second chapter is on railway timetable designing methods, the third chapter deals specifically with the AA-LRT timetable characteristics. It discusses on the current AA-LRT timetable including the rules and regulations of AA-LRT working manual. Hence to design an appropriate timetable those regulations are taken as prerequisites.

The fourth chapter is on designing models for the AA-LRT. Here the main parameters for the design of a timetable are discussed including their Mathematical formulas to find the appropriate values. The fifth chapter is simulation and result parts. In this chapter, the numerical values found in chapter four are used as the inputs to the simulation model of the Arena software and their results are compared. The last part is chapter 6, which deals on conclusions and recommendations.

CHAPTER TWO

Railway Timetable System

To get the best use of the railway service, there are a lot of parameters and one of these parameters is the train timetable. To design the best timetable we should know the available technologies. Hence in this chapter, some general methods to design a train timetable based on some literature reviews are discussed.

2.1 Railway Transport

Rail transport refers to the land transport of people or goods along guided path called railway [4]. It has a significant role in the transport system of many countries because the development of trade, industry and commerce of the countries may largely depend on the development of railway systems. In the case of our country Ethiopia, the railway is planned to enhance the Ethiopian transformation plan since it connects the most important sites including Djibouti port. Hence, it will be an aid for the Ethiopian transformation plan to be succeeded. Specifically, The AA-LRT helps to reduce the shortage of public transport and enhances the image of the city, as Addis Ababa is the capital city of Ethiopia and headquarters of many organizations including the African union (AU).

Advantages and Disadvantages of Railway System: Generally, as any other transport modes, railway transport system has its own advantages and disadvantages. Hence, some of them are:

Advantages:

- ❖ It facilitates long distance travel and transport of bulky goods which may not be easily transported through motor vehicles.
- ❖ It is a quick and more regular form of transport because it helps in the transportation of goods with speed and certainty.
- ❖ Railways perform many public utility services. Their charges are based on charge what the traffic can bear principles which help the poor.
- ❖ It helps in the industrialization process of a country by easy transportation such as raw materials at a cheaper rate.

- ❖ It helps in the quick movement of goods from one place to another at the time of emergencies like famines and scarcity.
- ❖ The railways provide greater employment opportunities for both skilled and unskilled labor
- ❖ The railway is the safest form of transport. The chances of accidents and breakdown of railways are less as compared to other modes of transport.
- ❖ The carrying capacity of the railways is extremely large. Moreover, its capacity is elastic which can easily be increased by adding more wagons.

Disadvantages: Although railway transport has many advantages, it suffers from certain serious limitations:

- ❖ The railway requires a large investment of capital. Hence not so profitable considering the initial investment and operation costs.
- ❖ The railway transport is inflexible. Its routes and timings cannot be adjusted to individual requirements.
- ❖ Rail transport cannot provide door to door service as it is tied to a particular track. Intermediate loading or unloading involves greater cost, more wear and tear and wastage of time. The time cost of terminal operations is a great disadvantage of rail transport.
- ❖ Railways require huge capital outlay; they may give rise to monopolies and work against public interest at large. Even if controlled and managed by the government, lack of competition may breed in inefficiency and high costs.
- ❖ It involves much time and labor in booking and taking delivery of goods through railways as compared to motor transport.
- ❖ Security threat as it is prone to attacks and severity of accidents is high

2.2 Railway Timetable

Railway timetable is a program for space and time-wise running of railway passenger and/or freight traffic on a railway line. A timetable for a railway line or railway network, at least it contains a list of stations per railway line with the arrival and departure times for trains. Operating economy wise the timetable is the result of the traffic production planning for a given time period i.e. the validity period for the timetable [2].

To have an effective railway transport service it involves many procedures for railway operators. Obviously, the timetable is not the only plan that needs to be composed in order to operate a railway system but also areas like demand estimation, rail line planning, rolling stock scheduling and crew scheduling too. This also indicates the dependencies between the timetabling process and other railway planning processes [13].

Demand Estimation: Travel demand is estimated as the number of people that wish to travel from an origin to a destination. Some methods to know the demand are passenger counts, passenger interviews, and counting ticket sales.

Rail Line Planning: A rail line is a direct train connection between an origin station and a destination station, via a certain route through the railway network.

Timetabling: Once the rail line plan is complete, a timetable for its train lines can be constructed.

Rolling Stock Scheduling: This deals with the assignment of train units to the rail lines in the timetable. When allocating the trains it is with the consideration of peak and off-peak hours since train canceled from or added to the timetable service regularly happens.

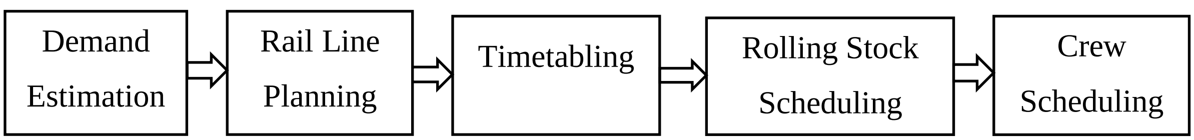

Figure 2: Operation areas and steps in a railway planning process

Crew Scheduling: Each train has to be manned by a driver and one or more assistants. Hence, the crew scheduling needs to respect labor rules such as working day, lunch and breakfast time, shifting of working times, etc. Generally, this category involves complex situations to make a plan.

Main Advantages and Disadvantages of Railway Timetable

Advantages:-a train timetable have so many advantages, some of them are

- It helps to use resources efficiently
- It minimizes traffic accidents
- It helps to give satisfactory service to the customers.

- ❖ It helps to complete tasks on their time.
- ❖ It helps to control the traffic movement.

Disadvantages:- timetable has also several disadvantages. Some of them are

- ❖ There is no positive confirmation that the track ahead is clear, only that it is scheduled to be clear. The system does not allow for engine failures and other such problems, but the timetable should be set up so that there should be sufficient time between trains for the crew of a failed or delayed train to walk far enough to set warning signals to alert any other train crew.
- ❖ The timetable system is inflexible. That is trains cannot be added, delayed, or rescheduled without advance notice.
- ❖ Another problem is a corollary of the above one: that is the system is inefficient. To provide flexibility, the timetable must give trains a broad allocation of time to allow for delays, so the line is not in the possession of each train for longer than is otherwise necessary.

2.3 Main Objectives and Requirements to Design a Timetable

2.3.1 Objectives to Designing a Timetable

There are a lot of objectives which, they should be satisfied when constructing a timetable. For instance, the main objectives are satisfying customers, creating a stable and robust railway system, and controlling the costs. But, those objectives may be conflicting with each other. As an example, passengers would be greatly satisfied if each of them was offered a direct train connection, without any intermediate stops (dwell times), and at exactly the preferred time of travel. But such a system would clearly result in huge costs, or it may be impossible to operationally achievable. Now let’s see some important points to get those objectives.

Travel Time

One of the main important factors for customer satisfaction is the travel time. However, there is only limited freedom in providing passengers fast travel opportunities with few transfers, since the train lines and their trip times are assumed to be given and fixed. Still, through dwell times and headway times, the timetable has some influence on the total travel time. In fact, the objectives that aim at offering customers fast travel times correspond to the dwell and headway times. Rather than just satisfying these requirements (dwell time, headway, etc.), the objective is to satisfy the customers as much as possible. So, rather than making sure as it has sufficient dwell time for passengers to alight and board these objectives (for instance, satisfying the customers by decreasing travel time) should be incorporated into the timetable design [13].

Robustness

Another important factor for customer satisfaction is the robustness of a timetable. In a timetable which meets the safety requirements (such as speed limit, headway, braking distance, etc.), trains may follow one another at exactly the minimum headway time. A small delay of one train may then be easily propagated onto other trains, and then propagated through the entire network. Therefore, another timetabling objective is to construct a robust timetable that contains some buffer time above the minimum headway time to absorb small disturbances. While planning a timetable, a certain buffer time is generally added to the minimum headway time. Still, when track capacity is available, one can argue that timetable robustness is increased by pulling apart the trains as far as possible since a delayed train is then less likely to interfere with the other trains on the track [13].

Costs

The major cost components of a railway system are formed by the infrastructure, the rolling stock, and the train crews. The infrastructure is assumed to be fixed and given, and the rolling stock scheduling and crew scheduling occur in a later planning phase. However, within this limited freedom, one can still pursue the objective of constructing a timetable that requires a minimum number of rolling stock compositions [13].

Generally, some requirements are not allowed to be violated for instance the safety requirements. Others could, however, be violated, such as commercial requirements. In practice, since it is impossible to construct a timetable that meets all requirements. The clear objective is to find an acceptable timetable which minimally violates the initial requirements.

2.3.2 The Timetable Requirements

A well-designed timetable should meet several requirements, such as safety regulations, service levels to be achieved, and restrictions considering the operational feasibility of the timetable. These requirements belong to one of the categories described below.

Dwelling at Stations: In practice, limits are specified for the time that a train dwells at a station. On one hand, a minimum dwell time specifies the minimum time needed for passengers to alight and board. On the other hand, one might also want to limit the dwell time at a station because stations only have a limited capacity and because each dwell minute adds to the train's total travel time. Hence, station dwell times are the major component of headway time.

Headway: It is a time which separates two trains running to the same direction and on the same track. It guarantees that the departures and arrivals of the two trains on the same track have a safe minimum headway time. The headway time is only a simplification of the real safety system used in the railway world. For any pair of trains using the same track, the minimum headway time must be respected both at the origin station and at the destination station of the track.

Synchronizing Train Lines: When two different lines use a shared line, coordinating the trips of those different lines is desirable for several reasons: Some of them are to offer customer friendly transfer relations, to guarantee a balanced service on tracks operated by several lines.

In a transportation network, different lines may share sections of the route. Without synchronization, the trains may arrive at the common stations in quick succession which may not yield a very balanced service. Ideally, we ensure a nearly equal headway time interval between the trains coming from different lines towards the common line [15].

Changing Direction at Terminal: When the train reaches the end of the route, the train will change its direction. Before that few time is required, for shunting, cleaning the train, or idle time of the driver for going to the other end. In either case, a feasible timetable has to respect this minimum changing direction time.

Fixed Arrival and Departure Times: For some trains, the freedom of selecting arrival and departure times is very limited. This especially applies to international trains and hence this has less correlated with the AA-LRT system since the service is local.

Safety Requirements: In a transportation network, many vehicles are in transit simultaneously and they use the same tracks. To prevent collisions and to reduce huge waiting time, minimum headway times between the vehicles have to be ensured.

In practice, it may not be sufficient when a timetable just satisfies the above requirements. But, depending on the point of view, there may have several criteria that make a timetable reasonable.

2.4 Timetable Design Methods

2.4.1 Timetable Prioritized Preferences

There are many prioritized preference items to make a timetable. Even though different countries have different preferences evaluations based on their context, here are the most common preference evaluation criteria for a given railway timetable system.

- Safety
- Systematic timetables
- Capacity consumption on railway line sections
- Robustness of the timetable
- Societal acceptance of the timetable
- Attractive transfer options and travel times

2.4.2 Railway Timetable Types

Generally speaking, there are two fundamental railway timetable types [13]. Those are non-periodic and periodic timetables. Additionally, those can further divide into smaller categories such as periodic symmetric and asymmetric as well as non-periodic symmetric and asymmetric. Both the fundamental type of timetables has their own advantages and disadvantages.

Non-Periodic Timetable: A non-periodic timetable contains no structure. It consists of individually scheduled trips that are based on travel demand. Most departures during a day are unique. This indicates that train runs often have different stopping patterns and different levels of scheduled waiting times in the timetable.

The non-periodic timetable type was the most commonly used for long-distance railway traffic in Europe when looking back in history. Only in the 1970s and early 80s did the national railway companies introduce periodic timetables in large scale for their train services. Some countries like France still use non-periodic timetables for the larger part of their travel relations [2]. Generally speaking, nonperiodic train timetabling is especially relevant on heavy-traffic, long-distance corridors where the capacity of the infrastructure is limited due to great traffic densities.

Periodic Timetable: Periodic timetable contains a structure capable of repeating itself within some fixed time interval called period. In this timetabling each trip is operated in a periodic way. That is, each period of the timetable is the same. The events are scheduled for one cycle in such a way that the cycle can be repeated. An advantage of a periodic railway system is the fact that such a system's timetable is easy to remember for the passengers. A drawback is that such a system is expensive to operate from the point of view of the use of resources such as rolling stock and crews [2].

Periodic Versus Non-Periodic Timetables

Table 1: Comparisons between periodic and non-periodic timetables

Periodic timetable	Non-periodic timetable
❖ Easy to memorize for passengers ❖ In practice a more optimal utilization of rolling stock due to simpler planning ❖ Logic and coherent timetable for the entire network ❖ Minimizing waiting time for randomly arriving passengers at stations ❖ Reducing risk for passengers concerning train to train transfers ❖ Less work for the timetable planners	❖ Easily adaptable to market demands ❖ High level of flexibility in the planning process ❖ It has a potential for optimal utilization levels of rolling stock due to a higher degree of freedom in timetable planning. ❖ Potential for reduced operational costs due to a higher degree of freedom in timetable planning. ❖ Attractive transfer times for the most used transfer connections

Furthermore, both Periodic and non-periodic timetables can be divided into symmetric and non-symmetric timetables. The symmetric timetable means, that for every directed line there exists another directed line serving the same stations just in opposite direction. Moreover, the concept of symmetry makes a sense, if for every traffic line, the running and stopping times of its opposite directions are the same. Hence trains of different train lines, running according to a symmetric periodic timetable, meet twice in one period [13]. Also for the minimum headways, dwell times, signaling systems and other operational constraints they should be identical in both directions; whereas, the non-symmetric timetable has no similar properties in both direction.

Currently, the Ethiopian Railways Corporation (ERC) uses periodic timetable with a period of 2 hours [8]. The reason to use the 2 hours period is because using the speed of 20km/h it take 2 hours to make a complete trip (for instance to make a trip from Kality to Menelik II square and then back from Menelik II square to Kality and similarly for the other line from Ayat to Torhailoch and then from Torhailoch to Ayat). Hence, the period depends on the time taken to make a complete trip. Specifically speaking it is also symmetric timetable. In general periodic timetable is more and more international standard, because cyclic timetables are easy to remember for passengers and easier to handle for railway personnel. The scheduled intervals between the trains of the same line of a cyclic timetable are regular over the (daily) service period, but may be increased to an integer multiple of the base interval or decreased by an integer divisor e.g. during peak periods [13].

The period of a periodic timetable has different values with respect to different consideration. For instance for AA-LRT, if we consider the period with respect to the trains, the period will be the total time taken to make a single complete trip (which is 2 hours). But, if we consider with respect to the passengers waiting at stations the period will be the headway time (which is few minutes and of course it varies in peak and off-peak hours.)

Timetable Type Choosing Criteria

To use some type of timetable we select based on its suitability to our railway systems. The options to meet are very limited and depend on different parameters: for instance on available infrastructure (its capacity, single or double track etc.), switches, signaling facilities, the characteristics of the trains and number of customers, etc. [16]. Also, the advantages and disadvantages of each type of the timetable will be one of the main criteria for selecting the appropriate type. Now a day the periodic timetable is more internationally common than non-periodic timetable and there are a lot of models or software developed based on the periodic timetable.

2.4.3 Methods Used in Timetable design

To design a timetable a lot of methods are available starting from selecting a timetable type (see section 2.4.2) up to using software to automatically display the required timetable. Hence, some of those will be discussed here.

Time Window: This has a flexible platform allocation time window instead of precise arrival/departure times and a flexible order of trains at overtakes and junctions. With this flexibility, the ability to recover from disturbances in the operational run can increase together with the punctuality. The idea with time windows is that there are no precise arrival and departure times, only a time gap in which the trains can arrive and depart. That is it has a variable block but with a fixed gap. The passengers only get the time for the latest possible arrival time and the earliest possible departure time.

The trains can be a little late according to schedule but the passengers will perceive that they are on-time anyway. This will however not increase the actual robustness of the trains. The trains run according to the same timetable as before and in the case of delays, the trains will disturb each other just as much [10].

Fixed Block: If the block is fixed (with the help of signals), the sliding time window is no more used. Hence, in the fixed block system appropriate values for the basic parameters such as the travel time, headway, dwell time, braking distance etc. are to be obtained to offer an advisable service to passengers.

Approach: In design a timetable particularly for periodic timetable there are some approaches of designing. These are Periodic Event Scheduling Problem (PESP) and Genetic Algorithm (GA).

PESP: The PESP considers the scheduling of periodically recurring events under periodic time window constraints. For railway timetabling, one should think of an event as a combination of (train, station, arrival) or (train, station, departure) [13].

GA: Genetic algorithms are computer-based search and optimization algorithms. GAs begins with the population of string structures created at random. Thereafter, each string in the population is evaluated. The population is then operated by three main operators: - reproduction, crossovers, and mutation, to create a hopefully better population. The population is further evaluated and tested for termination. If the termination criteria are not met, the population is again operated by the above three operators and evaluated. This procedure is continued until the termination criteria are met [5].

Typical Software: There are a lot of software applications used to design a timetable. Even though, in this thesis the Arena software is used, here are other commercial software technologies applicable for the design of a timetable.

DONS: The DONS system is a practical example of how mathematics and computer science can support the tactical and strategic design of railway timetables, developed in Netherlands. The goal of DONS is to provide long-term planners with a tool to generate a timetable in less time than it would take to construct them by hand, thereby enabling them to conduct more extensive scenario studies. DONS system consists of three parts those are the graphical user interface, database and intelligent modules [18].

TAKT: This is another example of automatic timetabling system development. It accelerates and facilitates the construction of a representative set of periodic timetable scenarios to improve the evaluation of different infrastructure measurements. It was already successfully tested in Germany, with this experience and ongoing research projects; the development is modified through time [18].

CHAPTER THREE

AA-LRT and Its Timetable

3.1 General Characteristics of AA-LRT System

The AA-LRT system is newly introduced to the capital city of Ethiopia, Addis Ababa, with two main routes having a total length of 34.25 km (including the reserved track for future extension). The north-south line is 16.90 km from Kality to Menelik II squared and the east-west line is 17.35km from Ayat to Torhailoch with a 2.662km common line to both routes. It already starts service for passengers in 16 hours per day. This service is given by a total of 41 trains including five trains which are not ready for operation due to technical problems. Out of those 41 trains, 20 trains are allocated to the EW line and 21 are to NS line including the reserved trains and trains with a technical problem [8].

