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

Development of Timetable Using a Communication Based Train Control in the Case of Addis Ababa Light Rail Transit

A Thesis Submitted in Partial Fulfillment of the Requirement for the Degree
of Master Science in Railway Engineering
(Traction and Train Control)

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APPROVAL

A thesis submitted to African Railway center of excellence, Addis Ababa University Institute of Technology, School of Graduate studies in partial fulfillment of the requirements for the award of Masters of Science in Railway Engineering (Traction and Train Control).

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UNDERTAKING

I certify that research work titled “Development of Timetable Using a Communication Based Train Control in the Case of Addis Ababa Light Rail Transit” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

Atsedemariam Gebeyehu

ABSTRACT

Currently, Addis Ababa light rail transit is using the traditional fixed block signaling system. Fixed block-signaling divides the track into small blocks, which determines how far apart the trains will be kept for safety and how frequently the stations will be serviced. This signaling system of Addis Ababa light rail transit make the headway of the system unnecessarily long which handcuff the operator in terms of the number of trains they can push through the system. On the other hand, in moving block signaling system the train location is continuously updated through the real-time communication between the train and the wayside. There are no fixed block boundaries which allows trains to run closer to each other while ensuring safety. As a result, the operators have two choices to improve their headway and capacity: build more subway lines or squeeze more out of their existing infrastructure by adapting new technologies like Communication based train control.

In this thesis, a communication based train control system have been used to develop a new timetable for Addis Ababa light rail transit. The key parameters required to develop a communication based train control systems timetable such as, dwell time, speed, braking distance, emergency braking distance, time for lock switches, and synchronization of trains are discussed in detail and their values are calculated. Depending on those results a new headway for the new timetable is obtained. The validity of newly modeled timetable is tested using Arena simulation software. Finally, the calculated values and simulating results shows that the current headway of Addis Ababa light rail transit can be improved to 8.84 minutes (minimized by 58.93%) from 15 minutes only by changing the signaling system to a moving block based on Communication based train control system.

Key Words: Communication based train control, Train timetable, Headway, Moving block, Fixed block, Arena Software

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May the Almighty God richly bless all of you!

Atsedemariam
Addis Ababa, Ethiopia

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LIST OF ABBREVIATIONS

AALRT	Addis Ababa Light Rail Transit
AB	Active Balise
ATO	Automatic Train Operation
ATP	Automatic Train Protection
ATS	Automatic Train Supervision
BTM	Balise Transmission Module
CBI	Computer Based Interlocking Subsystem
CBTC	Communication Based Train Control
CP	Conflict Point
CTCS	Chines Train Control System
DCS	Data communication System
FIFO	First In First Out
HMI	Human Machine Interface
IATP	Interim Automatic Train Protection
IEEE	International Electrical and Electronics Engineers Association
IXL	Interlocking System
LEU	Line side Electronic Unit
LMA	Limits Of Movement Authority
LMAs	Limits Of Movement Authority
LRT	Light Rail Transit
MRP	Media Redundancy Protocol
MSS	Maintain and Support Subsystem
MTIB	Mobile Train Initialization Beacon
OCC	Operation Control Center
ODO	Odometer System
OEM	Original Equipment Manufacturer
OMT	Operating Margin Time
PB	Passive Balise

PTC	Positive Train Control
Rx ID	Receiver Identification
SA	Station Adapter
SIMAN	Simulation Model Analysis
STF-DL	Space Time Frequency
TCP/IP	Transmission Control Protocol/Internet Protocol
TIU	Train Interface Unit
TWC	Train Wayside Communication
Tx ID	Transmitter Identification
UDP/IP	User Datagram Protocol/Internet Protocol
UTO	Unattended Train Operations
WLAN	Wireless Local Area Networks
ZC	Zone Controller

CHAPTER ONE

INTRODUCTION

1.1 Background

The timetable is an important concept in a railway system. It describes the product that is offered to the customers: the passengers and the cargo forwarders. These are mainly interested in the departure and arrival times of the trains in the stations and in the number of transfers. On the other hand, the timetable also contains elements that are needed for guaranteeing its feasibility: the passing times of the trains at relevant underway locations such as bridges and junctions, and the routes of the trains inside the railway stations. The timetable also acts as the basis for further planning processes within the railway system, related to the rolling stock circulation, the crew schedules, and the maintenance of the infrastructure.

Advanced train control systems enable the efficient driving of trains, which becomes more and more important because of the operation costs and environmental concerns. The Automatic Train Operation (ATO) system of an advanced train control system drives the train according to a predefined train trajectory (i.e., a speed profile) to ensure punctuality and energy saving. In addition, signaling systems in train control systems is important for running safety of trains [1].