The Addis Ababa railway line is double track and it is a homogeneous system, i.e. the trains are all the same as well as the track lines are uniform and all are electrified track lines. Now let's see the main characteristics of AA-LRT:

- Its operational speed is 20-70kmph with maximum speed of 80kmph
- The maximum regression speed of a passenger train is 10km/h.
- Its infrastructure line comprises tunnels, bridges, and the ground level.
- The battery capacity can support a failed train for at least 30 minutes for the functions of door control, emergency lighting, onboard equipment, and communication system.
- It has a total length of 34.25 km (North-South line 16.90 km and East-West line 17.35 km with about 2.662km common line to both routes.
- It negotiates steep gradient(50‰)[1] and sharp curves
- It gives service 16 hours per day
- It is fully electrified LRT and hence environmentally friendly
- Standard Gauge (1.435 meters) and double track for the whole route
- Expected headway: 6 minutes with a potential of reducing to 90 seconds
- The fare system is passenger-km based

[1] 50‰ = 50/1000, just like 4% = 4/100

- Minimum Curve Radius: 50m for mainlines, 30m for parking garage
- Minimum vertical curve Radius: 1000m
- Steel rail: all the main and auxiliary tracks and the depots use 50kg/m steel rails with cut-length of 25m.
- Sleeper arrangement: the arrangement is 1,600pairs/km for main tracks and 1,440pairs/km for tracks inside and outside the garages in rolling stock depots.
- The operation of train adopts the mode of manned visual driving
- Average acceleration for startup: $1m/s^2$
- Average deceleration for braking :-
  - The average deceleration of normal braking with rated load (including control response time):$\geq 1.0m/s^2$
  - The average deceleration of emergency braking with rated load (including control response time): $\geq 1.5m/s^2$

3.2 Details of the AA-LRT Tramcars

The trains for AA-LRT are operated in two directions with 6-axle double-articulated light rail tramcar. One unit of the tramcar is formed with three modules parts. In the front and rear module of the tramcar body, a bi-axial power bogie is installed, and a bi-axial driven bogie with the independent wheel is installed under its middle module part.

Figure 3: Typical single unit trains of AA-LRT

A single tramcar of AA-LRT has a length of 28400mm, the width of 2650mm, and the weight of 43t. The wheel diameter of its motor wheel is 660mm and its driven wheel is 600mm as well as the distance between track top and tramcar top is 3700mm. In the initial stage, one unit of the tramcar is arranged to be operated. The rated passengers are 317 persons in one tramcar with 64 seats and 6 standing persons per m^2. In its long-term two units are coupled together to form one train. The rated passengers will be double of the single unit tramcar.

The train has 10 doors, including 4 pairs of doors in passengers' cars and one side door of driver's cab on the right side of each end. But at a time, only 5-doors will give a service. The four doors allocated for passengers are two at the front module and two at the rear module. Those doors are electric sliding doors. The effective opening of each of the passenger door is 1250mm, and their effective height is 1850mm. Three passengers can move through the doorway simultaneously.

Currently, the AA-LRT has 41 total trains (20 to EW-line and 21 to NS line) but due to the technical problem only 36 trains are capable of giving the required service. Still all these trains will not give service as some of them should standby as a reserve. The maximum number of trains that can be operated during an hour is generally set by the line capacity (see in Chapter 4).

The maximum length of a train to be operated in the AA-LRT can be found by coupling two trains which are 2x28400mm = 56800mm long. Considering the connecting length in between the two coupled trains, the total length of the coupled trains (from tip-to-tail) is about 59m. Simply from the station platform a maximum of two trains can only be coupled because of the designed curve radius of the AA-LRT infrastructure.

The Addis Ababa Light Rail Transit (AA-LRT) adopts the way of double-line, single-direction, and right-hand running.

- East-West line from Ayat (EW1) to Torhailoch (EW22) is up direction; while East-West line from Torhailoch to Ayat is down direction;
- South-North line from Kality (NS6) to Menelik II Square (NS27) is up direction; while South-North line from Menelik Square to Kality is down direction;

The signaling signs are installed on the left side of the track according to the traffic direction; track signs are installed on the left side of the track according to the distance counting direction at a distance of not less than 3100mm from the outer track centerline.

3.3 Stations of the AA-LRT

The platform of the AA-LRT stations has a length of 60m. The AA-LRT has a total of 22 stations in the EW line and similarly 22 stations in the NS line but, it has a total of 39 stations in both routes with five stations in common (see Figures 4 and 5 below). The name of the stations is written in two ways, the first one is they use the local name of the city. The other and systematic name (i.e. easy to handle) uses the abbreviation letters EW following a number of the east-west direction and the letters NS following some number of the stations of north-south directions. The naming of stations for the EW direction starts from EW1, EW2, EW3, ..., EW22, to mean Ayat, Meri, CMC, …, Torhailoch, and for the NS line is NS6, NS7, NS8, …, NS27 to mean Kality, Abo Mazoria, Saries, …, Menelik II square.

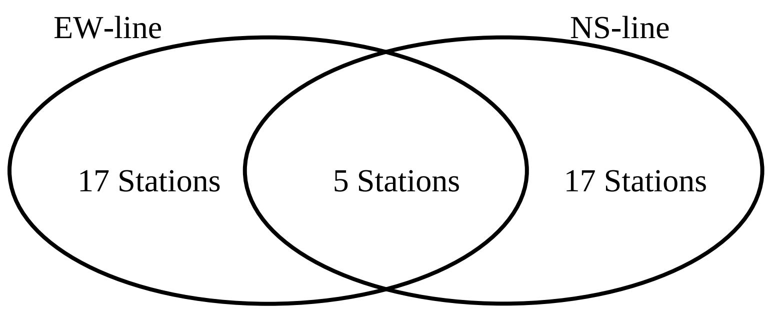

Figure 4: Diagram indicating the number of stations in each line

The common lines are represented either as EW16, EW17, EW18, EW19 and EW20 or NS16, NS17, NS18, NS19, and NS20.We can use those names interchangeably but most of the time the name EW is used. The reason why the NS line starts from NS6 instead of NS1 is in order to have a similar pattern with the EW line by numbers following the letter at the common stations.

The overall length of the East-West line is 16.998km (the terminal station is designed to be after the line from stations EW1 to EW22). Stations EW9 to EW13 are semi-underground stations; EW15 to EW20 are elevated stations (stations EW16 to EW20 use the common rail with stations NS16 to NS20 of the north-south line, approximately 2.662km in length); the remaining stations are ground stations.

The overall length of the North-South line is 16.689km (the terminal station is designed after the line from stations NS6 and NS27). Station NS27 is the only underground station; stations NS16 to NS22 and NS24 are elevated stations (stations NS16 to NS20 use the common rail with stations EW16 to EW20 and the remaining stations are ground stations [8].

Ayat rolling stock depot near EW1 is a base of the east-west line for the parking, servicing and periodical repair of vehicles. A parking lot is reserved near EW1 and EW22 for long-term operation. Kality rolling stock depot near NS6 is a base of the north-south line for the parking, servicing and periodical repair of vehicles. A parking lot is reserved near NS6 and NS27 for long-term operation.

In the EW route of AA-LRT, there are a total of 22 stations and the distance between them is not evenly distributed. The longest interval is about 1260 meters, the shortest interval is 445 meters and the average interval is 761.928 meters [refer table 2].

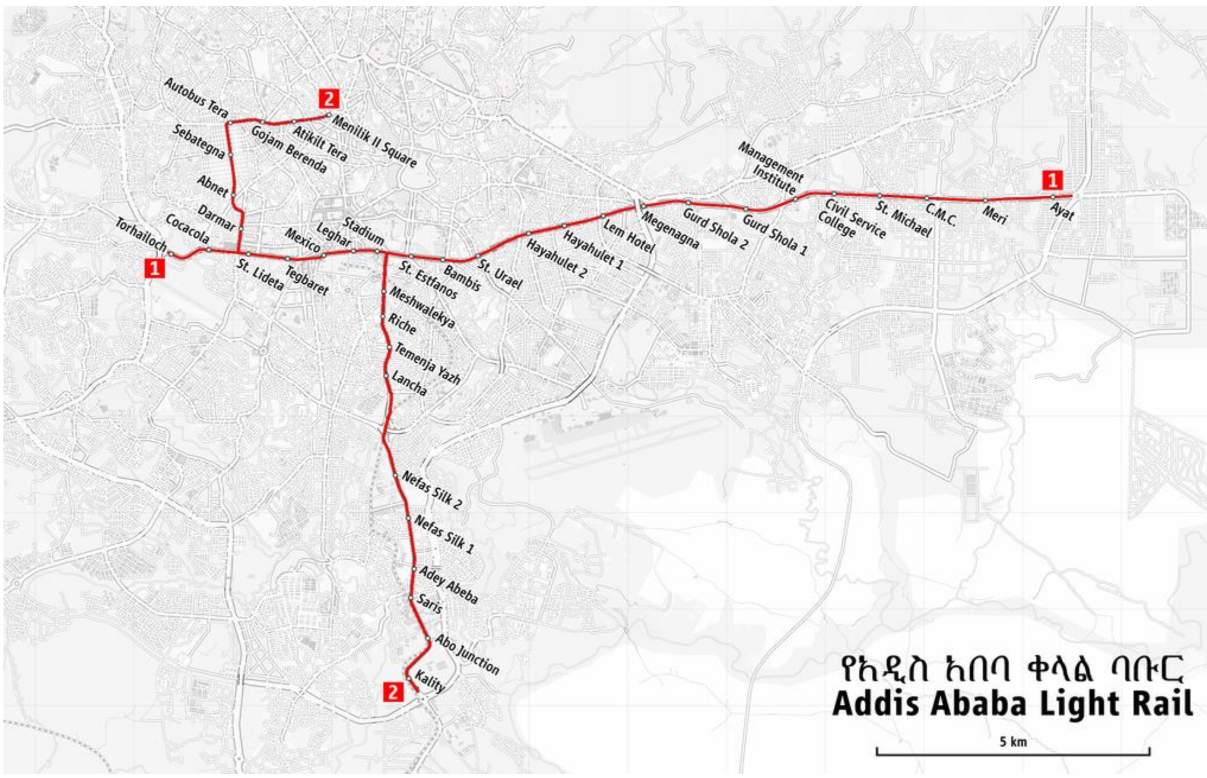

Figure 5: Map of rail lines and stations of the AA-LRT phase-I [7]

In the NS route, there is a total of 22 stations and the distance between them is not evenly distributed. The longest interval is about 1972 meters, the shortest interval is 445 meters and the average interval is 738.289 meters [refer table 3].

Some of the basic reasons for the variation of the distance between stations are: Master Plan of the city, consideration of civil work and construction, consideration of future expansion, consideration to avoid from danger areas like a gas station and others that can harm people and property during any improper functioning, etc. [8].

Table 2: Platform station type and distance between stations of EW line [8]

Station name	Distance between Stations(m)	Station type
Origin		
	52	
EW22		Ground station
	769	
EW21		Ground station
	732	
EW20		Elevated common rail station
	735	
EW19		Elevated common rail station
	688	
EW18		Elevated common rail station
	560	
EW17		Elevated common rail station
	445	
EW16		Elevated common rail station
	640	
EW15		Elevated station
	593	
EW14		Ground station
	675	
EW13		Semi-underground station
	963	
EW12		Ground station
	758	
EW11		Ground station
	746	
EW10		Ground station
	776	
EW9		Semi-underground station
	829	
EW8		Ground station
	1083.6	
EW7		Ground station
	970	
EW6		Ground station
	724.82	
EW5		Ground station
	860	
EW4		Ground station
	863	
EW3		Ground station
	1092	
EW2		Ground station
	1260	
EW1		Ground station
	182	
Terminal		

Table 3: Platform station type and distance between stations of NS line

Station name	Distance between stations (m)	Station type
Origin	196	
NS27	743	Underground station
NS26	945	Ground station
NS25	604.88	Ground station
NS24	667	Elevated station
NS23	812.71	Ground station
NS22	739	Elevated station
NS21	591	Elevated station
EW20	735	Elevated common rail station
EW19	688	Elevated common rail station
EW18	560	Elevated common rail station
EW17	445	Elevated common rail station
EW16	908	Elevated common rail station
NS15	481.12	Ground station
NS14	610	Ground station
NS13	555	Ground station
NS12	1971.66	Ground station
NS11	861	Ground station
NS10	995	Ground station
NS9	535	Ground station
NS8	845	Ground station
NS7	950	Ground station
NS6	269	Ground station
Terminal		

3.4 Signaling System of AA-LRT

3.4.1 Introduction

Signaling is a mechanism by which the station master conveys information to the train driver to stop, go with caution or proceed. When designing the timetable it will be best if it is aided by the signaling system that is the timetable will be guided by the signal if the train tries to travel out of the timetable or if it tries to enter the occupied path ahead. Hence, the main role of signaling is to safely separate trains from each other and protect specific paths through the interlocking at junctions and crossovers. Specifically for the case of AA-LRT the signaling systems are clearly stated below.

Cab Signaling

Cab signaling uses codes inserted into each track circuit and detected by an antenna on each train. The code specifies the maximum allowable speed for the block occupied, and may be termed the reference or authorized speed. This speed is displayed in the driver's cab often so that the authorized speed and actual speed can be seen together.

The authorized speed can change while a train is in a block, as the train ahead proceed, allowing drivers to adjust train speed close to the optimum with less concern about overrunning a trip stop. Problems with signal visibility on curves and in bad weather are reduced or eliminated by cab signaling.

In short:-

- Cab signaling sets authorized, safe train speeds
- Authorized speeds displayed in driver's cab
- Problems with signal visibility reduced or eliminated

Both Kality and Ayat rolling stock depots uses CASCO intelligent computer interlocking system and the signal devices are under the centralized control of the signal building of the depot.

The most common train detection devices are track circuits and axle counters. Furthermore, the AA-LRT signaling system uses axle counter and have a length of one section (block length). That is the signal will give green light if at least one station ahead is free. The axle counter will count both the in and out axle for a section. If the count-in differs from the count-out, it indicates the block ahead is occupied and hence the red light turns on to indicate stop entering the block ahead. Unless if the count in is equal to the count out , it indicates the block ahead is free and hence, the green light will turn on to allow entering the block ahead.

In order to check the idle and occupied state of the track area, the axle counter system sets axle counter points on the track. Wheel transducers are installed at the axle counter points to detect the number of axles and direction of operation of wheels. The principle of the setting of axle counter points is that all ends in an axle counter section that allow a train to pass through shall be configured with an axle counterpoint (no axle counter point will be set at the end of dead end tracks) [8].

The main track of Phase I project is designed double-tracks, and the train operation adopts two-track one-way operation on the right. The operation direction from EW1 to EW22 of the East-West line and from NS6 to NS27 is taken as the upward direction while the opposite direction is taken as downward.

The main track uses CASCO signal system which consists of the following subsystems

1) Interim Automatic Train Protection (IATP) it is a train control subsystem (including ATP automatic train protection);

   Automatic train protection (ATP) systems have been developed to support train drivers and avoid human errors or failure. ATP shows signal information in the cabin (cab signaling), checks whether the driver respects the signaling commands, and intervenes when necessary.

   ❖ The IATP has two components:

      - Trackside IATP equipment

Beacon: the beacons are active beacons, including mobile train initialization beacon (MTIB), relocation beacon (RB) and rapid location beacon, etc.

      - On-board IATP equipment

On board IATP equipment includes onboard controller, driver display unit (DMI), coded mile meter and beacon antenna, etc.

2) CBI (Computer Based Interlocking Subsystem): The interlocking equipment mainly includes: turnouts, signals, axle counters and interlock control terminals, etc.

3) ATS (Automatic Train Supervision) subsystem works with interlocking system, track-side integrated signal transfer point equipment, and other signal systems to implement centralized monitoring of signal equipment and to control trains to automatically operate in main tracks according to predetermined operation plans. ATS equipment mainly distributes in the control center and the signal equipment rooms in Kality/Ayat rolling stock depots.
4) DCS data transmission subsystem consists of cable parts and wireless parts, mainly including backbone network, a rail-side wireless access point (AP), on-board DCS antenna, onboard wireless modem and onboard Ethernet, etc.

All network channels for the transmission of CBI, ATP, and ATS information adopt redundant design. When one channel has any fault, the other channel will be automatically used for information transmission.

3.4.2 Block (Section) Safety of AA-LRT

The scope of the lines between two adjacent end walls of two adjacent stations is defined as a section. The scope of the lines connected to the up line between two adjacent end walls of two adjacent stations is defined as Up section from S1 (station name) to S2 (station name). The scope of the lines connected to the down line between two adjacent end walls of two adjacent stations is defined as Down section from S2 (station name) to S1 (station name) [8].

Under normal circumstances, the operation of the train must ensure spacing of one station matching with one section it allows only one train occupancy between two adjacent signals in the same direction within one route (except train which gives a help to other trains in problem), and the train runs with the display of ground signal [8].

3.5 The Current AA-LRT Timetable

The AA-LRT have its own time specifications like trip time, dwell time and the headway, which are the main restrictions to design the train timetable. Hence because of this importance here is their definition with their specified time.

Total Trip Time: This time is the time needed to make a complete single trip. As an example a trip from Kality station to Menelik II station and then back to Kality station. Currently to make a single trip time for AA-LRT it takes two hours. Of course, this total trip time is the sum of all time spends on traveling from station to station and the dwell times at each station.

Dwell Time: The dwell time is the duration that a train stops in a station. This constraint connects arrival and departure event of a train. Dwell times should be long enough for boarding of new passengers and possibly for some loading/unloading or maintenance work on the train. It should not be much longer than necessary since travelers would like to move on and platform capacity within a station might be small. To be specific the AA-LRT has a dwell time ranging from 25 to 60 seconds and in average 30 seconds.

Headway: As described in chapter two (section 2.3.2); Headway is a time which separates two trains running in the same direction and on the same track. The AA-LRT system currently uses headway of 15 minutes (which must be reduced by half at the common line). But, the designed headway time (expected for the future) is 6 minutes with a capability of reducing to 90 seconds.

Operational Regulations for Train Leaving/Entering the Depot for AA-LRT

Train Leaving the Depot Arrangement

- ❖ In peak hours, when the trains leave the depot, the operation dispatcher strictly controls the trigger time of the depot-leaving route and return route to ensure train operation in accordance with train timetable.
- ❖ The train leaving depot is based on planned route, but the OCC can make flexible adjustments under special circumstances.

Train into the Depot Arrangement

- ❖ In peak hours, when trains enter depot, the operation dispatcher should strictly control the trigger time of the depot-entering route to ensure train operation in accordance with train diagram/timetable.
- ❖ Train entering depot should base on planned route, and OCC can make a flexible adjustment under special circumstances. Additionally:
- ❖ Under special circumstances, the trains cannot come back to the depot according to the plan, OCC should contact DCC immediately, and DCC makes the plan to ensure trains leave depot according to the plan.
- ❖ OCC and DCC need to strengthen contact, to check as the plan works accordingly.

Every morning before 4:30am, DCC provides trains number scheduling to OCC. A train number is a code number given for a train for the duration of one day and still the last two digits will change when the train reaches at each end point during its service time [8].

3.5.1 The North-South Line (NS-Route)

According to the ERC working manual the current situation in the north-south line, the following main technical details are considered.

- ❖ The working time 16 hours per a day that is from 6:00 in the morning to 22:00 at noon.
- ❖ The number of total trains (commercial trains) passing through a station in a day (16 hours/day), in both directions on an NS line, is 122. These are:
  - Upward commercial trains in NS line (NS6-NS27) are 61trains.
  - Downward commercial trains in NS line (NS27-NS6) are 61 trains.
- ❖ The number of total trains (non-commercial trains) passing through a station in a day (16 hours/day), in both directions on an NS line, is 6. These are:
  - Upward trains leaving depot (NS6-NS27) are 3 trains. The trains will go empty from Kality depot to start transporting passengers from the Menelik II square station in the morning (6:00)
  - Downward trains entering depot (NS6-NS27) are 3 trains. The trains will go empty after finishing their task to go from Menelik II square to Kality depot at the end of the day

Table 4: Time list for first/last train and running interval for the AA-LRT NS line [8]

Station / Time		N-S line			
		NS6		NS27	
First train		06:00	20402[2]	06:00	20101
Last train		22:00	20318	22:00	20615[3]
Route plan		NS6 - NS27			
Running interval	20 min	06:00 - 08:00/19:00 - 22:00			
	15 min	08:00 - 19:00			

[2] A temporary code number of the first train for NS-up direction and for the followed trains will be like 20404, 20406, 20408…

[3] A temporary code number of the last train to make a trip, odd numbers indicates up direction and even indicate downward

This table indicates the time list for the first and last trains and running interval for the AA-LRT NS line. Similarly for the remaining trains, it follows a similar pattern. Furthermore, the detailed time parameters are given in the following table (see table 5 below).

Table 5: Technical time details of the current timetable of AA-LRT NS line

<table>
<tr><td rowspan="2">Stop time for middle station</td><td>NS7-NS8
NS12-NS15
NS21-NS23</td><td>NS6, NS9,
NS11
EW16-EW20
NS24-NS26</td><td>NS27,
NS10</td></tr>
<tr><td>25s</td><td>30s</td><td>35s</td></tr>
<tr><td>Return time in NS6 (Kality station)</td><td colspan="3">7 min 38 s</td></tr>
<tr><td>Return time in NS27 (Menelik II Square)</td><td colspan="3">7 min 03 s</td></tr>
<tr><td>NS6-NS27) Operation time for upward one-way (including stop time)</td><td colspan="3">56 min 02 s</td></tr>
<tr><td>(NS27-NS6) Operation time for downward one-way (including stop time)</td><td colspan="3">51 min 27 s</td></tr>
<tr><td rowspan="3">Numbers of trains for operation</td><td colspan="2">Running interval</td><td>N-S line trains</td></tr>
<tr><td colspan="2">20 min interval</td><td>6</td></tr>
<tr><td colspan="2">15 min interval</td><td>8</td></tr>
<tr><td>NS6-NS27 Running period (min) per a train</td><td colspan="3">120 min</td></tr>
<tr><td rowspan="2">Average running speed (km/h)</td><td>Upward</td><td colspan="2">Downward</td></tr>
<tr><td>17.6</td><td colspan="2">19.2</td></tr>
</table>

3.5.2 The East-West Line (EW-Route)

According to the ERC working manual the current situation in the East-West line, the following main technical details are considered.

- The working time is 16 hours per a day that is from 6:00 in the morning to 22:00 at noon.
- The number of total trains (commercial trains) passing through a station in a day (16 hours/day), in both directions on an EW line, is 122. These are: re:
  - Upward commercial trains in E-W line (EW1 - EW22) are 61trains.
  - Downward commercial trains in E-W line (EW22 - EW1) are 61trains.

- The number of total trains (non-commercial trains) passing through the station in a day (16 hours/day), in both direction on an EW line, is 6. These are
  - Upward trains leaving depot (EW1-EW22) are 3 trains. The trains will go empty from Ayat depot to start transporting passengers from Torhailoch station in the morning(6:00)
  - Downward trains entering depot (EW22-EW1) are 3 trains. The trains will go empty after finishing their task to go from Torhailoch station to the Ayat depot starting at 22:00 noon.

Table 6: Time for first/last train and running interval for the AA-LRT EW line [8]

Time \ Station		E-W line			
		EW1		EW22	
First train		06:00	10402[4]	06:00	10103
Last train		22:00	10418	22:00	10119
Route plan		EW - EW22			
Headway	20 min	06:00 - 08:00 / 19:0 - 22:00			
	15 min	08:0 - 19:00			

Similarly like the NS line, this table indicates the time list for the first and last trains and running interval for the AA-LRT EW line. Similarly for the remaining trains, it follows a similar pattern. Furthermore, the detailed time parameters such as the headway time, dwell time, returning time, total travel time, a number of trains (line capacity) during peak and off-peak hours, period and speed are given in the following table 7 below.

[4] A temporary code number of the first train for EW-up direction and for the followed trains will be like 10404, 10406, 10408…

Table 7: Technical details for operation timetable for the AA-LRT EW line

<table>
<tr><td rowspan="2">Stop time for middle station</td><td>EW16-EW20</td><td colspan="2">EW5-EW9 EW12-EW15</td><td>EW3, EW4, EW21</td><td>EW11, EW2</td><td>EW1, EW10</td></tr>
<tr><td>30s</td><td colspan="2">45s</td><td>50s</td><td>55s</td><td>60s</td></tr>
<tr><td>Return time in EW1</td><td colspan="6">13 min 25 s</td></tr>
<tr><td>Return time in EW22</td><td colspan="6">5 min 19 s</td></tr>
<tr><td>(EW1-EW22) Operation time for upward one-way (including stop time)</td><td colspan="6">50 min 41 s</td></tr>
<tr><td>(EW22-EW1) Operation time for downward one-way (including stop time)</td><td colspan="6">52 min 25 s</td></tr>
<tr><td rowspan="3">Numbers of trains for operation</td><td colspan="4">Running interval</td><td colspan="2">E-W line</td></tr>
<tr><td colspan="4">20 min interval</td><td colspan="2">6</td></tr>
<tr><td colspan="4">15 min interval</td><td colspan="2">8</td></tr>
<tr><td>EW1-EW22 Running period per a train</td><td colspan="6">120 min</td></tr>
<tr><td rowspan="2">Average running speed (km/h)</td><td colspan="2">Upward</td><td colspan="4">Downward</td></tr>
<tr><td colspan="2">19.9</td><td colspan="4">19.2</td></tr>
</table>

The current timetable is not only good for safety reasons but also it is good to introduce the technology step by step to the society instead of going directly to its full operation. The current timetable has an average speed of 20kmph, this is very low speed. But, since the operation is in its initial stage starting by the lowest speed can be reasonable until some experience is gained for both the crew members as well as the Addis Ababa residents who are new for the railway technology. Due to the lower speed used the travel time, line capacity, headway time, etc. are on their lower level. Hence, the lower level of the parameters such as speed, headway, line capacity, etc., causes the customers to be dissatisfied. Because travel time is too longer due to a lower speed, the waiting time is large due to large headway and consequently, overcrowding of the passengers is a common phenomenon.

Those problems can be solved (minimized) by increasing the speed, decreasing the headway and increasing the line capacity (i.e. adding trains). But, at the initial stage of the system increasing the speed may not be feasible due to lack of experience and also since it is new technology to the residents directly increasing the speed can introduce other problems especially in safety. But, still even without changing the speed (i.e. 20kmph) a lot of problems can be solved (minimized). For instance, with this speed, the current timetable has headway time of 15minute and consequently the line capacity is 4 trains per hour for a single direction. With the same speed, the headway can be reduced to 8 minutes and the line capacity can be increased to 7.5 trains (see the detail calculations on chapter 4). Additionally, due to lack of proper synchronization, there is a significant waiting time at the entrance of the common lines from both directions. Hence, a proper synchronization is necessary to reduce (avoid) the waiting time at the entry of the common lines.

To find the optimal values of the main parameters of timetable such as headway time, dwell time, braking distance, speed, line capacity, synchronization time etc. are considered individually for the EW line, NS lines and the common lines. Then, finally by comparing the results a common and proper results for each parameter are taken for all the line system.

CHAPTER FOUR

Timetable Design Model for AA-LRT

In this chapter, the main parameters that have a big influence in the design of any railway timetable and specifically for AA-LRT timetables such as train speed, recovery time, block safety, braking distance, dwell time, headway, capacity and synchronization of trains are discussed in detail.

4.1 Key Parameters of Timetable Design

4.1.1 Train Speed

Speed is one of the key parameters for designing a timetable. In designing a timetable the train speed has a lot of effects in most of the other parameters to be considered. For instance, the train speed affects the headway consequently; this headway has a huge effect on the train capacity. That is if the train runs slowly it decrease the capacity because it needs more travel time and hence they need more headway. In contrast, if the train speed increase, the capacity of the line increases because it needs less headway time to the train which follows the train ahead. Also, the braking distance mostly depends on the train speed. In the AA-LRT the speed designed ranges from 20-70km/h and hence for a matter of comparison for selecting the best case speeds like 20, 30, 45, 55 and 70km/h are selected for the parameters in most of the following sub-topics.

4.1.2 Primary and Secondary Delays

Railway track usually operates according to a timetable. Because disturbances originating from external factors (weather, the number of passengers, special events like holidays, demonstrations football games, etc.) as well as from internal factors (like the reliability of infrastructure, a vehicle equipment, the behavior of personnel, etc.) may create delays.

In the railway transport, there are two different types of delays. These are the primary and secondary delays. A primary delay is a schedule deviation caused by some disruption at any location due to variations in a process, such as restricted acceleration and speed due to low electricity supply, an unusually high number of boarding/alighting passengers, or behavior of train driver, conductor, and dispatcher. Primary delays are managed by adding margins in running and dwell times. In heavily utilized networks, a deviation of one train from its schedule can affect other trains in the network and create a secondary delay.

The secondary delay is a process time extension caused by another train, e.g. catching up a delayed slow train on an open track or giving priority to the train coming from another line towards the common line. Secondary delays are managed by buffer times between pairs of subsequent train paths to prevent or reduce hindrance and delay propagation and well synchronized to the train coming toward the common line [4].

Recovery Time from Unexpected Delay

The time it takes the train to cover a certain distance, traveling at maximum allowed velocity is called the minimum trip time. When constructing a train timetable, some recovery time will be added to the minimum trip time. So to add a certain time to the minimum trip time the train must schedule at a lower than maximum velocity. According to [13] about 7% recovery time is added to the minimum trip time. Therefore, small delays can be compensated by having the train travel at a higher than scheduled velocity to recover from the unnecessary delay as well as to reduced/remove the propagated delay. A timetable is to be called good if a train travels according to the planned time slot despite small delays and without causing unrecoverable propagating delays to other trains and it also has the possibility to recover from small delays.

4.1.3 Section (Block) and its Safety System in AA-LRT

The scope of the lines between two adjacent end walls of two adjacent stations is defined as section or block [8]. The scope of the lines connected to the up line between two adjacent end walls of two adjacent stations is defined as up section from x-station to y-station. The scope of the lines connected to the down line between two adjacent end walls of two adjacent stations is defined as down section from x-station to y-station. For instance, take EW1 station to EW2 station, the section and its naming is as follows.

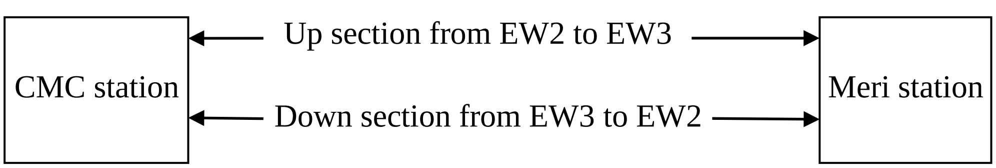

Figure 6: Naming system of a section in AA-LRT

Boundaries between the Station and Section: - Tracks on the inside of the edges at both ends of the station platform are in station tracks and a track between the adjacent edges of two adjacent stations is a section [8].

Under normal circumstances, the operation of the train must ensure spacing of one station matching with one section [8]. It allows only one train occupancy between two adjacent signals in the same direction within one route (except train succor), and the train runs with the display of ground signal [8].

4.1.4 Dwell Time

Dwell time is the duration between the stopping time of the train at a station and the departure time from the station. It is measured between the instance the train wheel stops and the instance it starts to move again. The minimum dwell time is the necessary time for passengers to alight and board the train and sometimes it includes the door opening time.

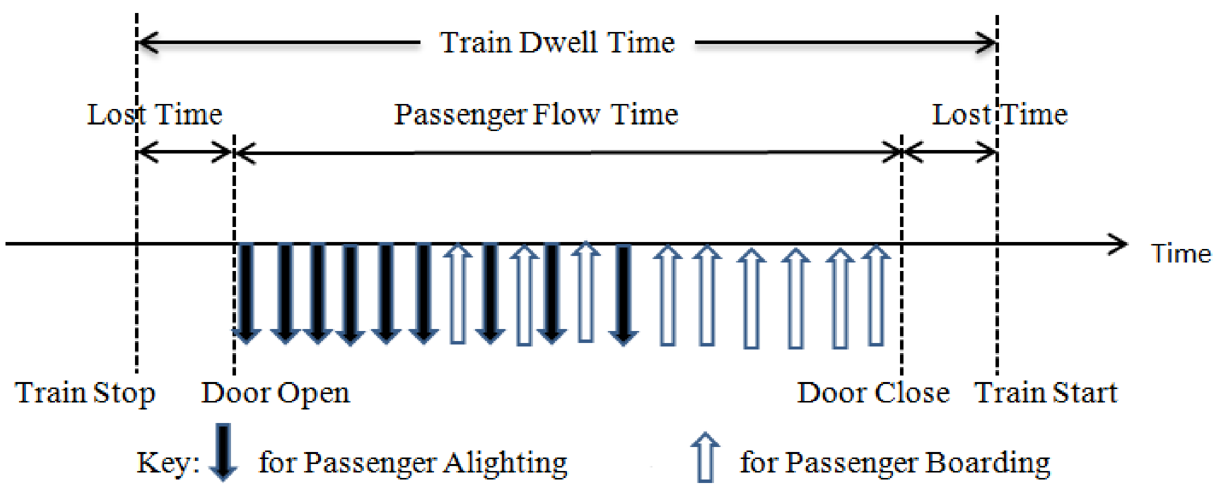

Figure 7: Activates during train dwell time [12]

As depicted in the above figure the dwell time includes the following three activities.

- The time interval between train stop and the door opened.
- The time interval during which passengers alight from and board to the train.
- The time interval between doors closed and train start traveling.

The first lost time can be obtained by calculating the time difference between train stop and door opened. Similarly, the second lost time can be obtained by computing the difference between doors closed and train start traveling. In the Current AA-LRT situation the lost time in the third interval is longer than the lost time in the first interval. The main reason for this difference is that when the door is closed the train driver will come to his side's door as a rule for a matter of checking as the doors are closed and for indicating as the train is immediate to start traveling and of course to give the drivers code of greetings. Hence, during this activity, there is some lost time which leads to more time lost in the third interval than the first interval although they use the same mechanism (via electrically sliding) to open and close the doors.

The duration of the second interval depends on the number of passengers flow. In some stations, the number of passengers can be fewer than other stations and hence the duration varies from one station to other stations. For instance in the case of AA-LRT stations like Megenagna (EW9), Lem Hotel(EW10), Stadium(EW16), Autobus Tera (NS24), and Saris (NS8) have a lot of passenger movement hence they need longer dwell time than others which have few number of passenger movements. According to [20], the proportion of dwell time productively used for passenger movements ranges from 31 to 64% of the total dwell time.

Generally, station dwells are governed by

- Average number of passengers alighting and boarding
- Number, width and height of the train door.
- Platform of the station (i.e. the platform must be capable enough to reduce congestion)
- Door operation that is opening and closing time and door warning time. Here the opening and closing time of doors is considered as a part of dwell time since doors must be opened and closed while the train is still standing at the platform. But, still the opening and closing time is very few seconds since the door operations are done electronically for the case of AA-LRT.
- Dispatching time: This is the time when the driver prepares for departure (for instance to check if the doors are closed and to make the departing symbol) or waits for permission of signals to depart. In some cases, this also includes the door closing times.
- Buffer time: is the additional time which can be used to compensate for arrival delays and/or variations in alighting or boarding times

Currently, the AA-LRT has a dwell time ranging from 25 to 60secnds (see table 5 and 7). This difference comes due to the nature of each station such as the number of passengers boarding and alighting at each station, location of the station, layout of the station (whether the station is shared or not), door opening/closing time, the status of the block ahead (free or occupied). Generally, train dwell time is one of the most unpredictable components of railway operations mainly due to the varying volumes of alighting and boarding passengers.

4.1.5 Braking Distance

Braking distance is the distance the train travels from when the train driver makes a full-service brake application to when the train stops. The braking distance depends on the speed of the train, geography of the track (gradient and curve) and on the response of the brake. The change in braking rate affects both the braking time and the safe separation time (distance). Generally, braking capacity in a railway is small due to minimal friction between metal wheels and rails.