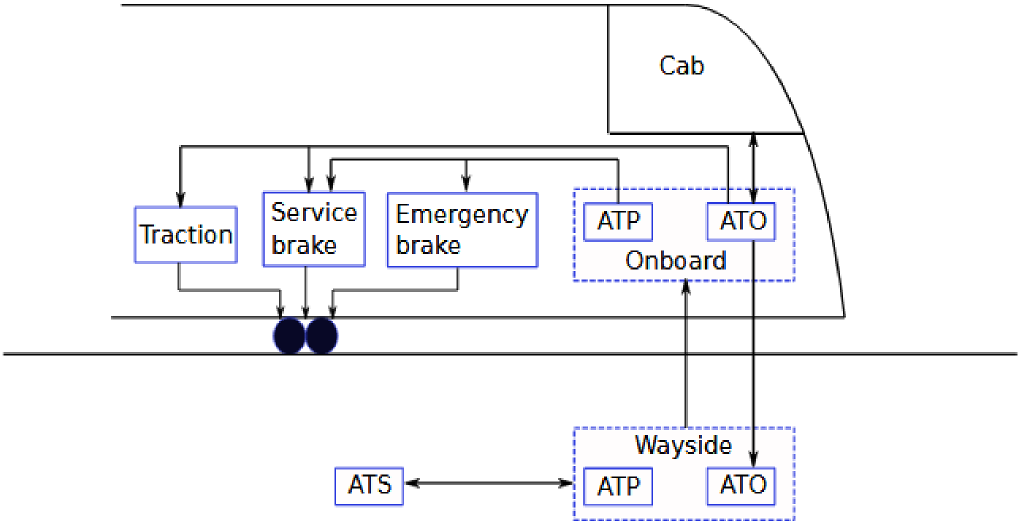
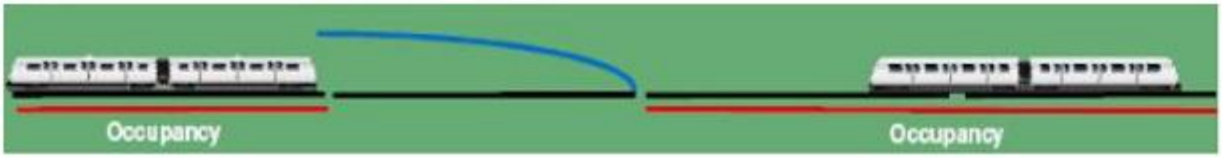


Figure 1.1: Structure of an Advanced Automatic Train Control [2]

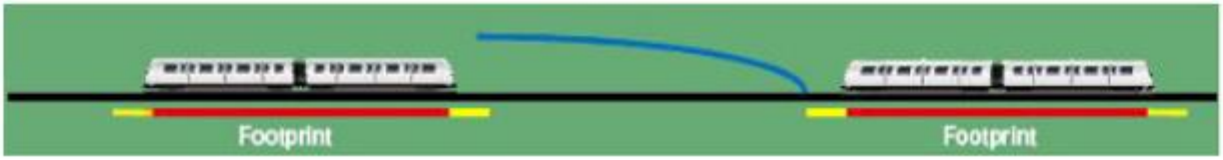
Nowadays, several dedicated high-speed railway lines and urban rail transit systems with short headways are operated with a high degree of automation. This requires advanced train control systems to fulfill safety and operational requirements, such as the European Train Control System and Communication-Based Train Control systems, which include equipment on board of trains as well as in control centers [2].

Communications-based train control (which is an automatic train control system) is a railway signaling system that makes use of the telecommunications between the train and track equipment for the traffic management and infrastructure control.

By means of the Communication based train control system, the exact position of a train is known more accurately than with the traditional signaling systems. This results in a more efficient and safe way to manage the railway traffic [3]. Railway systems are able to improve headways while maintaining or even improving safety (Which is recommended for Addis Ababa light transit).



Fixed block



Moving block

Figure 1.2: Effect of Moving Block to Minimize Headway [4]

The Addis Ababa Light Rail Transit introduced on September 20,2015 to the capital city of Ethiopia, Addis Ababa, with two main routes having a total length 31.025 kilometers, with 39 stations. It gives service for passengers in 16 hours per day. Currently the AA-LRT uses fixed block system in which a train is not permitted to enter a block until a signal indicates that the train may proceed, a dispatcher or signalman instructs the driver accordingly, or the driver takes possession of the appropriate token. The Addis Ababa light rail transit at present uses headway of 15 minutes but, the designed headway time is 6 minutes with a capability of reducing to 90 seconds. Therefore, in this thesis a new timetable is developed by adapting Communication Based Train Control for AA-LRT to show its positive impact on headway and capacity.