Full-service brake (also called emergency brake) is the maximum rate of deceleration so as to minimize the risk of injury to passengers or damage to goods or cause damage to the train. The typical value of deceleration of AA-LRT is $1 m/s^2$ and its maximum rate is $1.5\ m/s^2$ for full service [1].

Effect of Train Mass

To stop a train it requires a work. This work equals the sum of the change in the train's kinetic energy and the change in its potential energy (change in height due to the gradient of the rail line).

The work is the energy in decelerating the train over the stopping distance, i.e. the product of the train's mass (m) the train's deceleration rate (a) (deceleration is negative of acceleration) and the stopping distance (s).

The change in kinetic energy relates to the change in the train's speed that is the difference of the speed at which deceleration began (u) and when it stops i.e. final speed, $v = 0$

The change in potential energy relates to the change in height of the train's center of mass due to the gradient of the track i.e. the difference in height at which deceleration began (h_1) and its height at the stopping point (h_2)

Mathematically given as:-

$(m)(a)(s) = \frac{1}{2}m(v^2 - u^2) + mg(h_2 - h_1)$ ………………. Equation 4.1

Where: m = mass of the train

u = speed of the train when it starts decelerating

v = final speed of the train which is zero

a = acceleration of the train

s = braking distance (stopping distance)

g = acceleration due to gravity

h_1 = the height of the track from ground when the train starts decelerating

h_2 = the height of the track from the ground when the train stops.

Mass is common in all the terms in the equation, and therefore can be canceled out. This suggests that mass has no direct effect on stopping distance. However, mass has an effect on the stopping distance as the location of the train's center of mass varies with the mass distribution. Mass also affects the deceleration rate of a particular item of rolling stock. For freight wagons, where the mass can vary from no load to full load, there are two levels of brake force used i.e. 'empty' and 'loaded' [3].

$(a)(s) = \frac{1}{2}(v^2 - u^2) + g(h_2 - h_1)$ ………………. Equation 4.2

The change in height relates to the track gradient. The track gradient is the change of vertical height over the corresponding change in horizontal distance i.e. tanα, where α is the angle of the slope (refer figure 8 below). For small α, which is the case for railways, tanα equals sinα. Sin α is the change in height ($h_2 - h_1$) over the stopping distance(s) which is given as follows.

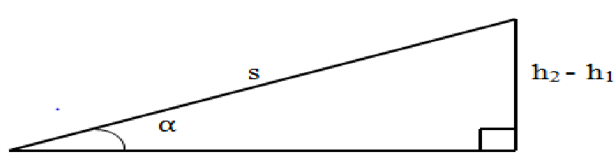

Figure 8: Sample of the gradient for braking distance calculation.

$h_2 - h_1 = s(\sin\alpha) = s(\tan\alpha)$ ………………. Equation 4.3

Here if $h_2 - h_1 > 0$, $\tan\alpha$ will be positive that is the gradient (slope) is uphill where as if $h_2 - h_1 < 0$, $\tan\alpha$ will be negative that is the gradient is downhill, hence the decision depends on the sign of $\tan\alpha$ and of course on α too.

Now substituting equation 4.3 to 4.2, and then putting final speed, $v = 0$ gives

$s = -u^2 / (2(a - g(\tan\alpha)))$ ………………. Equation 4.4

Where 'a' is the deceleration, hence it is negative.

To calculate braking distances it is , therefore, a matter of knowing the train braking parameters for each type of train and the gradient of the track and apply Newtonian physics. However, to compensate for these simplifications and the variable factors, an allowance of 15-20% is usually added [3].

In the AA-LRT the maximum grade of the main track is 55‰, and the minimum grade is 0‰. For intervals with a grade of 30‰ or above on the main track, see table 8 and 9 below.

Table 8: Intervals with a grade of 30‰ or above on the main track of the EW line [8]

Interval	Grade (‰)	Length of grade section (m)
EW22-EW21	-55	142
EW21-EW20	55	435
EW20-EW19	-55	280
EW19-EW18	46	165
EW17-EW16	-46	155
EW15-EW14	-49	356
EW13-EW12	44.5	195
EW12-EW11	-53.5	315
EW9-EW8	43.5	205
EW7-EW6	53.5	220
EW4-EW3	40	145
EW2-EW1	-50	225
EW2-EW1	50	90

Table 9: Intervals with a grade of 30‰ or above on the main track of the NS line

Interval	Grade (‰)	Length of grade section (m)
NS27-NS26	-50	225
NS26-NS25	47	295
NS25-NS24	55	150
NS24-NS23	-54	370
NS23-NS22	-46	420.171
NS23-NS22	55	326
NS22-NS21	-46	615
NS21-NS20	-48.866	107
NS20-NS19	-55	280
NS19-NS18	46	165
NS17-NS16	-46	155
NS16-NS15	-47	160
NS15～NS14	-43	72
NS14-NS13	-55	142
NS12-NS11	50	185
NS12-NS11	45	185
NS12-NS11	42	155
NS12-NS11	-40	130
NS12-NS11	-50	110
NS10-NS9	-47	103
NS10-NS9	-44	258
NS9-NS8	-50	130
NS8-NS7	-40	115

Now let's see some numerical value for the braking distance. To find the braking distance we need the speed when the brake applies to the train. The range of the speed in the AA-LRT is from 20km/h to 70km/h. But in some track lines, the speed is not as those ranges. For instance, there is a restricted speed when the track involves a curve, level crossing or due to any other special case. (For detail values see on the tables of Appendix A).

Here is the calculation of the braking distance between some selected stations using the formula of equation 4.4. But, this may not indicate for the whole section, instead, it is for some part of the given section (block). The blocks used here are selected based on the length of the block, which have a big effect on the calculation of headway time and synchronization of trains.

- For EW22-EW21 here u = 50km/h = 13.889m/s, α = -55/1000, the speed is restricted to 50km/h due to the curve in between the stations.

  $s = (-u^2)/(2(a - g\tan\alpha))$ = - $(13.889)^2$/ [2(-1-9.8tan (-0.055))] = 97.368m

- EW15-EW14 here u = 60km/h = 16.6667m/s, α = -49/1000, the speed is restricted to 60km/h due to the curve in between the stations.

  $s = (-u^2)/(2(a - g\tan\alpha))$ = - $(16.6667)^2$/[2(-1-9.8tan(-0.049))] = 140.208m

- EW2-EW1(up direction) here u = 70km/h = 19.4444m/s, α = 50/1000, here it has no restricted speed hence we can take the operated speed i.e. 70km/h

  $s = (-u^2)/(2(a - g\tan\alpha))$ = - $(19.4444)^2$/[2(-1-9.8tan(0.050))] = 187.4393m

- EW1-EW2 (down direction) here u = 70km/h = 19.4444m/s, α = -50/1000, here it has no restricted speed hence we can take the operated speed i.e. 70km/h

  $s = (-u^2)/(2(a - g\tan\alpha))$ = - $(19.4444)^2$/[2(-1-9.8tan(-0.050))] = 190.665m

Similarly, for u = 20km/h, s = 15.565m

for u = 30km/h, s = 35.02m

for u = 45km/h, s =78.795m

for u = 55km/h, s = 117.71m

- EW19-EW20 here, u = 60km/h = 19.444m/s, α = -55/1000, the speed is restricted to 60km/h due to the curve in between the stations.

  $s = (-u^2)/(2(a - g\tan\alpha))$ = - $(16.6667)^2$/[2(-1-9.8tan(-0.055))] = 140.21m

  Similarly, for u = 20km/h, s = 15.578m

  for u = 30km/h, s = 35.050m

  for u = 45km/h, s = 78.864m,

  for u = 55km/h, s = 117.809m

- NS23-NS22 here u = 70km/h = 19.4444m/s, α = -46/1000, here it has no restricted speed hence we can take the operated speed i.e. 70km/h

  $s = (-u^2)/(2(a - g\tan\alpha))$ = - (19.4444)^2/[2(-1-9.8tan(-0.046))] = 190.542m

- NS16-NS15 here u = 20km/h = 5.5556m/s, α = -47/1000, the speed is restricted to 20km/h due to the curve involvement in that station.

  $s = (-u^2)/(2(a - g\tan\alpha))$ = - (5.55556)^2/ [2(-1-9.8tan (-0.047))] = 15.557m

- NS12-NS11 (upward direction) here u = 45km/h = 12.5m/s, α = 45/1000, the speed is restricted to 45km/h due to the curve involvement in that station.

  $s = (-u^2)/(2(a - g\tan\alpha))$= - (12.5)^2/ [2(-1-9.8tan (0.045))] = 77.528m

- NS11-NS12 (downward direction) here u = 45km/h = 12.5m/s, α = -45/1000, the speed is restricted to 45km/h due to the curve involvement in that station.

  $s = (-u^2)/(2(a - g\tan\alpha))$ = - (12.5)^2/ [2(-1-9.8tan (-0.045))] = 78.731m

Similarly, for u = 20km/h, s = 15.552m

for u = 30km/h, s = 34.99m

for u = 55km/h, s = 117.61m

for u = 70km/h, s = 190.5m

Those braking distance calculations are the minimum possible distance for the maximum possible operated speed. In the AA-LRT a minimum of one empty block must separate for consecutive trains. To do so, these blocks must be long enough for the braking distance plus a safety distance. So, when we compare the distance between stations and the braking distance, the braking distance is much shorter than the distance between any stations, hence, this criterion is fulfilled.

4.1.6 Headway Time

In its simplest case, headway time is the time gap between two consecutive trains running to the same direction through the same rail line. Hence to protect any collision, theoretically, those two trains must be separated by at least the braking time plus the length of the train ahead.

That is: $H = \frac{s + L}{V}$ …………… Equation 4.5

Where: H = headway time s = the braking distance

L = the length of the train V = speed of the train.

But, using only this headway time has many risks, in case, the train ahead is suddenly stopped it can collide with the train following it and even it is impossible to design signals with this minimum headway time. To solve this problem the two trains running consecutively must have a gap time (separation distance of at least one section) called headway time to avoid any collision and to reduce delays in the process.

Hence, the designed headway time is a function of Block (section) length, Operating speed, Station dwells, Train length and, Operating margin time.

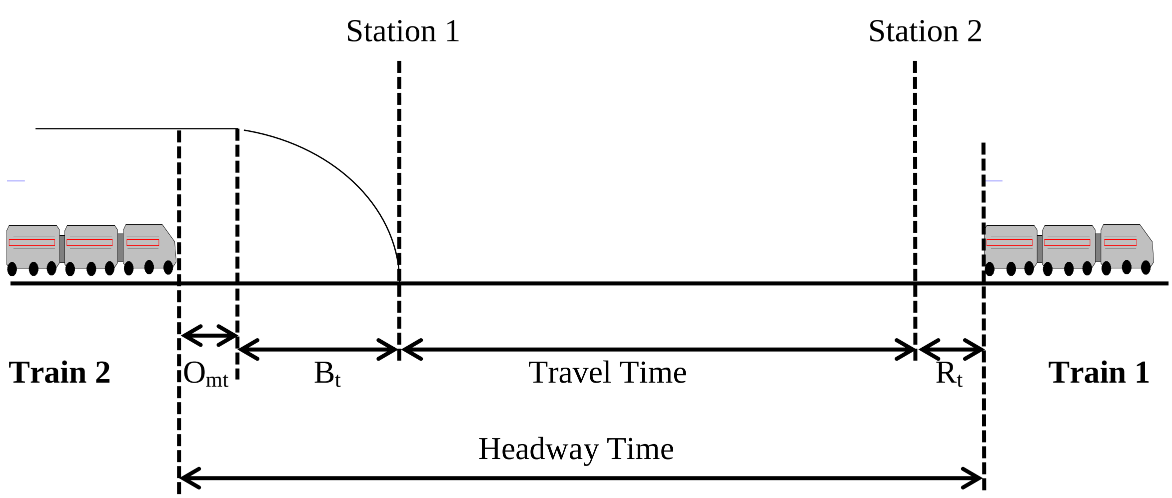

Figure 9: Diagram indicating the headway time components

So that the headway time is given by the following formula according to of the ERTMS and after calculating the headway time for each section (signals) we will take the maximum headway time from those individual headways. So for our case in AA-LRT, the headway between all consecutive pair of stations is calculated as follows [14].

$$H_t = T_t + B_t + R_t + D_t + O_{mt} \quad \ldots\ldots\ldots\ldots\ldots \quad \text{Equation 4.6}$$

Where:- H_t = Headway Time T_t = Travel Time between two consecutive stations

B_t = Braking Time R_t = Release Time

D_t = Dwell Time O_{mt} = Operating Margin Time

Notations: In this part some notations are used. Those are capital letters followed by a subscript small letter and a subscript number. Their indication is that the letters are abbreviations for some terms according to the subtopic discussed and the subscript numbers are represented for speeds. For instance, T_{t45} the T_t is for Travel time and the 45 is for traveling speed at 45km/h.

Now let's see all elements one by one to obtain the required headway via mathematical formulas.

Travel Time (T_t): - It is the time taken to cover one section that is to travel from one station to the next station. Hence, the total time is given as, $T_t = \text{Distance}/\text{Average speed}$

To find the numerical values we will consider all the [maximum, average and minimum] values of speed and the distance. In AA-LRT the operating speed ranges from 20-70km/h, the distance between stations for NS-line are [longest, average, shortest] given as [1972, 738.289, 445m] and for the EW-line are [longest, average, shortest] given as [1260, 761.928, 445m] using those distances let's calculate the possible travel time. To calculate the possible headway time this thesis considers the two lines (NS and EW line) independently and even the common line is considered explicitly. So that, the governed headway time can be found in common line or in the other two lines.

For NS Line

$T_{average}$ = average distance/average speed = 738.3m/45kmph = 59.1 seconds = 0.984 minutes

$T_{shortest}$ = shortest distance/ maximum speed = 445m/70kmph = 22.89 seconds = 0.381 minutes

Based on the different case the speed can be varied but the distance between stations is already fixed. Again let's see some travel time values for some selected speeds. Here, since we are concerned for the maximum governed headway, let's seek for the travel time using the maximum and average distances between the stations. Accordingly let's calculate the travel time for speeds of 20,30,45,55 and 70km/h, using the longest and average distances between the stations of NS-line.

Travel time using the longest distance:

- T_{20} = 1972m/20kmph = 1972/5.5556 = 354.9571 seconds = 5.9159 minutes
- T_{30} = 1972m/30kmph = 1972/8.3333 = 236.64 seconds = 3.994 minutes

- T_{45} = 1972m/45kmph = 1972/12.5 = 157.76 seconds = 2.629 minutes
- T_{55} = 1972m/55kmph = 1972/15.2778 = 129.076 seconds = 2.151 minutes
- T_{70} = 1972m/70kmph = 1972/19.4444 = 101.417 seconds = 1.690 minutes

Again let's see using the Average distance between Stations

- T_{20} = 738.289m/20kmph = 738.289/5.5556 = 132.8909 seconds = 2.215 minutes
- T_{30} = 738.289m/30kmph = 738.289/8.3333 = 88.595 seconds = 1.477 minutes
- T_{45} = 738.289m/45kmph = 738.289/12.5 = 59.0630 seconds = 0.984 minutes
- T_{55} = 738.289m/55kmph = 738.289/15.2778 = 48.3243 seconds = 0.805 minutes
- T_{70} = 738.289m/70kmph = 738.289/19.4444 = 37.969 seconds = 0.6328 minutes

For EW Line

With similar procedure as for NS-line, let's find the typical values for the EW-line

$T_{longest}$ = longest distance/lowest speed = 1260m/20kmph = 226.789 seconds = 3.780 minutes

$T_{average}$ = average distance/average speed = 761.928m/45kmph = 60.954 seconds = 1.016 minutes

$T_{shortest}$ = shortest distance/ maximum speed = 445m/70kmph = 22.89 seconds = 0.381minutes

Again, let's calculate the travel time for speeds of 20,30,45,55 and 70km/h, using the longest and average distances between the stations of EW-line.

- T_{20} = 1260m/20kmph = 1260/5.5556 = 226.789 seconds = 3.780 minutes
- T_{30} = 1260m/30kmph = 1260/8.3333 = 151.20 seconds = 2.520 minutes
- T_{45} = 1260m/45kmph = 1260/12.5 = 100.8 seconds = 1.68 minutes
- T_{55} = 1260m/55kmph = 1260/15.2778 = 82.473 seconds = 1.375 minutes
- T_{70} = 1260m/70kmph = 1260/19.4444 = 64.801 seconds = 1.080 minutes

Again let's see using the Average distance between stations which is 761.928m

- T_{20} = 761.928m/20kmph = 761.928/5.5556 = 137.1459 seconds = 2.286 minutes
- T_{30} = 761.928m/30kmph = 761.928/8.3333 = 91.432 seconds = 1.524 minutes
- T_{45} = 761.928m/45kmph = 761.928/12.5 = 60.954 seconds = 1.016 minutes
- T_{55} = 761.928m/55kmph = 761.928/15.2778 = 49.872 seconds = 0.831 minutes
- T_{70} = 761.928m/70kmph = 761.928/19.4444 = 39.185 seconds = 0.653 minutes

For the Common Line

In the common line there are five stations and the distance between each station is as follows: [EW16-EW17-EW18-EW19-EW20]=[445-560-688-735] meters respectively and their average distance is 607meteres. Based on this data let's consider some typical values.

$T_{longest}$ = longest distance/lowest speed = 735m/20kmph = 132.299 seconds = 2.205 minutes

$T_{average}$ = average distance/average speed = 607m/45kmph = 48.56 seconds = 0.809 minutes

$T_{shortest}$ = shortest distance/ maximum speed = 445m/70kmph = 22.89 seconds = 0.381 minutes

Again let's calculate the travel time for speeds of 20,30,45,55 and 70km/h, using the longest and average distances between the stations of the common line-line.

Using the longest distance between stations which is 735m, the following results are obtained.

- T_{20} = 735m/20kmph = 735/5.5556 = 132.299 seconds = 2.205 minutes
- T_{30} = 735m/30kmph = 735/8.3333 = 88.20 seconds = 1.470 minutes
- T_{45} = 735m/45kmph = 735/12.5 = 58.8 seconds = 0.98 minutes
- T_{55} = 735m/55kmph = 735/15.2778 = 48.109 seconds = 0.802 minutes
- T_{70} = 735m/70kmph = 735/19.4444 = 37.80 seconds = 0.63 minutes

Using the average distance between stations which is 607m

- T_{20} = 607m/20kmph = 607/5.5556 = 109.259 seconds = 1.821 minutes
- T_{30} = 607m/30kmph = 607/8.3333 = 72.840 seconds = 1.214 minutes
- T_{45} = 607m/45kmph = 607/12.5 = 48.56 seconds = 0.809 minutes
- T_{55} = 607m/55kmph = 607/15.2778 = 39.731 seconds = 0.662 minutes
- T_{70} = 607m/70kmph = 607/19.4444 = 31.217seconds = 0.520 minutes

Release Time (R_t): After the train make some dwell at a station and then it starts traveling. Then the release time is the time required for the entire length of a train to cross a signal at a station. Mathematically it is given as: $\text{Release time} = \text{Length of the train/Speed}$

Now to find the release time for the case of AA-LRT this thesis considers the maximum possible length of the train (i.e. considering the worst case), which is found when two trains are coupled. Hence, they make a total length of about 59 meters.

Hence R_t = 59m/speed, now let's see some numerical value for selected speeds of 20, 30.45, 55,70km/h

- R_{t20} = 59m/20kmph = 59/5.5556 = 10.620 seconds
- R_{t30} = 59m/30kmph = 59/8.333 = 7.080 seconds
- R_{t45} = 59m/45kmph = 59/12.5 = 4.72 seconds
- R_{t55} = 59m/55kmph = 59/15.2778 = 3.862 seconds
- R_{t70} = 59m/70kmph = 59/19.4444 = 3.034seconds

Braking Time (B_t)

This time is the time taken by the train to cover the braking distance after the driver applies the brake when approaching to the station. Mathematically it is given as:

$$B_t = \text{Braking distance/Speed}$$

To see numerical values lets calculate the braking time in between two stations having the longest distance. The braking time to find here is the maximum braking time found in between the sample stations using the allowed maximum speed.

For NS Line

- B_{t20} = 15.553m/5.5556ms^{-1} = 2.80 seconds this is the braking time between stations of NS11-NS12 with a speed of 20km/h
- B_{t30} = 34.99m/8.3333ms^{-1} = 4.199 seconds this is the braking time between stations of NS11-NS12 with a speed of 30km/h
- B_{t45} = 78.731m/12.5ms^{-1} = 6.298 seconds this is the maximum braking time between stations of NS11-NS12
- B_{t55} = 117.61m/15.2778ms^{-1} = 7.698 seconds this is the braking time between stations of NS11-NS12 with a speed of 55km/h
- B_{t70} = 190.5m/19.444ms^{-1} = 9.798 seconds this is the braking time between stations of NS11-NS12 with a speed of 70km/h
- B_{t70} = 190.542m /19.444ms^{-1} = 9.79 seconds this is the braking time between stations of NS23-NS22

For EW-line

- B_{t20} = 15.565m/5.5556ms^{-1} = 2.801 seconds this is the braking time between stations of EW1-EW2 with a speed of 20km/h
- B_{t30} = 35.05m/8.3333ms^{-1} = 4.21 seconds this is the braking time between stations of EW1-EW2 with a speed of 30km/h
- B_{t45} = 78.795m/12.5ms^{-1} = 6.304 seconds this is the braking time between stations of EW1-EW2 with a speed of 45km/h
- B_{t55} = 117.71m/15.2778ms^{-1} = 7.705 seconds this is the braking time between stations of EW1-EW2 with a speed of 55km/h
- B_{t70} = 190.665m /19.444ms^{-1} = 9.81 seconds this is the braking time between stations of EW1-EW2 with a speed of 70km/h
- B_{t60} = 140.208m /16.6667ms^{-1} = 8.41 seconds this is the braking time between stations of EW1-EW2 with a speed of 60km/h

For the common line

- B_{t20} = 15.578m/5.5556ms^{-1} = 2.804 seconds this is the braking time between stations of EW19-EW20 with a speed of 20km/h
- B_{t30} = 35.050m/8.3333ms^{-1} = 4.21 seconds this is the braking time between stations of EW19-EW20 with a speed of 30km/h
- B_{t45} = 78.864m/12.5ms^{-1} = 6.309 seconds this is the braking time between stations of EW19-EW20 with a speed of 45km/h
- B_{t55} = 117.809m/15.2778ms^{-1} = 7.711 seconds this is the braking time between stations of EW19-EW20 with a speed of 55km/h
- B_{t70} = 190.83m /19.444ms^{-1} = 9.81 seconds this is the braking time between stations of EW19-EW20 with a speed of 70km/h

Dwell Time (D_t): As figure 9 on page 44 indicates, to find the possible headway it involves two stations. So that, those stations are considered in finding the headway. For instance, the stations having the maximum distance in between them are to be taken their dwell time. To be specific the maximum distance is found in NS11-NS12, EW1-EW2 and EW19-EW20 for all the three sections and their average dwell time is taken as 30 seconds and hence 60 seconds in two consecutive stations (refer figure 9 on page 44).

Operating Margin Time (O_{mt}): This time is the constant time in which the train spends for the reaction time to give commands (e.g. to apply the brake). The constant time is set by the infrastructure managers and most of the time it is a small number. Numerically 5-10 seconds. For AA-LRT it has about duration of 7 seconds.

Headway Time: now we are at a point of finding the required headway at different sampled stations and using different sampled speeds based on the calculations of the main elements of the headway in the above subtopics.

In the NS Line: For the longest distance with speeds of 20,30,45,55 and 70km/h, the headway becomes

$H_{t20} = T_{t20} + B_{t20} + R_{t20} + D_t + O_{mt}$ =132.891 + 2.800 +10.620+60+7 = 435.377 sec = 7.26minutes

$H_{t20} = T_{t20} + B_{t20} + R_{t20} + D_t + O_{mt}$ = 132.891 + 2.800 +10.620+60+7 = 435.377 sec = 7.26minutes

$H_{t30} = T_{t30} + B_{t30} + R_{t30} + D_t + O_{mt}$ = 236.640 + 4.19 + 7.080+60+7 =307.839 sec = 5.13minutes

$H_{t45} = T_{t45} + B_{t45} + R_{t45} + D_t + O_{mt}$ = 157.760 + 6.298 + 4.72+60+7 = 235.778 sec = 3.93minutes

$H_{t55} = T_{t55} + B_{t55} + R_{t55} + D_t + O_{mt} =$ 129.076 + 7.698 + 3.862+60+7 = 207.636 sec = 3.46minutes

$H_{t70} = T_{t70} + B_{t70} + R_{t70} + D_t + O_{mt} =$ 101.417 + 9.798 + 3.034+60+7 =181.249 sec = 3.02minutes

In the EW Line: For the longest distance with speeds of 20,30,45,55 and 70km/h

$H_{t20} = T_{t20} + Bt20 + R_{t20} + D_t + O_{mt}$ = 226.79 + 2.801 + 10.620 + 60 +7=307.21 sec = 5.12 minutes

$H_{t30} = T_{t30} + B_{t30} + R_{t30} + D_t + O_{mt}$ = 151.20 + 4.210 + 7.080 + 60 + 7 = 229.49 sec = 3.83 minutes

$H_{t45} = T_{t45} + B_{t45} + R_{t45} + D_t + O_{mt}$ = 100.80 + 6.304 + 4.720 + 60 + 7 = 178.83 sec = 2.98 minutes

$H_{t55} = T_{t55} + B_{t55} + R_{t55} + D_t + O_{mt}$ = 82.473 + 7.705 + 3.862 + 60 + 7 = 161.04 sec = 2.69 minutes

$H_{t70} = T_{t70} + B_{t70} + R_{t70} + D_t + O_{mt}$ = 64.801 + 9.810 + 3.034 + 60 + 7 = 144.65 sec = 2.41 minutes

In the Common Line: For the longest distance with speeds of 20,30,45,55 and 70km/h are considered in the common line. The stations from EW16 to EW20 are the common lines for the trains coming from two independent directions. Hence in this intersection route the headway time is reduced by half because it involves trains coming from different routes. Due to this clear reason the headway found in calculation using the characteristics of the common line must be doubled.

$H_{t2o}= T_{t20} + B_{t20} + R_{t20}+ D_t + O_{mt}$ = 132.30 + 2.81+10.62 + 60 + 7 = 212.723sec = 3.55 minutes

Note: the headway in this line must be doubled hence 3.55×2→7.1 minutes

$H_{t30}= T_{t30} + B_{t30} + R_{t30}+ D_t + O_{mt}$ = 88.20+4.21+ 7.08+60+7=166.49sec = 2.775×2→5.55minutes

$H_{t45}= T_{t45} + B_{t45} + R_{t45}+ D_t + O_{mt}$ = 58.80+6.31+ 4.72+60+7=136.829sec =2.28×2→4.56 minutes

$H_{t55}= T_{t55} + B_{t55} + R_{t55}+ D_t + O_{mt}$ = 48.80+7.71+ 3.86+60+7=127.37sec = 2.123×2→4.25minutes

$H_{t70} = T_{t70} + B_{t70} + R_{t70}+ D_t + O_{mt}$ =37.80+9.81+ 3.04+60+7 =117.65sec = 1.96×2→3.92 minutes

Conclusion: The above-calculated headway values are classified into three different parts. That is headway in the common line, headway in the other parts of NS-line as well as on the other parts of EW line. In both the EW and NS lines a common headway must be used due to the following two reasons. The first reason is that since both lines use a common line so that to share this common line uniformly for trains' coming from different lines they should come with uniform frequency. So, that to come with uniform frequency trains coming from different lines toward the common line must have a common headway but, they should be synchronized properly.

The second reason is that having a common headway has some advantages. To mention having a common headway helps to use the common synchronizing method, to have a uniform way of designing the timetable, to have uniform allocating resources, to use similar speeds in both lines, etc. So, that to own those advantage the calculated headway on the three different parts (common line, EW line and NS line) is already given in the above section. Now, to be safe in any circumstance it is a must to take the maximum calculated headway from all the three parts. Comparing the headways calculated in the above section according to the sampled speeds, the maximum headway is to be taken in order to be safe throughout the lines (see the double underlined headway values for each part found above); it will be found as follows.

H_{t20} = 7.26 minutes H_{t30} = 5.55 minutes H_{t45} = 4.56 minutes

H_{t55} = 4.25 minutes H_{t70} = 3.92 minutes

Hence, the recommended headways for the AA-LRT for the speeds of 20, 30, 45, 55, and 70km/h are 7.26, 5.55, 4.56, 4.25 and 3.92 minutes respectively. These headways are the maximum calculated values from all the three parts (the common line, EW line and NS line). For a matter of simplification (easily handling the numbers) let's approximate the headways to the next higher integer i.e. to 8, 6, 5, 5, and 4 minutes for H_{t20}, H_{t30}, H_{t45}, H_{t55}, and H_{t70} respectively. Here the most interesting part is that the headway found in all the three parts are close to each other although the dominant part is from the calculated headways of the common line. Since all headways calculated from the three parts are close to each other this can be taken as another encouragement for using a common headway for all the lines.

4.1.7 Capacity

Here in this thesis capacity refers to two things, though they are related to each other. Those are Train capacity and Line Capacity.

Train Capacity: The maximum number of passengers in a train. If two trains are coupled together the number of passengers will be doubled. Mathematically it is given as:-

Number of passengers = Number of passenger seats + valid standing area in the train × allowable number of standing persons per m^2

For the case of AA-LRT, a train has a capacity of 317 passengers in total. Specifically, each train has 65 seats and 6 persons/m^2 for standings.

Line Capacity: Line capacity refers to the maximum number of trains that can be operated over a line in a peak hour that is in one direction on a single track. Mathematically it is given as

$$L_c = \frac{60}{H_t} \qquad \text{…………} \qquad \text{Equation 4.7}$$

Where: L_c = Line Capacity H_t = Headway time in minutes

Based on the headway we found earlier the possible maximum number of trains will be as follows based on their speed.

$L_{c20} = 60/H_{t20} = 60/8 = 7.5$trains, Lc30 = $60/H_{t30} = 60/6 = 10$trains, $L_{c45} = 60/H_{t45} = 60/5 = 12$trains

$L_{c55} = 60/H_{t55} = 60/5 = 12$trains, $L_{c70} = 60/H_{t70} = 60/4 = 15$trains

Those trains are for a single direction only. So, for both directions, the number of trains should be doubled i.e. the number of trains in one depot (at Kality or Ayat) should be as follows:

L_{c20} =15 trains, Lc30 = 20trains, L_{c45} = 24trains, L_{c55} = 24trains and L_{c70} = 30trains

Design Passengers Capacity: The maximum number of passengers in a train traveled past a single point in an hour, in one direction on a single track.

$$C_{DP} = C_L \times C_T \qquad \text{………… Equation 4.8}$$

Where: C_{DP} = Design Passengers Capacity (p/h);

C_L = Line Capacity (trains/h)

C_T = Train Capacity (p/train).

In practice, part of the infrastructure capacity must also be reserved for traffic control to manage disruptions.

Now let's see numerically for the nominated speeds.

- $C_{DP20} = C_L \times C_{T20} = 7.5 \times 317 = 2377$passenges/h
- $C_{DP30} = C_L \times C_{T30} = 10 \times 317 = 3170$passenges/h
- $C_{DP45} = C_L \times C_{T45} = 12 \times 317 = 3804$passenges/h
- $C_{DP55} = C_L \times C_{T55} = 12 \times 317 = 3804$passenges/h
- $C_{DP70} = C_L \times C_{T70} = 15 \times 317 = 4755$passenges/h

This number will be doubled when two trains are coupled together. Furthermore to find the total passengers traveled in one hour in all directions it will be multiplied by four. And then to find total passengers travel in a day it will be multiplied by 16 (the service hours per a day).

4.1.8 Travel Time

Travel time is defined as the time taken to complete a given trip. As the speed increases, travel time required to reach the destination also decreases and vice-versa. Hence, travel time is inversely proportional to the speed. However, in practice, the speed of a train fluctuates over time and the travel time represents an average measure. Additionally, the travel time includes the time spent on the stations i.e. the dwell times. So the total travel time is given as:

$T = T_d + \frac{S}{V}$ where: T = total travel time from origin station to final destination station

S = the distance from the origin station to destination station.

T_d = the total dwell time of all stations, V = the average speed

To see numerical values: T_d = sum of all dwell times from origin stations to destination equals 11 minutes.

For NS-Route for Average Speeds of 20, 30, 45, 55 and 70km/h

- $T_{20} = T_d + S_{total}/V_{ave}$ = 11 minutes + 16.9km/20kmph = 11 + 50.7 = 61.7 minutes
- $T_{30} = T_d + S_{total}/V_{ave}$ = 11 minutes + 16.9km/30kmph = 11 + 33.8 = 44.8 minutes
- $T_{45} = T_d + S_{total}/V_{ave}$ = 11 minutes + 16.9km/45kmph = 11 + 22.5 = 33.5 minutes
- $T_{55} = T_d + S_{total}/V_{ave}$ = 11 minutes + 16.9km/55kmph = 11 + 18.5 = 29.5 minutes
- $T_{70} = T_d + S_{total}/V_{ave}$ = 11 minutes + 16.9km/70kmph = 11 + 14.5 = 25.5 minutes

For EW-Route for Average Speeds of 20, 30, 45, 55 and 70km/h

- $T_{20} = T_d + S_{total}/V_{ave}$ = 11 minutes + 17.35km/20kmph = 11 + 52.1 = 63.1 minutes
- $T_{30} = T_d + S_{total}/V_{ave}$ = 11 minutes + 17.35km/30kmph = 11 + 34.7 = 45.7 minutes
- $T_{45} = T_d + S_{total}/V_{ave}$ = 11 minutes + 17.35km/45kmph = 11 + 23.1 = 34.1 minutes
- $T_{55} = T_d + S_{total}/V_{ave}$ = 11 minutes + 17.35km/55kmph = 11 + 19 = 30 minutes
- $T_{70} = T_d + S_{total}/V_{ave}$ = 11 minutes + 17.35km/70kmph = 11 + 14.9 = 25.9 minutes

4.1.9 Synchronizing Train Departure/Arrival

When trains from different track lines share part of their routes, their departure times should be synchronized to offer a higher frequency service on that common part and to reduce a possible waiting delay at the entrance of the common line. In this thesis the common line for the NS and EW line from Stadium station to St.Lideta station (or the reverse direction). As an example, if those two train routes have a headway time of 't' time at the separate route, then they will have headway time of half of 't' (t/2) at the common line if they are well synchronized. Synchronization can also be applied to spread the multiple trains of the common line evenly across the cycle time.

To synchronize the trains (say in the up direction), trains coming from Kality and Ayat must use the common line when they arrive at the Stadium station. So that, those trains should have half of the scheduled headway time to the other uncommon routes after they enter the common line. To put the specific synchronization time the time taken in which the train arrives at the stadium must be calculated based on the distance from both depots to the Stadium station. For the train starting traveling from Ayat towards Torhailoch, to find its time taken to reach at stadium station is given as:

$t = \frac{S}{v} + d_t$ where: S = Total distance from Ayat station to Stadium station

v = Speed of the train, d_t = Total dwell time at all station from Ayat to Stadium

Similarly, for the train starting traveling from Kality towards Menelik II square, to find its time taken to reach stadium station is given as the above formula but, obviously, the stations will be stations from Kality to Stadium and hence there will be a difference on distance covered and total dwell times.

Numerical Examples: These numerical examples will be used as an input to the simulation model provided in the next chapter, chapter 5.