1.2 Statement of the Problem

The passenger demand for urban rail transit systems increases dramatically and varies significantly along urban rail transit lines nowadays. To satisfy the passenger demand, trains are operated with small headway. Therefore, the scheduling of trains according to the passenger demand becomes more and more important for reducing the operation costs and for guaranteeing passenger satisfaction. In particular, the passenger satisfaction can be characterized by waiting times at platforms, onboard travel times, the number of transfers, the onboard crowdedness, and so on.

Flexible and reliable train scheduling 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.

Even though the 31.025 kilometers, with 39 stations Ethiopia’s capital, Addis Ababa light-rail transportation system is playing a great role in the transportation sector of the city administration; the estimated time for the arrival of each consecutive train was planned to be 6 minutes but in reality, the waiting time goes more than15 minutes.

This thesis clearly analyzes the effect of an advanced automatic train control (communication based train control) to improve the robustness of timetables for a passenger train services in the case of Addis Ababa light rail transit. The analysis is performed in terms of many parameters such as time requirements dwell time, braking time, switch lock time etc. to develop an enhanced timetable with less headway and high capacity.

1.3 Objective of the Thesis

1.3.1 General Objective

The general objective of this thesis is to develop an enhanced time table for the case of Addis Ababa Light Rail Transit using an advanced train control system specifically communication based train control.

1.3.2 Specific Objective

The specific objective of this thesis are to:

- Study communication based train control and observe the trend in other countries
- Analyze the effect of communication based train control in train scheduling
- Propose communication based train control for Addis Ababa light railway transit and investigate its effect on the current train scheduling scheme
- Compute a minimize headway time for the proposed communication based train control signaling system
- Evaluate the system by Arena simulation software
- Compare and analyze the newly developed timetable with the existing system timetable of AALRT

1.4 Methodology

In literature review, different researches related to the topic are studied. Having brief understanding of the problem, collection of necessary information, which is essential to achieve the objective of this thesis, is done. The essential data on timetable are collected from kality depot of Addis Ababa light rail transit. Similarly, the necessary timetable design requirement for communication based train control system are studied and selected from different literatures. However, due to unavailability of the required documents like tachometer errors, assumptions and information from international railway manufacturing companies is used.