For the Upward Direction: The time taken from Ayat to Stadium, using the formula (given in section 4.1.8: Travel Time), the total distance from Ayat to stadium is about 13km and the total dwell time in between this line is 8minutes hence the time taken for the selected speeds will be:-

- $T_{20} = T_d + S_{total}/V_{ave}$ = 8 minutes + 13km/20kmph = 8 + 39 = 47 minutes
- $T_{30} = T_d + S_{total}/V_{ave}$ = 8 minutes + 13km/30kmph = 8 + 26 = 34 minutes
- $T_{45} = T_d + S_{total}/V_{ave}$ = 8 minutes + 13km/45kmph = 8 + 17.3 = 25.3 minutes
- $T_{55} = T_d + S_{total}/V_{ave}$ = 8 minutes + 13km/55kmph = 8 + 14.2 = 22.2 minutes
- $T_{70} = T_d + S_{total}/V_{ave}$ = 8 minutes + 13km/70kmph = 8 + 11 = 19 minutes

Time Taken from Kality to Stadium: The total distance from Kality to Stadium is about 8.982km and the total dwell time in between this line is 5.5minutes hence the time taken for the selected speeds will be

- $T_{20} = T_d + S_{total}/V_{ave}$ = 5.5 minutes + 8.982km/20kmph = 5.5 + 27 = 32.5 minutes
- $T_{30} = T_d + S_{total}/V_{ave}$ = 5.5 minutes + 8.982km/30kmph = 5.5 + 18.5 = 24 minutes
- $T_{45} = T_d + S_{total}/V_{ave}$ = 5.5 minutes + 8.982km/45kmph = 5.5 + 11 = 16.5 minutes
- $T_{55} = T_d + S_{total}/V_{ave}$ = 5.5 minutes + 8.982km/55kmph = 5.5 + 9.8 = 15.3 minutes

- $T_{70} = T_d + S_{total}/V_{ave}$ = 5.5 minutes + 8.982km/70kmph = 5.5 + 7.7 = 13.2 minutes

Now to synchronize each train coming from both lines to the upward direction, for instance for speed 30km/h the first few trains coming from Ayat arrives at Stadium according the following patterns [with headway of 6minutes (for 30km/h) and assuming the first train starts at 00:00 o'clock]. The patterns are (in minutes):- 34, 40, 46, 52, 58, 64, 70…

Similarly for the first few trains coming from Kality arrives at Stadium according the following patterns [with headway of 6minutes (for 30km/h) and assuming the first train starts at 00:00 o'clock]. The patterns are (in minutes):- 24,30,36,42,48,54,60,66,62,68,74,…..

According to the pattern, the first train coming from Ayat should be arrived earlier than its schedule by one minute on the way to Stadium in order to have 3 minutes headway time in the common route. Hence, the trains coming from Ayat will arrive at Stadium as according to the following patterns(in minutes): 33, 39, 45, 51, 57, 63, 69, 75, 81, 87, 93,… and trains coming from Kality will arrive at Stadium according the following pattern(in minutes):24, 30, 36, 42, 48, 54, 60, 66, 72, 78, 84, 90,…

For the Downward Direction

Time Taken from Torhailoch to St.Lideta: Using the formula in the (section 4.1.8: Travel speed), the total distance from Torhailoch to St.Lideta is about 1.553km and the total dwell time in between this line is 1.5minutes hence the time taken for the selected speeds will be:

- $T_{20} = T_d + S_{total}/V_{ave}$ = 1.5 minutes + 1.553km/20kmph = 1.5 + 4.66 = 6.2 minutes
- $T_{30} = T_d + S_{total}/V_{ave}$ = 1.5 minutes + 1.553km/30kmph = 1.5 + 3.5 = 5 minutes
- $T_{45} = T_d + S_{total}/V_{ave}$ = 1.5 minutes + 1.553km/45kmph = 1.5 + 2 = 3.5 minutes
- $T_{55} = T_d + S_{total}/V_{ave}$ = 1.5 minutes + 1.553km/55kmph = 1.5 + 1.7 = 3.2 minutes
- $T_{70} = T_d + S_{total}/V_{ave}$ = 1.5 minutes + 1.553km/70kmph = 1.5 + 1.3 = 2.8 minutes

Time Taken from Menelik II Square to St.Lideta: The total distance from Menelik II Square to St.Lideta is about 5.3km and the total dwell time in between this line is 4minutes hence the time taken for the selected speeds will be:

- $T_{20} = T_d + S_{total}/V_{ave}$ = 4 minutes + 5.3km/20kmph = 4 + 15.9 = 19.9 minutes
- $T_{30} = T_d + S_{total}/V_{ave}$ = 4 minutes + 5.3km/30kmph = 4 + 11=15 minutes
- $T_{45} = T_d + S_{total}/V_{ave}$ = 4 minutes + 5.3km/45kmph = 4 + 7 = 11 minutes

- $T_{55} = T_d + S_{total}/V_{ave}$ = 4 minutes + 5.3km/55kmph = 4 + 5.8 = 9.8 minutes
- $T_{70} = T_d + S_{total}/V_{ave}$ = 4 minutes + 5.3km/70kmph = 4 + 4.5 = 8.5 minutes

Now to synchronize each train coming from both lines to the downward direction, for instance for speed 30km/h the first few trains coming from Torhailoch arrives at St.Lideta according to the following patterns [with a headway of 6minutes (for 30km/h) and assuming the first train starts at 00:00 o'clock]. The patterns are (in minutes):- 5, 11, 17, 23, 29, 35, 41, 47, 53, 59, 65, 71, 77…

Similarly for the first few trains coming from Menelik II Square arrives at St.Lideta according to the following patterns [with headway of 6 minutes (for 30km/h) and assuming the first train starts at 00:00 o'clock]. The patterns are (in minutes):- 15, 21, 27, 33, 39, 45, 51, 57, 63, 69, 75, 81, 87…

According to the pattern, the first train coming from Menelik II square should be arrived earlier than its schedule by one minute on the way to St.Lideta in order to have 3minutes headway time in the common route. Hence, the trans coming from Menelik II Square will arrive at St.Lideta as according to the following patterns (in minutes): 14, 20, 26, 32, 38, 44, 50, 56, 62, 68, 74, 80, 86, 92… and trains coming from Torhailoch will arrive at St.Lideta according the following pattern (in minutes): 5, 11, 17, 23, 29, 35, 41, 47, 53, 59, 65, 71, 77...so on. Similarly, for the other speeds we can find the corresponding arrival time patterns using the same procedure.

4.2 Comparisons between Parameters of the Current and Calculated Timetables

The calculations done in this chapter are based on the standard formulas, such as the braking distance, time, speed, line capacity and the headway. To design the safety block (refer figure 9) it is based on the standard methods especially used on ERTMS systems. Hence as far as the standard ways are used, the calculation results are valid. Moreover, since those calculated values are used as input for the simulations done in chapter 5, the output gives valid results.

Currently, the trains of the AA-LRT travels at a speed close to 20km/h, with a headway 15 minutes in the peak hours, but according to the details stated above, the headway can be reduced to 7.26 minutes for the peak ours. Additionally, if we want to reduce this headway time we must increase the speed of the train according to the headway we want to have.

According to the peak hours, headway time of the current AA-LRT the line capacity is only 4 trains. But practically, every train is overcrowded usually by the passengers; this indicates a mismatch between passengers and the number of trains. Hence to reduce the overcrowding, it is required to increase the number of trains consequently, the line capacity will be increased. By increasing the line capacity it needs to decrease the headway time. So that, to achieve these requirements increasing the speed may seem the only solution. But, the calculated values of the previous sections suggested that without increasing the speed we can improve the headway time to some extent and consequently a lot of parameters can be improved such as the line capacity, waiting time of passengers, dwell time, travel time, etc.

As an example, with this current speed (i.e. 20km/h) the current timetable has headway time of 15 minute and hence the line capacity is 4 trains per hour for a single line and direction. With the same speed, the headway can be reduced to 8 minutes and the line capacity can be increased to 7.5 trains per hour for a single direction [see the detail calculations on the previous sections]. So, due to those modifications, the waiting time of passengers can be reduced and the overcrowded can be reduced by the increase of frequency and the number of trains (i.e. line capacity). To improve beyond this, the speed must be increased. Consequently, most of the problems can be solved (minimized) further.

Table 10: Comparisons between parameters of the current and calculated timetables

Speed (km/h)	Current Values		New Values	
	Headway Time (min)	Line Capacity (Number of Trains in 1 hr. for one route)	Headway Time (min)	Line Capacity (Number of Trains in 1 hr. for one route)
20	15	8	7.26	15
30	-	-	5.55	20
45	-	-	4.56	24
55	-	-	4.25	24
70	-	-	3.92	30

The main cause for the difference on some parameters between the current and calculated parameters is that the current timetable doesn't use optimal values according to the speed it uses.

Such as the headway, synchronization, travel time, braking distance, line capacity etc. These parameters are already modified even if for the same speed (see table 10 above). Hence, an easy task of comparisons can be made between parameters currently used and the calculated ones.

Another point is that the synchronizations of trains. In the current timetable when two trains coming from different directions towards the common line, often they meet each other at Stadium and St.Lideta, so that one train must wait for some minutes until the section ahead is free. This indicates as the synchronization of the train is not correctly implemented. Hence, one solution for this occurrence is presented in detail in section 4.1.9 above.

Apart from the current timetable, the expected headway for the future time is 6 minutes with a capability of reducing to 90 seconds. Hence, according to the calculated results the 6-minute headway can be achieved when the speed is close to 30km/h but the headway of 90 seconds seems impossible to achieve with a range of speed from 20-70km/h. With the maximum operated speed i.e. 70km/h, the minimum possible headway is 3.92minutes. If we consider the headway of 90 seconds, at the common line the headway will be halved i.e. 45 seconds. But, some sections (blocks) in the common line require more than 45 seconds for traveling even by the maximum operated speed. Again, outside of the common lines a lot of blocks (sections) require more than 90 seconds to travel even with the highest possible speed. Hence reducing the headway to 90 seconds is not feasible unless collision or unwanted waiting time can happen. But why the design engineers say the headway can reduce to 90s? The reason behind this is that, because it was planned before the design is completed but in the process there are some changes, to mention the operating speed was decreased and the distance between stations becomes more non-uniform than it was planned before the railway design was begun.

Finally, after calculating the values of the main parameters a comparison between the existing and calculated parameters is done. Hence, the result indicates that the main parameters to design the timetable depends on speed and for a different speed, different values of the parameters can be achieved. That is why most of the calculations on the previous sections are done based on some selected speeds. Hence, a decision can be made by comparing between one speed (and its calculated parameters) on one side and on another speed (and its calculated parameters) on the other side. Further, the effect of all these parameters is clearly seen on the output of the Arena simulating software discussed in chapter 5.

CHAPTER FIVE

Simulation Result and Discussion

In this chapter, the results found in chapter 4 are to be used as inputs to the simulation model and then detail discussions are presented based on the output of the simulation result.

5.1 Software Used

There are software models like RailSys, Open Track, DONS and many others used to design a train timetable. Therefore, here for designing, the software called Arena is used. Because it has a lot of applications in transportation modeling system (see next sections) also it is easy to understand and to work with it. Additionally, it has free version software although the free version has some limitations.

5.1.1 Introduction to Arena Software

Arena is discrete event simulation and automation software developed by systems modeling and acquired by Rockwell Automation in 2000. It uses the SIMAN processor and simulation language. As of June 2014, it is in version 14.7, providing significant enhancements in optimization and animation.

Arena is an advanced simulation system that provides an interactive environment for building, animating, verifying, and analyzing simulation models. With Arena, a unique Arena template can be designed that is specific to a particular project, company, or industry. The modules have specific actions relative to entities, flow, and timing, the precise representation of each module and entity relative to real-life objects is subject to the modeler. Statistical data, such as cycle time and WIP (work in process) levels, can be recorded and outputted as reports. The Arena template is the core collection of more than 60 modules provided as part of the general Arena system. Generally with Arena software, the following features can be done [6].

- Simulate the future performance of a system to understand complex relationships and identify opportunities for improvement.
- Visualize operations with dynamic animation graphics.
- To model processes to define, document, and communicate.

- ❖ Analyze how the system will perform in its "as-is" configuration and under a countless of possible "to-be" alternatives so that we can confidently choose the best way to run a business.

The Arena software has two types of versions these are commercial software versions and academic software versions. The commercial version of arena software have two types of editions, these are Professional edition and Standard edition. The Academic version of arena software have three types of editions, these are Academic Lab package edition, Research edition, and Student Edition. From those all editions, only the Student edition is freely accessed.

Main Properties of Arena

- ❖ It is general-purpose simulation package
- ❖ Process-oriented
- ❖ Highly customizable and flexible but, painfully tedious and error prone)
- ❖ It is high-level simulator
- ❖ It has animations to indicate as how the designed model behaves.
- ❖ Dynamic graphical animation of system components as they move around and change
- ❖ Model building using
    - Drag-and-drop modules from project bar into model window
    - Connect them, so define flow of entities
    - Detail modules and entities in dialog boxes and in spreadsheet window
- ❖ It can run independent replications [6]

5.1.2 Main Parts of the Arena Software Modeling

Project Bar: This has the main panel templates which include the Basic Process panels, Advanced Process panels, Advanced Transfer panels, Block panels, Element panels, Flow process panels, Flow process Util panels, Packaging panels and Util Arena panels. They all contain many block elements and spreadsheet blocks and each panel has block parameters categorized in Flowchart modules and Data modules.

The term flowchart module refers to a module that permits entity flow in and/or out, such as the following modules displayed in Arena's Basic Process panel: Create, Dispose, Process, Decide, Batch, Separate, and Assign. These are the fundamental processing modules that act on entities.

On the other hand, the term data module refers in which entities do not flow into or out of data modules. These data modules are placed to supply information about elements of a simulation model. Data modules in the Basic Process panel include Entity, Queue, Resource, Variable, Schedule, and Set.

While flowchart modules are placed in the model window flowchart and are connected to form a flowchart and describe the logic of the system, data modules are not placed in the model window. Instead, they are edited from a spreadsheet interface [6].

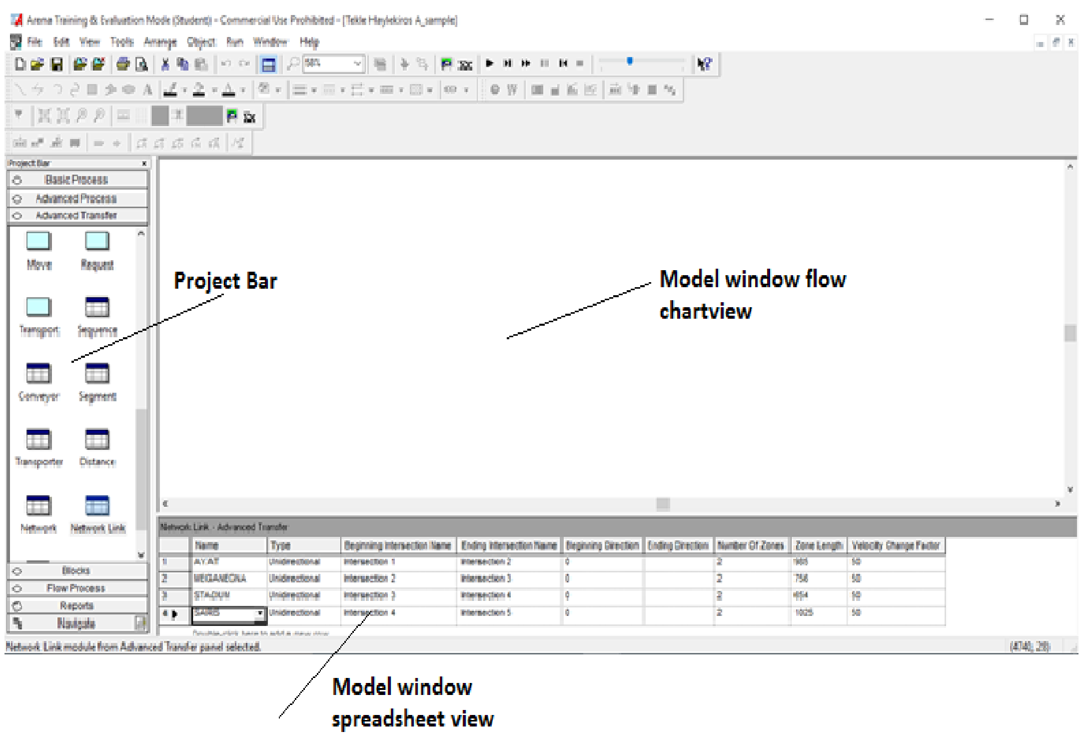

Figure 10: The main parts of Arena software in its start page when opened

Model Window Flowchart: In this area we use for modeling purpose by taking the required module from the Project bar. For example, we can take modules like Create, Process, Dispose, Transport, Station, Request, Free Route, Delay, Signal, Hold etc.

Model Window Spreadsheet View: This spreadsheet view displays model data, such as times, costs, distance, line segments, network, network link and other parameters. Hence based on the designed system it gives the necessary data inputs in order to perform well according to the designed system [6].

Application Areas of Arena Software: Arena software enables to bring the power of modeling and simulation to a business. It is designed for analyzing the impact of changes involving significant and complex redesigns associated with supply chain, manufacturing, processes, logistics, distribution, transportation and warehousing, and service systems. Arena software provides the maximum flexibility and breadth of application coverage to model any desired level of detail and complexity [6].

Typical applications include:

- Analysis of global supply chains that include transportation, warehousing, and logistics systems
- Detailed analysis of any type of manufacturing system, including material-handling components
- Analysis of complex customer service and customer management systems
- Predicting system performance based on key metrics such as costs, throughput, cycle times, and utilizations
- Identifying process bottlenecks such as queue buildups and over-utilization of resources
- Planning staff, equipment, or material requirements.

Performance Measures of Arena Simulation Results

- Total production of a given system
- Average waiting time in queue
- Maximum waiting time in queue
- Time-average number of parts waiting in the queue
- Maximum number of parts that were ever waiting in the queue
- Average and maximum total time in a system
- Utilization

5.2 Simulation Design Using Arena

In this topic, the simulation model, details of the system parameters as well as performance indicators are going to be discussed. The design model used is the arena Rockwell software which has the free version of edition even though with a very limited access.

5.2.1 The Simulation Design

To simulate the model of the AA-LRT it divides into four parts, i.e. one part for each direction (route) of the AA-LRT having the effect of common line in mind. In this section, the design for one route namely for up direction of NS-route is given. For the up direction of EW-route, it is given in the Appendix B. For the remaining directions i.e. the NS-downward and EW-downward directions the simulation design is not given because all the designs are very similar with the already designed of NS-up direction and EW-up direction respectively except the directions and some related cases.

In the simulation design, each block will take input parameters like the resource we use (in this case the track line and number of trains available), the distance between each station, the velocity of the train , the dwell time at each station, the headway, acceleration, deceleration etc.