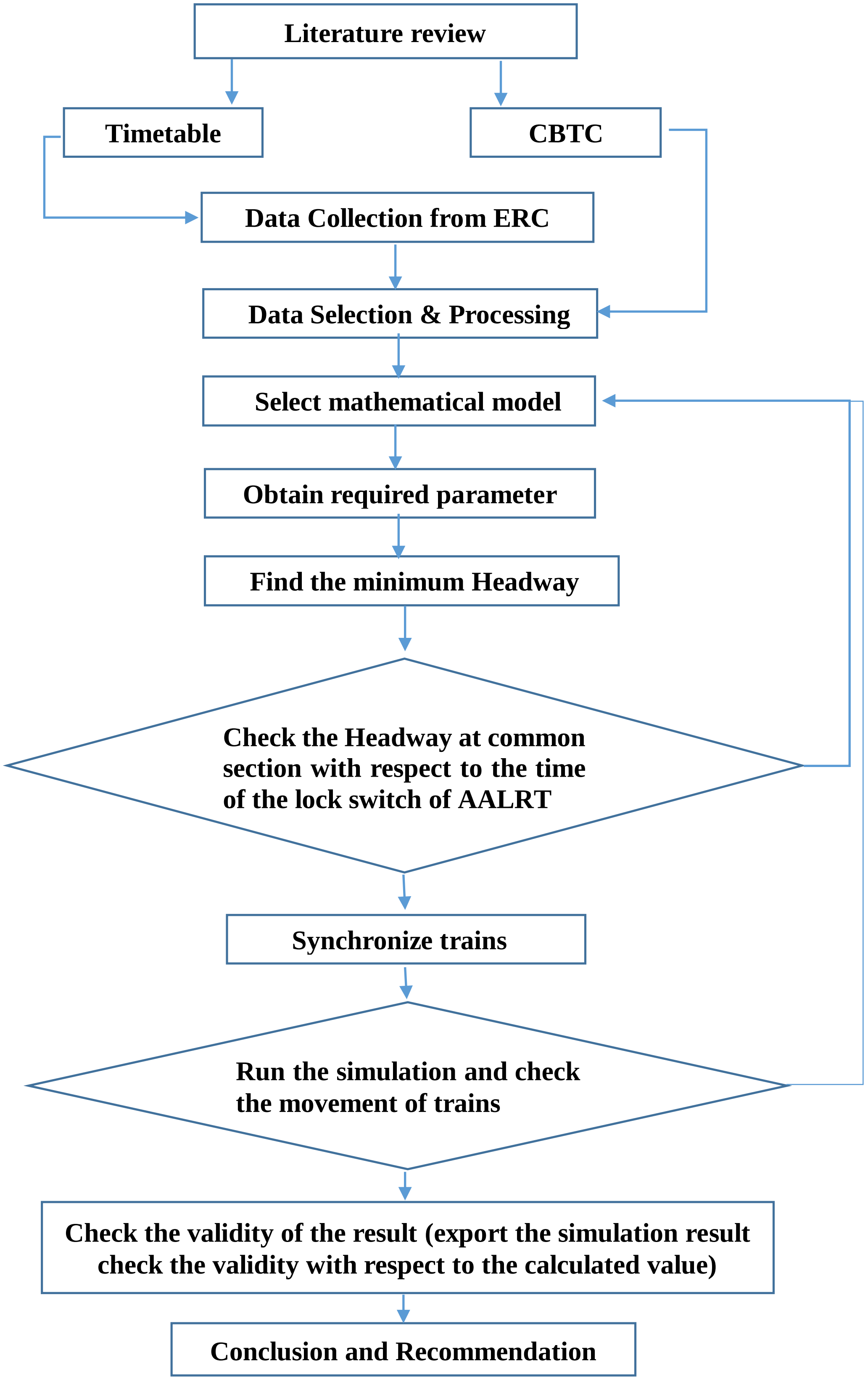


Figure 1.3: Methodology

It is essential to find the correct mathematical model to design the new communication based train control timetable and to achieve the appropriate headway, considering the interlocking system when designing a timetable is necessary as well. Since the switches in AA-LRT are Time lock switches the switch cannot be thrown until a timer has counted down otherwise the route for the train coming from the other direction cannot be created.

Finally using the calculated parameters Arena simulation software is used to check whether the system is working well or not. Based on the valid results conclusion and recommendations are given.

1.5 Scope

The scope of this thesis point towards developing an efficient train scheduling model, through applying suitable technique or analytical method and software simulation by adapting a Communication Based Train Control(CBTC) in the case of Addis Ababa light railway transit. However, this thesis does not consider level crossings and the switches found in both depots of AA-LRT.

1.6 Significances of the Thesis

This thesis work is able to provide documented findings and recommendations related to the effects of Automatic Train Control specifically Communication Based Train Control (CBTC) in train scheduling of Addis Ababa light rail transit and analyze the effect of moving block system if applied in the Addis Ababa light rail transit, in comparison to the existing fixed block system.

1.7 Thesis Organization

This thesis has six chapters. The first chapter includes introduction, which provides clear information about the background of the thesis work, statement of the problem, research method and limitation of the thesis.

Chapter two is about theoretical background and literature review. This section provides strong understanding of railway timetable, types of timetable, objectives of designing timetable and requirements for timetable. In addition, on this chapter different literature reviews about communication based train control and its structure is discussed briefly.

The third chapter deals specifically with the Addis Ababa light rail transit timetable characteristics. It discusses on the Addis Ababa light rail transit timetable including the signaling system used currently.

The fourth chapter is on designing models for the Addis Ababa light rail transit. 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, result and analysis part. In this chapter, the numerical values found in chapter four are used as the inputs to the simulation model of the Arena software. The outputs of the system are clearly discussed and used to validate the calculation done on the previous chapter.

The last chapter of the thesis give conclusions and recommendation about the development of timetable using a communication based train control in the case of Addis Ababa light rail transit.

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

From its early beginnings, the railway was a public transport system, starting as an entertainment attraction called "Steam Circus" in 1808 and developing into the opening of the first public railway line: The Stockton – Darlington Railway Line in 1825 (Holland 2012). To make a public means of transportation attractive to the public, it is necessary to announce the available services to attract as many customers as possible. This can be done by publishing a list of planned daily arrivals and departures of trains for each station: a timetable [6].

The Liverpool and Manchester Railway in north-western England opened in 1830 and was the first railway line where all trains, both passenger and freight trains, ran according to a timetable. The published timetable for the railway line from the year 1838 can be seen on Figure 2.1[6].

TRAVELLING

Liverpool & Manchester Railway,
1838.

The following are the Times of Departure both from Lime-street Station LIVERPOOL, and from Liverpool Road Station MANCHESTER.

FIRST CLASS.	SECOND CLASS.
7 o'Clock	7¼ o'Clock
9 "	10 "
11 "	12 "
2 "	3 "
5 "	5½ "
7 "	7

ON SUNDAYS,

First Class.	Second Class.
8 o'Clock	7 o'Clock
5 "	5½ "

FARES.

LUGGAGE.

LIVERPOOL AND MANCHESTER TO
WIGAN.
By the First Class Train 7 o'Clock in the Morning.
By the Second Class Trains 10, 12 and 5½ o'Clock.
ON SUNDAYS,
By the Second Class Trains 7 and 5½ o'Clock.

LIVERPOOL AND MANCHESTER TO
BOLTON.
By the First Class Train 9 o'Clock in the Morning.
By the Second Class Trains 7¼, 12, 3 and 5½ o'Clock.
ON SUNDAYS,
By the Second Class Trains 7 and 5½ o'Clock.

LIVERPOOL AND MANCHESTER TO
ST. HELENS.
By the Second Class Trains 7¼, 10, 12, 3 and 5½ o'Clock.
ON SUNDAYS,
By the Second Class Trains 7 and 5½ o'Clock.

LIVERPOOL AND MANCHESTER TO
RUNCORN GAP.
By the Second Class Trains 7¼ and 3 o'Clock.
ON SUNDAYS,
By the Second Class Trains 7 and 5½ o'Clock.

Figure 2.1: Timetable of Liverpool and Manchester Railway [6]

Timetabling may be one of the topics with major influence on users' quality of service perception. In fact, this subject has received the attention of many researches and has been widely studied in the literature, where, nowadays the main lines of research tend to improve the solving methods of the corresponding optimization problems [7].

An effective railway transport service 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 [8] [9].

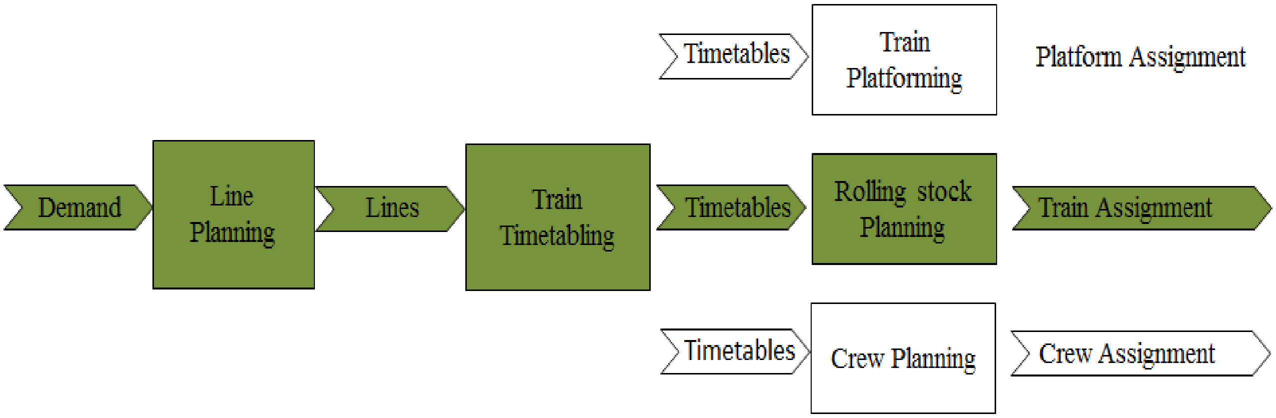


Figure 2.2: A Railway Operator's Planning processes [8]

The timetable determines the environment in which a rolling stock plan and a crew plan are constructed. This means that, in constructing a timetable, one has to take into account the implications for the depending plans [9].

2.2 Railway Timetable Types

Generally, there are two fundamental railway timetable types. Those are cyclic Timetable and non-cyclic Timetable. Both the fundamental type of timetables has their own advantages and disadvantages [8] [9].

2.2.1 Cyclic Timetabling

Cyclic or Periodic timetable contains a structure capable of repeating itself within some fixed time interval. The main advantage of cyclic timetables is the fact that these schedules are easy to operate and remember for passengers. On the other hand, these timetables are expensive to operate since no distinction between off-peak and peak hours are made. The only way to handle those differences for a train operator is to vary the length of the performed trains. This modifies the variable operating costs, variable rolling stock as well as crew costs. e.g. shorter trains require less personal to be conducted.

2.2.2 Non-cyclic Timetabling

A non-cyclic (Non-periodic timetable) 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. Generally speaking, non-cyclic train timetabling is especially relevant on heavy-traffic, long distance corridors where the capacity of the infrastructure is limited due to great traffic densities.

Table 2.1: Comparisons Between Periodic and Non-periodic Timetables [10]

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

2.3 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 [9].

One of the main important factors for customer satisfaction is the travel time. 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.

Additional 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 [9].

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 [9].

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.

2.4 Timetable Requirements

A timetable should meet various requirements, such as safety regulations, service levels to be achieved, and restrictions considering the operational feasibility of the timetable. The main requirement for timetable are connecting Trains, dwelling at stations, synchronizing trains, turning around at termini, fixed arrival and departure times, safety Regulations [9]. Each requirement for timetable belongs to one of the categories described.