Table 11: Simulation parameters

Simulation parameters	Typical values for AA-LRT
Speed	operational speed:20-70km/h, for the simulation part 30km/h is used
Headway time	varies according to the speed and typical value of 6 minutes is used
Dwell time	typically 30 seconds
Distance	the distance between each adjacent stations in meters
Resources	the block (section) of the railway line
Type of transporter	has two options: free and guided path, and the guided path is used
Type of queue	first in first out (FIFO)
Acceleration	$1m/s^2$
Deceleration	$1m/s^2$
Number of trains	depends on headway, typically 10 trains for a single line, one direction is used, that is the line capacity
Synchronization time	33 minute for trains coming from Ayat and 24 minutes for trains coming from Kality

After feeding those inputs to the simulation design it gives simulation report. In the simulation report, there is almost all information of the model we designed and based on the report it is possible for further modifications/ improvements of the simulation design. The simulation report includes processing time, total time, a number of trains, queuing time, time delay at stations, efficiency and utilization of the resources etc.

The simulated model is given in Figure 11 on page 68, for up direction of NS route or similarly it is given also in the appendix of Figure 13 on page 83, for up direction of EW-route. Both figure 11 and 13 are snipping sheet of the designed model from the arena software. Further, the main blocks and flow charts used in this design are of two types.

1) Flowchart modules: like Create, Seize, Release, Leave, Enter, Route, Station, Decide and Dispose. In the simulating model the stations of AA-LRT are represented by the Enter module. The Enter model will take the input of dwell time at each station. The distance between the stations to be traveled by the transporters is accessed in the Network and Network Link data modules. When traveling the train, block safety ahead is controlled using the Size and Release modules whether it is occupied or free. If it is occupied, the train will wait at the station until the block ahead is free. The shape and color of the Enter and Leave model are similar and the only difference is in the Leave module there is a blue bar above the block module. Similarly, the shape and color of the Seize and Release model are similar and the only difference is in the Release module there is a blue bar above the block module. The depot is represented by the Create module and the end stations (Torhiloch and Menelik II square stations) are represented by Dispose module. The decide module decides as which entity will go to which train at the common line starting at the St. Lideta station to Stadium station and finally send the train to its destination.
2) Data modules: it includes Entities, Queue, Resources, Network, Network Link and Transporters. Here the Transporter is used to declare the transport type (the train in this case) and to give the permitted speed of traveling. In the Network Link, it accepts inputs of the distance (length) between each station.

Main Elements of the Simulation Design

- ❖ Leave: used to control the train in the system.
- ❖ Enter: represents for stations
- ❖ Seize: uses as a resource, and the resource in this thesis is the rail line (safety block).
- ❖ Release: Used to release the occupied resource (safety block) when the train reaches at this point (at the end of the block).

- ❖ Decide: used to identify the train, whether it is coming from EW or SN.
- ❖ Transporter: Guided path unlike of free path it doesn't depend only on the distance and velocity but also on the traffic of the system.
- ❖ Network: used to give a name to the link between each station.
- ❖ Network Link: used to give the distance between each station.
- ❖ Animated lines: The Zigzag line used to animate the transporters (trains) as how they travel.

5.2.2 Details of the Simulation Design

The student version of the Arena software is free but it has too many restrictions like the number of flow chart modules, a number of elements and number of cinema objects, consequently, in the design of the AA-LRT some parameters gone beyond the limitation of the arena student version. Specifically the number of modules, Resources used, Network Link length, and the type of transporters to design the AA-LRT have been gone beyond the student version of arena software limitation and to buy the full version is too expensive. To solve those big problems the following two cases have been done.

1) The first case is to optimize the available software with its restrictions. Hence after analyzing on the available flow chart models some interesting modules which they can capable of working the task of two or more modules by a single module, such as the Leave and Enter module are found. The Enter module, for instance, is capable of working as a Station module and Exit module simultaneously. The Leave module is also capable of working as a Request module and Transport module simultaneously. The Network Link data module is also used its intersection point for two or more transport types. Based on those criteria the number of flowchart modules and data modules in the model design are minimized as far as possible.
2) Even with these opportunities, still it is not enough for the expected design. And the last option used is to design a single model representing one side and single direction only. That is at the first instance it was supposed to design two models having two routes (NS & EW upward direction and NS & EW downward direction) but, due to the arena limitation it forced to design four independent designs with one route each. But, with a consideration of the common lines as a train may come from the other direction. That is the stations are the

same but with different trains coming from other direction. For instance, the simulation design starts for upward direction of Kality-Menelik II Square route. In the design, the trains coming from Ayat in the upward direction will be joined the system model at the Stadium station after a duration time which takes the train to reach in Stadium station from the Ayat station. Then after, they leave the system when the trains coming from Ayat reaches the St.Lideta station. This analogy works similarly for all the remaining three designs (i.e. for the up and down direction of EW line and for the down direction of NS line).

Based on the above points the simulating design is given for NS-up and EW-up directions and their main important input parameters and their characteristics are herein discussed in detail.

- ❖ The distance between each station will be given as inputs in unit length and to know its exact unit it needs to consider its velocity unit length. For instance, given two distances with the length of 100m and 100km, now to cover those distances if a train travels with a velocity of 10meter per minute and 10km per minute respectively the time taken will be the same to cover the given distances. Hence, by this concept this thesis simply considers the unit of the distance as unit length and in the velocity, it will be unit length per seconds.
- ❖ The unit length is assumed to be in meters and the velocity is in meters per second (m/s). In some stations, the distance may have fractional numbers but the arena model accepts only integer numbers hence for those fractions are approximated to thier higher integer.
- ❖ The dwell time (a duration that a train stops at each station)
- ❖ The headway time (a gap time between any two consecutive trains when they start traveling from the initial station to the next station)
- ❖ The working hours per day (16hrs/day for the case of the AA-LRT)
- ❖ The number of trains (i.e. the line capacity)

Hence, based on these points the simulating design is given for NS-up ward direction in figure 11 below (on page 68) and for EW-upward direction it is given on the appendix part on page 83 (figure 12). For the remaining directions their design is similar except the direction, in which it is downward and hence their design is not included.

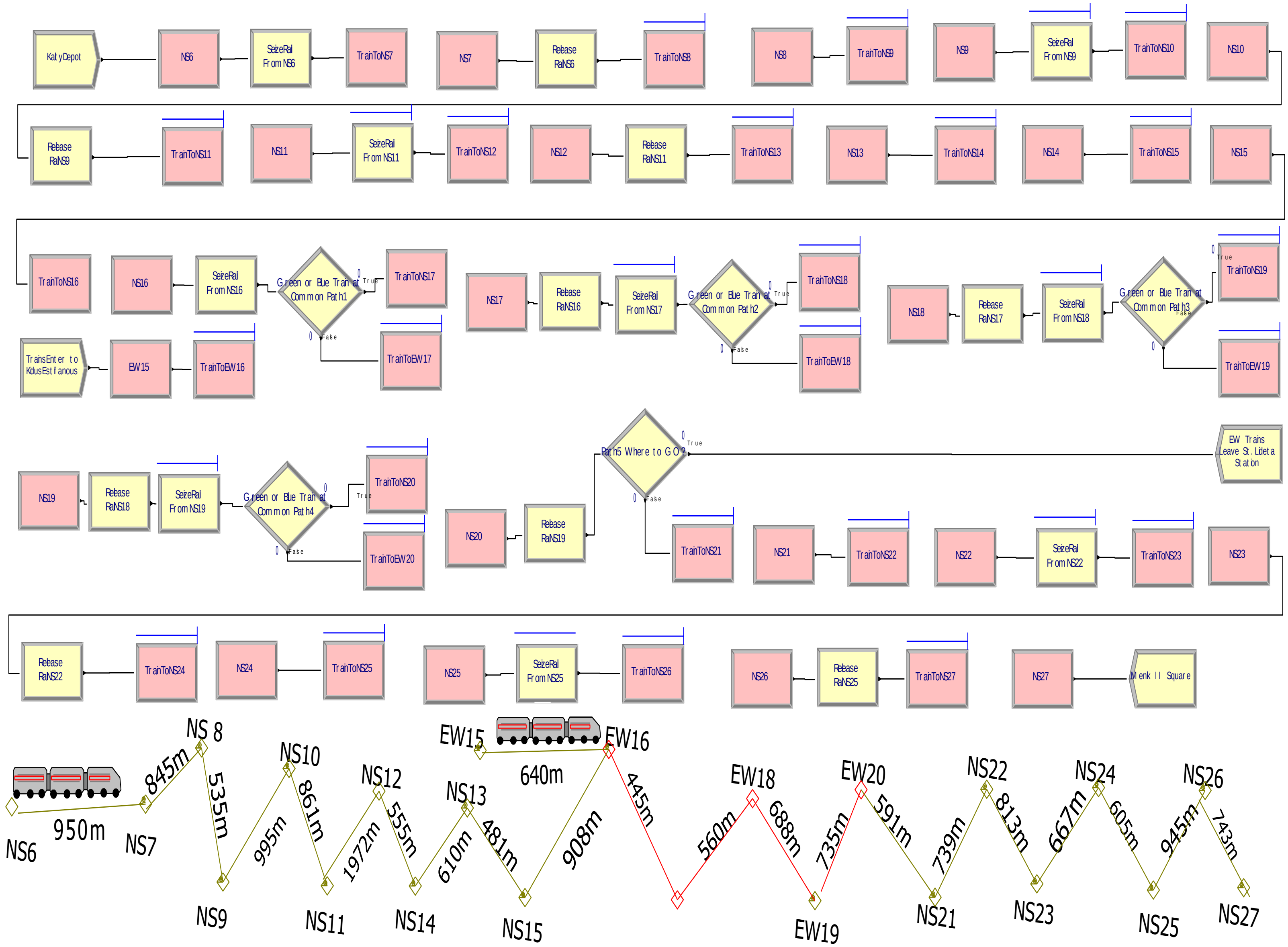

Figure 11: The simulation design of AA-LRT from Kality to Menelik II square

5.2.3 Key Performance Indicators of the Simulation

After giving the necessary inputs to the system model and ordered to run the system it gives the statistical analysis of the simulation result under some of the following groups according to our design model. Those are Entities, Stations, Resources, Queues, Processors, Transporters, Activity areas, etc. In this thesis, the statistical analysis of the simulation result is given under Entities, Queues, Resources, Stations, and Transporters.

Entity

The simulation result gives the details of the time spending on the trip from the origin station to the destination station. Based on the simulation result the different time spends during the trip are listed under the following terms such as the wait time, transfer time and total time.

- ❖ Wait Time: This time is the total time spending on each station when the train stops for boarding and alighting passengers or the wait time at the station if the block ahead is occupied. Hence based on the simulation result the waiting time is 11 minutes when traveling at 30km/h.
- ❖ Transfer Time: The total time spending by the train during running excluding of waiting time and other times. Hence based on the simulation result the transfer time is 34.40 minutes when traveling at 30km/h.
- ❖ Total Time: This time is the sum of all times spending by the train in the simulation starting from the initial station to the final destination station. Mathematically total time is the sum of all time spends during the trip, i.e.

$$\text{Total time} = \text{wait time} + \text{Transfer time} + \text{value added time} + \text{none value added time} + \text{other times.}$$

Hence based on the simulation result the total time is 46.40 minutes to travel from Kality station to Menelik II Square station at speed of 30km/h (see table 12 below).

- ❖ The times, like value added time, non-value added time and other time are not used in this modeling system
- ❖ The Number out = 167 indicates as the number of train frequency can be increased to 167 per a day from its current value of 122 trains frequency (see chapter three section 3.5.1).

- Work in Process (WIP): The WIP indicates the number of busy transporters in the whole process at a given time. That is the WIP gives the necessary number of transporters to be in service simultaneously. Based on the result of WIP it indicates as how many trains are needed. Hence based on this result at least 9 trains for each direction are needed to give full service at the speed of 30km/h. If the speed increases beyond this the number of trains must be increased.

Table 12: Simulation results showing time movement of trains of NS up direction

Wait Time	Average	Half Width	Minimum Value	Maximum Value
BlueTrain	11.0000	(Insufficient)	11.0000	11.0000

Transfer Time	Average	Half Width	Minimum Value	Maximum Value
BlueTrain	35.4038	(Insufficient)	35.4038	35.4038

Other Time	Average	Half Width	Minimum Value	Maximum Value
BlueTrain	0.00	(Insufficient)	0.00	0.00

Total Time	Average	Half Width	Minimum Value	Maximum Value
BlueTrain	46.4038	(Insufficient)	46.4038	46.4038

Number Out	Value
BlueTrain	167.00

WIP	Average	Half Width	Minimum Value	Maximum Value
BlueTrain	8.2578	(Correlated)	0.00	9.0000

Station

The station displays a number of entities (trains) transferring in each station. This indicates how much the station is busy during the whole day (see table 13 below). It also displays the total accumulating waiting time in each station during the whole working day.

Table 13: Stations usage during a service time for NS up direction

Number Entities Transferring	Average	Half Width	Minimum Value	Maximum Value
EW15.Station	0.00	(Insufficient)	0.00	0.00
NS10.Station	0.3851	0.006132810	0.00	1.0000
NS11.Station	0.3354	(Correlated)	0.00	1.0000
NS12.Station	0.7336	(Correlated)	0.00	1.0000
NS13.Station	0.2238	(Correlated)	0.00	1.0000
NS14.Station	0.2432	(Correlated)	0.00	1.0000
NS15.Station	0.1961	(Correlated)	0.00	1.0000
NS16.Station	0.5980	(Correlated)	0.00	2.0000
NS17.Station	0.3630	(Correlated)	0.00	1.0000
NS18.Station	0.4432	(Correlated)	0.00	1.0000
NS19.Station	0.5327	(Correlated)	0.00	1.0000
NS20.Station	0.5641	(Correlated)	0.00	1.0000
NS21.Station	0.2325	(Correlated)	0.00	1.0000
NS22.Station	0.2846	(Correlated)	0.00	1.0000
NS23.Station	0.3092	(Correlated)	0.00	1.0000
NS24.Station	0.2578	(Correlated)	0.00	1.0000
NS25.Station	0.2361	(Correlated)	0.00	1.0000
NS26.Station	0.3530	(Correlated)	0.00	1.0000
NS27.Station	0.2827	(Correlated)	0.00	1.0000
NS6.Station	0.00	(Insufficient)	0.00	0.00
NS7.Station	0.3717	0.005136795	0.00	1.0000
NS8.Station	0.3315	0.004873836	0.00	1.0000
NS9.Station	0.2191	0.004306755	0.00	1.0000

Resource

The resource gives the usage statistics of the resource used in the model. The block of rail track is represented as a resource. The numerical value of the resource is in the range between zero and one. If the given percentage of the resource is close to one it indicates as it is highly used resource and if it is close to zero, it indicates as it is almost unused resource (see table 14 below).

Table 14: Simulation results of the Resource usage of NS up direction

Instantaneous Utilization	Average	Half Width	Minimum Value	Maximum Value
RailFromNS11	0.8231	(Correlated)	0.00	1.0000
RailFromNS16COM	0.5390	(Correlated)	0.00	1.0000
RailFromNS17COM	0.6193	(Correlated)	0.00	1.0000
RailFromNS18	0.7082	(Correlated)	0.00	1.0000
RailFromNS19COM	0.7391	(Correlated)	0.00	1.0000
RailFromNS22	0.3967	(Correlated)	0.00	1.0000
RailFromNS25	0.4399	(Correlated)	0.00	1.0000
RailFromNS6	0.4628	(Correlated)	0.00	1.0000
RailFromNS9	0.4752	(Correlated)	0.00	1.0000

Queue

This indicates the forced waiting time (except the allowed dwell time) of the train and number of trains waiting to get free access to the block ahead. The train will wait at the station for some time if the block ahead is occupied. Hence, the system should be capable of minimizing the queuing time to reduce or avoid the unnecessary waiting time.

Table 15: Queuing time for accessing the available resource of NS up direction

Queue

Time

Waiting Time	Average	Half Width	Minimum Value	Maximum Value
SeizeRail FromNS11.Queue	0.00	(Insufficient)	0.00	0.00
SeizeRail FromNS16.Queue	0.7055	(Correlated)	0.00	1.4235
SeizeRail FromNS17.Queue	0.1143	(Correlated)	0.00	0.2300
SeizeRail FromNS18.Queue	0.1272	(Correlated)	0.00	0.2560
SeizeRail FromNS19.Queue	0.04658347	(Correlated)	0.00	0.0940
SeizeRail FromNS22.Queue	0.00	(Insufficient)	0.00	0.00
SeizeRail FromNS25.Queue	0.00	(Insufficient)	0.00	0.00
SeizeRail FromNS6.Queue	0.00	(Insufficient)	0.00	0.00
SeizeRail FromNS9.Queue	0.00	(Insufficient)	0.00	0.00

The queuing system is FIFO system and the designed system model tries to change this queuing time to zero or to very smaller number by optimizing the input parameters of the system such as the headway time, dwell time, speed and even the number of trains allotted for traveling.

Transporter

It gives the number of transporters (in this case trains) needed for a given trip. It displays under the following sub-topics.

- Number Scheduled: The scheduled number of transporters prepared for the trip those can be given manual input to the model. This indicates the available number of trains to give the service.

- Number Busy: This indicates the number of trains used simultaneously.
- Utilization: The utilized number of transporters based on the number busy and number scheduled. Mathematically utilization of the trains is given as:-

$$\text{Utilization} = \text{Number busy/Number scheduled.}$$

Since the track is double track it assumes when the first train reaches the terminal station, the other train reaches the initial station, of course, it is terminal considering by the other side.

Table 16: Simulation results of the transporters (trains) for NS up direction

Transporter

Usage

Number Busy	Average	Half Width	Minimum Value	Maximum Value
Trains From Kality To Menilik II	8.1666	(Correlated)	0.00	9.0000

Number Scheduled	Average	Half Width	Minimum Value	Maximum Value
Trains From Kality To Menilik II	10.0000	(Insufficient)	10.0000	10.0000

Utilization	Average	Half Width	Minimum Value	Maximum Value
Trains From Kality To Menilik II	0.8167	(Correlated)	0.00	0.9000

5.3 Comparisons between the Current and Newly Designed Timetables

When making a simulation using the current timetable parameters, like headway of 15minutes, the speed of 20km/h, 4 number of trains (for a single line and single direction). The simulating result gives the corresponding results. Its result indicates as it has: long traveling time, a significant waiting time at the entrance of the common line, less utilization usage of resources, and inappropriate use of the available trains. But, when simulating with the newly designed timetable parameters it gives a better result comparing with the existing one even with the same speed.