Two trains are said to be connected if there is a planned relation between their arrival and departure times at a certain node. A connection is desirable in two situations. The first situation occurs when a direct train connection between two nodes does not exist. In that case, passengers should still be offered a good travel scheme between these two nodes. This can be achieved by constructing a timetable in which a train for the destination node leaves from a transfer node shortly after the train from the origin node has arrived. Another situation requiring the connection of two trains arises when two trains need to be combined. This situation occurs when the two trains share a considerable part of their routes. Combining the two trains into one for their common route saves both human resources and infrastructure resources. The combining of trains also has disadvantages. It places an extra restriction on the timetable, and can be a source of delays since the combination procedure involves connecting the trains, a brake test, and other checks, during which failures may occur [11].

In practice, limits are specified for the time that a train dwells at a station, a minimum dwell time specifies the minimum time needed for passengers to alight and board. On one hand, one might also want to limit the dwell time at a station because stations only have a limited capacity, and also each dwell minute adds to the train’s total travel time.

When trains from different train lines share part of their routes, their departure times are often synchronized to offer a higher frequency service on that common part. As an example, if two train lines have frequency equal to one, then synchronizing their departures provides a service with frequency two on the common part of their route. When a single train line has frequency higher than one, synchronization can also be applied to spread the multiple trains of that line evenly across the cycle time. Since this synchronization of train lines, or of trains within a train line, leads to a train service with a higher frequency, the involved constraints are also known as frequency constraints [9].

A rolling stock composition is the set of carriages, either self-powered, or including a locomotive, which operate a certain train line. After a rolling stock composition has arrived at its terminus, it generally turns around after some time, and operates a different connection. Typically, the rolling stock composition operates the return journey of the train line it operated before, but one can also encounter other situations. Before leaving for the opposite trip, the rolling stock is scheduled to spend some time at the terminus in order to be cleaned, for shunting, as buffer time to absorb delays, etc.

For some trains, the freedom of selecting arrival and departure times is limited. This especially applies to international trains. The time at which an international train appears at the border of a country is usually the result of negotiations with the neighboring railway companies, rather than a variable to be decided upon in the timetable planning process.

A final, but clearly very important requirement for a timetable is railway safety regulations. These require any two trains using the same track to be separated by a certain minimum headway time. For any pair of trains using the same track, the minimum headway time must be respected both at the origin node and at the destination node of the track. Moreover, the safety regulations forbid the meeting and overtaking of trains on the same track [9].

2.5 Real-time Scheduling or Rescheduling of Trains

Since trains do not run exactly according to the predefined schedule in practice, real-time scheduling approaches have been proposed. In the literature, there are several interpretations for real-time scheduling. For interurban railway systems, real-time scheduling is based on the existing timetable data and is used to handle route conflicts due to train delays or incidents. However, in urban rail transit systems, real time scheduling regulates the headways between trains based on a train schedule with a constant headway. Several rescheduling approaches have been proposed for urban rail transit systems: holding, zone scheduling, short turning, dead heading, and/or stop-skipping [11].

- Holding is used to regulate the headways by holding an early-arriving train, or a train with a relatively short leading headway.
- In zone Scheduling the whole line is divided into several zones, where the trains stop at all stations within a single zone and then run to the terminal station without stopping. The required number of trains, drivers and passenger travel times may be reduced by the zone scheduling, where the zones are defined based on the passenger flows.
- Short-turning Trips serve only the zone with high demands and the full-length trips run the whole line.
- Deadheading Strategy involves some trains running empty through a number of stations at the beginning of their trips to reduce the headways at later stations.

- A Dynamic Stop-Skipping strategy is frequently used in lines with high demands, as it allows those trains that are late and behind the schedule to skip certain low-demand stations and in that way increase the running speed.

2.6 Train Operations and Scheduling

2.6.1 Operation of Trains

Nowadays, several dedicated high-speed railway lines and urban rail transit systems with short headways are operated with a high degree of automation. This requires advanced train control systems to fulfill safety and operational requirements, such as the European train control system and communication-based train control systems, which include equipment on board of trains as well as in control centers. Advanced train control systems enable the energy-efficient driving of trains, which becomes more and more important because of the rising energy prices and environmental concerns. The ATO system of an advanced train control system drives the train according to a predefined train trajectory (i.e., a speed profile) to ensure punctuality and energy saving. In addition, signaling systems in train control systems are important for running safety of trains [11].

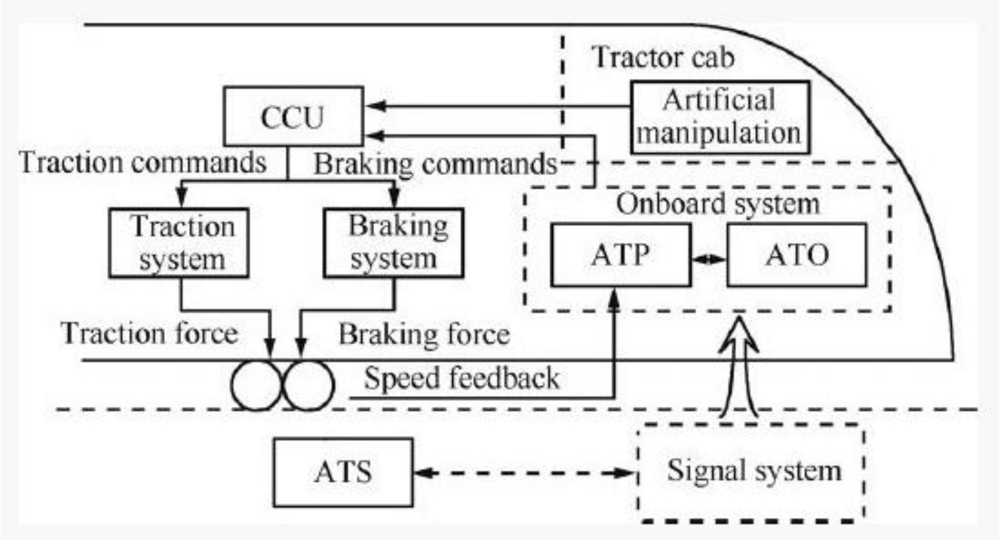


Figure 2.3: Automatic Train Operation Components [12]

With the development of modern railway systems, automatic train control systems have become vital equipment that ensures the running safety, shortens the train headways, and improves the quality of train operations. An advanced automatic train control system could consist of an automatic train protection (ATP) system, an automatic train supervision (ATS) system, and an ATO system.

The onboard ATP system is responsible for supervising the train speed according to the safety speed profile and for applying an appropriate braking force if necessary. In addition, the onboard ATP system also communicates with the wayside ATP system to exchange information (e.g., temporary speed limits and the limits of movement authority) to guarantee the safe operation of trains.

The ATS system acts as an interface between the operator and the railway system, managing trains according to the specific regulation criteria. The ATO system controls the traction and braking force to keep the train speed under the speed limit established by the ATP system. The ATO system can be used to facilitate the driver or to operate the train in a fully automatic mode; it thus plays a key role in ensuring accurate stopping, operation punctuality, energy saving, and riding comfort [11].

2.7 Communication Based Train Control (CBTC)

Conventional railway signaling is based on color light signals and train detection with the help of track circuits and axle counters. However, this technology is nearly half a century old. It is nearing its expiry in most of the installations worldwide and is responsible for most of the delays experienced every day. This is one reason why the conventional signaling systems are rapidly being replaced by modern signaling systems [13].

In modern, communication-based railway signaling, different means of telecommunication are used to transfer train control information between the train and the wayside. However, today the term is used almost exclusively for radio communication-based signaling. CBTC is a modern, radio communication-based signaling system. Using radio communication, it enables high resolution and real-time train control information, which increases the line capacity by safely reducing the distance (headway) between trains travelling on the same line, and minimizes the numbers of trackside equipment [13].

The CBTC (Communication Based Train Control) system has been known as the development direction of control systems for rail systems in the world. In particular, with quick development of modern mobile communication, its implementation and application become more and more easy. At present, CBTC has been used in city rail transportation systems, such as light rail and underground systems [14].

CBTC is a "*continuous, automatic train control system utilizing high-resolution train location determination, independent from track circuits; continuous, high-capacity, bidirectional train-to-wayside data communications; and train borne and wayside processors capable of implementing vital functions,*" as defined in the IEEE 1474.2 standard [15].

There is no standardization for CBTC systems. The CBTC systems from the different company cannot be compatible. It is easy for a kind of CBTC system from a company to monopoly the market. It is not good for commercial competition and technical development. For users of a railway network, it is not possible to select the best systems. Meanwhile, it is not easy for the CBTC system to be upgraded with technical development. Efforts are made to put forward the technical standardization for CBTC in terms of system configuration, function requirements, data format, interface definition and development in order to facilitate development and design of CBTC systems. Meanwhile, CBTC systems from the different companies can be compatible on a railway network and railway users have more choices in the CBTC markets. Of course, for every designer of a CBTC, it is easier for the whole system or part of the system of a CBTC to be upgraded with new technology advent [14].

2.7.1 CBTC System Architecture

Although a CBTC architecture is always depending on the supplier and its technical approach, the following logical components may be found generally in a typical CBTC architecture [16] [17].