5.4 Conclusions of the Simulation Output

The simulation output indicates as the design has a good frequency, safe (no collision), line capacity, minimum waiting time, less delay, optimal use of resources and satisfaction of customers. The detail values of these parameters can be seen in the simulation output of the arena software under the title of key performance indicators. When the design system runs the train movement goes smoothly as expected. Even it is easy to visually the movements of the train from the visualized animations through the zigzag lines of the simulation software. Hence, in the animation, there is no collision and it has less (or no) unexpected waiting time for the trains during the operation time as well as the line is utilized. Furthermore, the customers will be satisfied if they access a service with safety, less time (for both headway and travel time) and without overcrowding on trains during traveling. Hence, the calculated values, as well as the simulation result shows as those parameters, are fulfilled.

Another point is that due to the modification of the parameters, such as headway, traveling time, synchronization time, waiting time and line capacity, a given train can give more service (more trips) per a day. Hence, the frequency of the trains is highly increased. In the current timetable with the speed of 20km/h the number of total trains (commercial trains) past a single point in a day, in each EW and NS line, is 122. But this number (frequency of trains per a day) can be increased to 169 trains by increasing the speed to 30km/h and by using the modified parameters according to this speed. Furthermore, since the number of available trains in the AA-LRT is 41, the corresponding parameters fitted with the number of those trains are found at a speed of 30km/h. But, if we want to use a speed of more than this (30km/h) additional trains are necessary.

5.5 Validation of the Results

The input parameters for the simulation are the parameters we calculated in chapter 4. Based on those inputs the software simulation gives required values accordingly. It is obvious as some input parameters are dependent on speed hence whenever the speed changes those parameters changes. Hence to see some sample simulation result, the speed of 30km/h is used. Because when we use this speed the travel time, headway time, number of trains and line capacity are all agreed with the available resource of the AA-LRT. Furthermore, the future expected headway is 6 minute so that this headway is achieved when the speed becomes 30km/h. Moreover, this speed is relatively slow but gives appropriate values for the other parameters. For further simulation results, we can change this speed and take the corresponding inputs for the other outputs.

To check the validity of the simulation result, we can compare the calculated values in chapter 4 with the simulating output results of this chapter. The calculated parameters are obtained using standard formulas and then the output of the simulating result should be similar to the calculated parameters if they are calculated correctly. Additionally, the zigzag lines (see figure 11 on page 68) of the simulation design can be used as checking criteria since they show the flow of the traffic (movement of trains) by animations. For instance, it is possible to directly check whether the trains have enough headway; to check whether there is a delay; to check whether this delay is propagated or not from the animation. Hence using those calculated parameters as inputs to the simulation system it works well and runs correctly and gives valid results. Additionally, even the flow movement in the zigzag line shows valid train movement. Which is, without collision, with less or no waiting time, with no overtake, with good utilization of resources, with good usage of the available trains, with good synchronization time at the entrance of the common line etc.

CHAPTER SIX

Conclusions and Recommendations

6.1 Conclusions

Since the operation of AA-LRT is in its starting stage most of the parameters are on their lower levels. That is in order to be familiar with service equipment, with the infrastructure itself and at large to be familiar with residents of the city. It is also necessary to go step by step to avoid any accident occurring due to lack of experience for both crew members and the societies as well. So, due to this reason the operation starts based on the lowest possible parameters; for instance, it uses the minimum possible speed which is 20km/h and even the headway time is larger than the designed headway.

Despite having few months of experience on operation it is necessary to study the appropriate parameters. Hence, by carefully study the way of operation better service can be obtained by updating few parameters while for the remaining parameters keeping unchanged. For instance without changing the operational speed we can operate by better headways, in the AA-LRT case currently the planners uses 15 minutes of headway when the speed is 20km/h. According to the calculated values in chapter 4, this large headway can be minimized up to 7.5 minutes without changing the speed. Consequently, more trains can give service with a headway of 7.5 minutes than the number of trains with 15 minutes of headway hence the line capacity can be increased.

Generally to design the train timetable parameters like headway, dwell time, trip time, speed, signaling system, braking distance, synchronization of trains and other available resources should be considered. Hence, in this thesis those parameters are discussed in detail and their values are calculated and then checked their validations using the Arena software simulation.

6.2 Recommendations

The software used in this thesis is Arena software of student version and this is the only free software although, it has very limited capacity. Due to this limited capacity to design the whole route line (all the four routes of AA-LRT) in a single model is impossible. So that in this thesis the design is done for those four routes independently with giving big emphasis to the effect of the common line. Hence to design better result, it is advisable to have the full version of the arena commercial software then it will be possible to design all the four routes in a single simulation design. But, individually to own the Arena software is too expensive but if, ERC bought the full version of Arena it helps to design a better train timetable. Hence, one recommendation to ERC is to buy the full version of Arena to its train timetable planners and researchers of the railway system.

Another recommendation is that, currently ERC have 41 trains hence to use all the available trains, the appropriate speed is 30km/h with headway of 5.55 minutes or approximately 6 minutes. Otherwise, if the ERC wants to use the current speed which is 20km/h, headway of 7.5 minutes or approximately 8 minutes should be used.

The simulation design shows the traffic flow of the trains in the zigzag lines of the design. Hence based on the visualization of the animations the situation of the train's movement can be analyzed. So that, based on the visualized movement of trains, the timetable designers can make appropriate adjustments on the timetable parameters.

The way of calculation to find the headway doesn't consider the level crossing. Although the Addis Ababa Roads Authority gives priority to the train, but still it may have an effect on the headway and of course on most of the parameters like line capacity, speed, and travel time etc. the level crossing is not considered. Hence, it is recommended to involve the level crossing effect to obtain a better result.

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Appendix

In the appendix part, some important detail points about the AA-LRT are given in part A. In Part B, the simulation design with its output for the AA-LRT EW line is given.

A. Some Important Tables

The minimum curve radius of the main track is 194m. Let's see the table below for mileages with curve radius less than 400m.

Table 17: Mileages with curve radius less than 400m in the east-west line [8]

Interval	Track	Distance between stations	Curve radius	Length (m)	Speed restriction of curve	Reason for control
EW22-EW21	Right	776	190	274.469	50	Road alignment
	Left	773.797	194	263.879		
EW22-EW21	Right	776	240	235.413	60	Road alignment
	Left	773.797	236	252.490		
EW19-EW18	Right	688.000	204	131.430	45	Road alignment
	Left	685.124	200	149.637		
EW18-EW17	Right	571.965	200	150.783	45	Road alignment
	Left	571.965	204	127.499		
EW17-EW16	Right	435.000	250	140.660	55	Line route
	Left	436.224	254	127.030		
EW15-EW14	Right	583.000	400	109.347	60	Line route
	Left	583.001	400	109.272		

Table 18: Mileages with curve radius less than 400m in the north-south line

Interval	Track	Distance between stations	Curve radius	Length	Speed restriction of curve	Reason for control
NS27-NS26	Right	741.000	304.5	95.550	45	Construction control
	Left	747.538	304	94.359		
NS27-NS26	Right	741.000	65	137.366	20	Road alignment
	Left	747.538	70	124.163		
NS27-NS26	Right	741.000	305	195.606	65	Road alignment
	Left	747.538	300	218.383		
NS25-NS24	Right	608.000	304	182.652	65	Road alignment
	Left	605.983	300	206.038		
NS24-NS23	Right	612.000	54	97.403	20	Road alignment
	Left	604.346	50	111.299		
NS22-NS21	Right	739.000	104	162.891	35	Road alignment
	Left	739.106	100	173.165		
NS22-NS21	Right	739.000	100	175.318	35	Road alignment
	Left	739.106	104	165.131		
NS22-NS21	Right	591.000	55	98.183	20	Road alignment
	Left	583.225	50	94.536		
NS21-NS20	Left	583.225	300	20.765	35	Rail joint scheme
EW19-EW18	Right	688.000	204	131.430	45	Road alignment
	Left	685.124	200	149.637		
EW18-EW17	Right	571.965	200	150.783	45	Road alignment
	Left	571.965	204	127.499		
EW17-EW16	Right	435.000	250	140.660	55	Road

	Left	436.224	254	127.030		alignment
EW16-EW15	Right	908.000	300	19.821	35	Rail joint scheme
EW16-EW15	Right	908.000	50	93.480	20	Road alignment
	Left	915.388	55	97.194		
NS14-NS13	Right	610.000	290	201.946	65	
	Left	609.179	286	219.988	65	Road alignment
NS13-NS12	Right	555.000	290	238.746	65	Road alignment
	Left	554.963	294	220.936		
NS13-NS12	Right	555.000	240	177.116	60	Road alignment
	Left	554.963	236	195.164		
NS12-NS11	Right	1971.636	200	143.223	55	Line route
	Left	1971.162	204	124.888	45	
NS12-NS11	Right	1971.636	354	86.434	60	Line route
	Left	1971.162	350	85.796		
NS12-NS11	Right	1971.636	300	105.270	55	Line route
	Left	1971.162	304	106.207		
NS8-NS7	Right	840.000	234	172.524	55	Line route
	Left	837.751	230	190.429		
NS7-NS6	Right	951.000	146	232.569	45	Road alignment
	Left	949.808	150	222.434		
NS7-NS6	Right	951.000	150	247.468	40	Road alignment
	Left	949.808	146	256.936		

B. Simulation Results for EW-Line up Direction

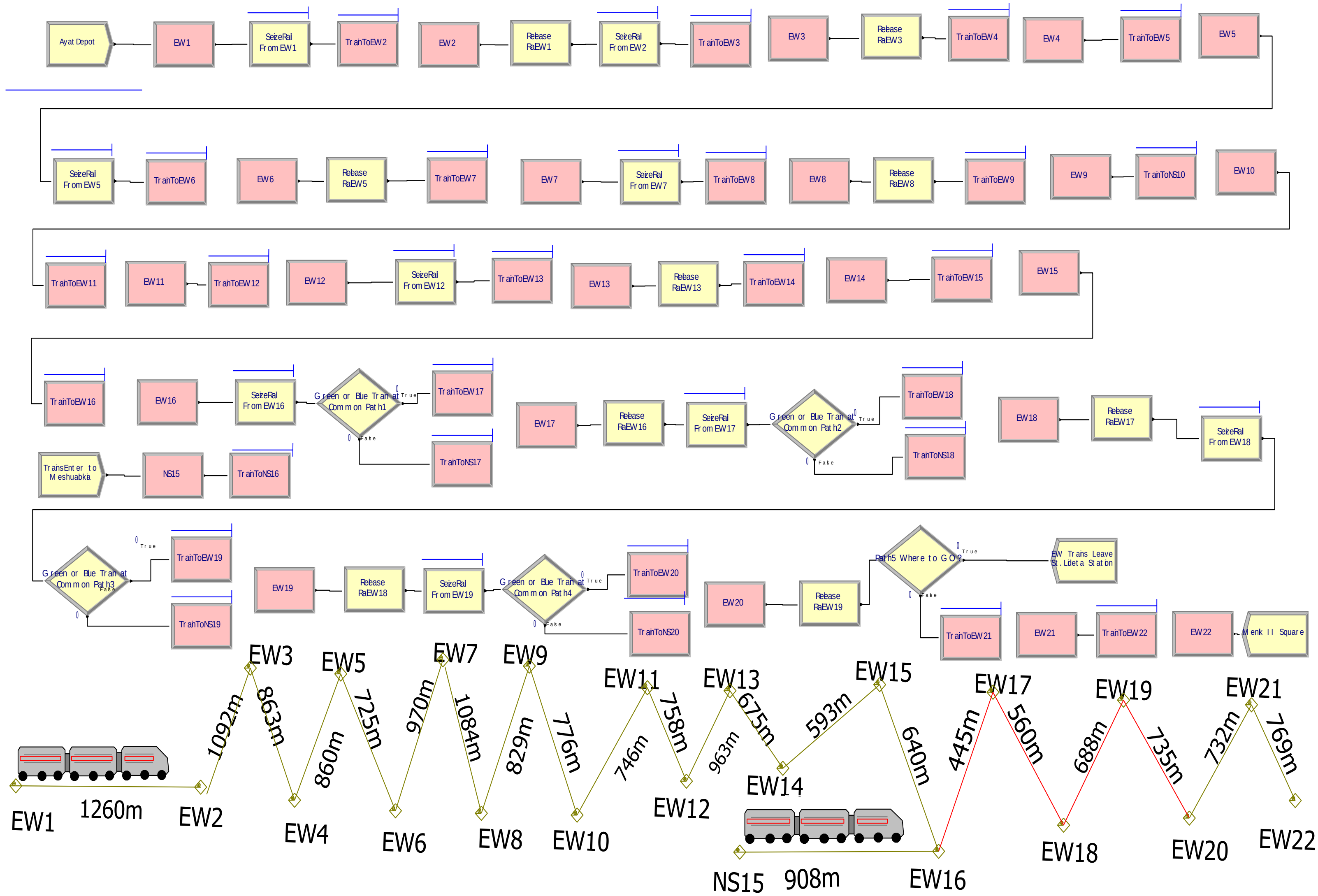

Figure 12: The simulation design of AA-LRT from Ayat to Torhailoch line

Train's Time Spending from the Simulation Output

Table 19: Time spending indicators in the trip for EW up direction

Wait Time	Average	Half Width	Minimum Value	Maximum Value
BlueTrain	3.0000	(Insufficient)	3.0000	3.0000
GreenTrain	11.0000	(Insufficient)	11.0000	11.0000

Transfer Time	Average	Half Width	Minimum Value	Maximum Value
BlueTrain	7.5107	(Insufficient)	7.5107	7.5107
GreenTrain	36.4439	(Insufficient)	36.4439	36.4439

Other Time	Average	Half Width	Minimum Value	Maximum Value
BlueTrain	0.00	(Insufficient)	0.00	0.00
GreenTrain	0.00	(Insufficient)	0.00	0.00

Total Time	Average	Half Width	Minimum Value	Maximum Value
BlueTrain	10.5107	(Insufficient)	10.5107	10.5107
GreenTrain	47.4439	(Insufficient)	47.4439	47.4439

Stations Utilization Result

Table 20: Station activities of EW upward direction

Number Entities Transferring	Average	Half Width	Minimum Value	Maximum Value
EW1.Station	0.00	(Insufficient)	0.00	0.00
EW10.Station	0.3012	(Correlated)	0.00	1.0000
EW11.Station	0.2905	(Correlated)	0.00	1.0000
EW12.Station	0.2931	(Correlated)	0.00	1.0000
EW13.Station	0.3657	(Correlated)	0.00	1.0000
EW14.Station	0.2626	(Correlated)	0.00	1.0000
EW15.Station	0.2332	(Correlated)	0.00	1.0000
EW16.Station	0.6220	(Correlated)	0.00	1.0000
EW17.Station	0.3625	(Correlated)	0.00	1.0000
EW18.Station	0.4432	(Correlated)	0.00	1.0000
EW19.Station	0.5319	(Correlated)	0.00	1.0000
EW2.Station	0.4845	(Correlated)	0.00	1.0000
EW20.Station	0.5636	(Correlated)	0.00	1.0000
EW21.Station	0.2788	(Correlated)	0.00	1.0000
EW22.Station	0.2917	(Correlated)	0.00	1.0000
EW3.Station	0.4210	(Correlated)	0.00	1.0000
EW4.Station	0.3380	0.005693605	0.00	1.0000
EW5.Station	0.3350	(Correlated)	0.00	1.0000
EW6.Station	0.2863	0.007511729	0.00	1.0000
EW7.Station	0.3732	(Correlated)	0.00	1.0000
EW8.Station	0.4133	(Correlated)	0.00	1.0000
EW9.Station	0.3209	(Correlated)	0.00	1.0000
NS15.Station	0.00	(Insufficient)	0.00	0.00

Table 21: Utilization of the allotted trains for EW up direction

Transporter

Usage

Number Busy	Average	Half Width	Minimum Value	Maximum Value
Trains From Ayat To Torhailoch	8.3471	(Correlated)	0.00	9.0000
Trains From Kality To Menilik II at common	1.7691	(Correlated)	0.00	2.0000

Number Scheduled	Average	Half Width	Minimum Value	Maximum Value
Trains From Ayat To Torhailoch	10.0000	(Insufficient)	10.0000	10.0000
Trains From Kality To Menilik II at common	3.0000	(Insufficient)	3.0000	3.0000

Utilization	Average	Half Width	Minimum Value	Maximum Value
Trains From Ayat To Torhailoch	0.8347	(Correlated)	0.00	0.9000
Trains From Kality To Menilik II at common	0.5897	(Correlated)	0.00	0.6667

Table 22: Usage of the resources and utilization for EW up direction

Resource

Usage

Instantaneous Utilization	Average	Half Width	Minimum Value	Maximum Value
RailFromEW1	0.5752	0.005242266	0.00	1.0000
RailFromEW12	0.4542	(Correlated)	0.00	1.0000
RailFromEW16COM	0.5386	(Correlated)	0.00	1.0000
RailFromEW17COM	0.6193	(Correlated)	0.00	1.0000
RailFromEW18COM	0.7074	(Correlated)	0.00	1.0000
RailFromEW19COM	0.7386	(Correlated)	0.00	1.0000
RailFromEW2	0.5117	(Correlated)	0.00	1.0000
RailFromEW5	0.3764	(Correlated)	0.00	1.0000
RailFromEW7	0.5029	(Correlated)	0.00	1.0000

Number Busy	Average	Half Width	Minimum Value	Maximum Value
RailFromEW1	0.5752	0.005242266	0.00	1.0000
RailFromEW12	0.4542	(Correlated)	0.00	1.0000
RailFromEW16COM	0.5386	(Correlated)	0.00	1.0000
RailFromEW17COM	0.6193	(Correlated)	0.00	1.0000
RailFromEW18COM	0.7074	(Correlated)	0.00	1.0000
RailFromEW19COM	0.7386	(Correlated)	0.00	1.0000
RailFromEW2	0.5117	(Correlated)	0.00	1.0000
RailFromEW5	0.3764	(Correlated)	0.00	1.0000
RailFromEW7	0.5029	(Correlated)	0.00	1.0000