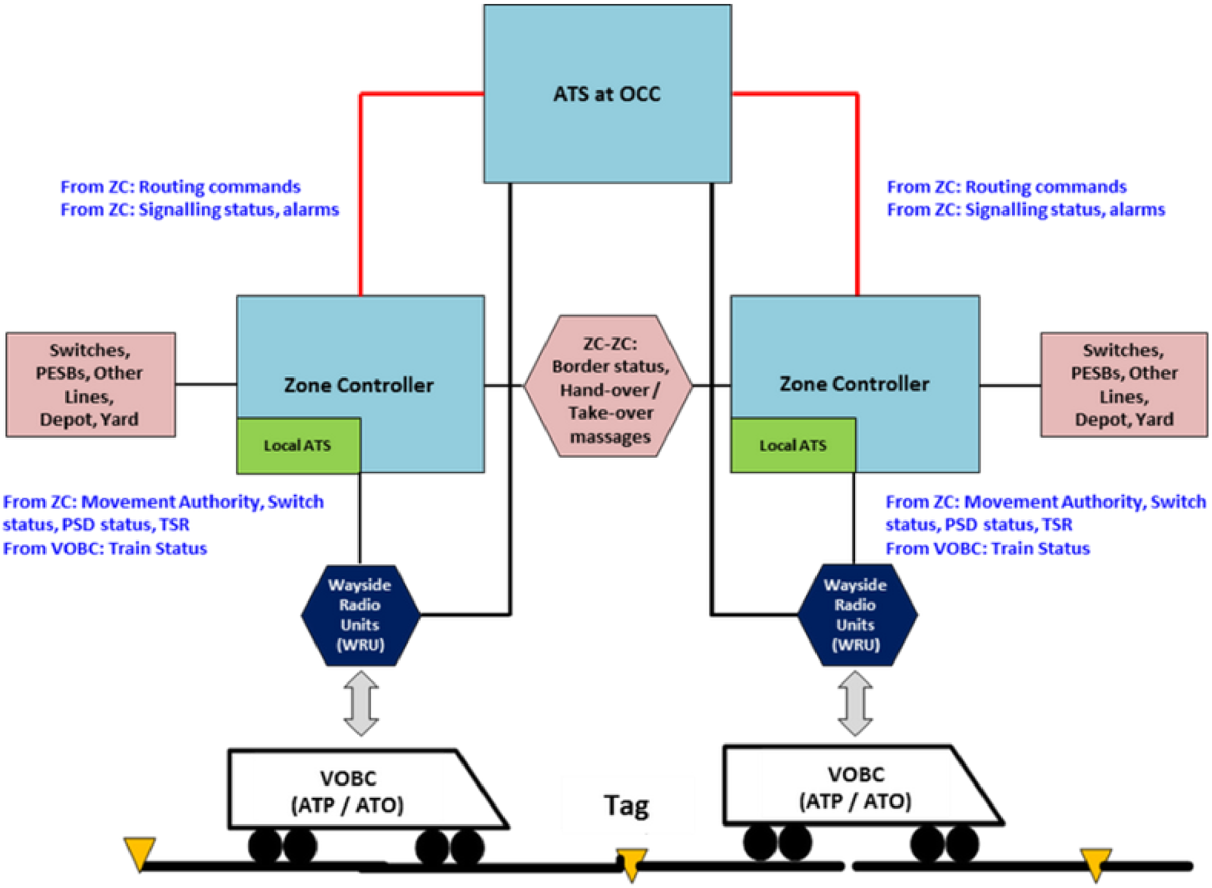


Figure 2.4: CBTC System Architecture [18]

1. Wayside Equipment. It includes the interlocking and the subsystems controlling every zone in the line or network (typically containing the wayside ATP and ATO functionalities). The control of the system is performed from a command ATS; though local control subsystems may also be included. Depending on the suppliers, the architecture may be centralized or distributed.

Wayside Equipment of any CBTC system will include Automatic train supervision, wayside ATP, Interlocking System (IXL), Active Balise (AB), Lineside Electronic Unit (LEU), Passive Balise (PB), Wayside ATO [16].

2. CBTC Onboard Equipment. It includes onboard ATP and onboard ATO subsystems in the vehicles. Onboard ATP is in charge of the continuous control of the train speed according to the safety profile and applying the brake if it is necessary. It is also in charge of the communication with the wayside ATP subsystem in order to exchange the information needed for a safe operation (sending speed and braking distance and receiving the LMA for a safe operation) [16] [12].

Onboard ATO is responsible for the automatic control of the traction and braking effort in order to keep the train under the threshold established by the ATP subsystem. Its main task is either to facilitate the driver or attendant functions or even to operate the train in a fully automatic mode while maintaining the traffic regulation targets and passenger comfort. It also allows the selection of different automatic driving strategies to adapt the run time or even reduce the power consumption.

The onboard equipment's consists of Odometer system (ODO), Train Interface Unit (TIU), Human Machine Interface (HMI), Balise Transmission Module (BTM), Train Wayside Communication (TWC) [16] [15].

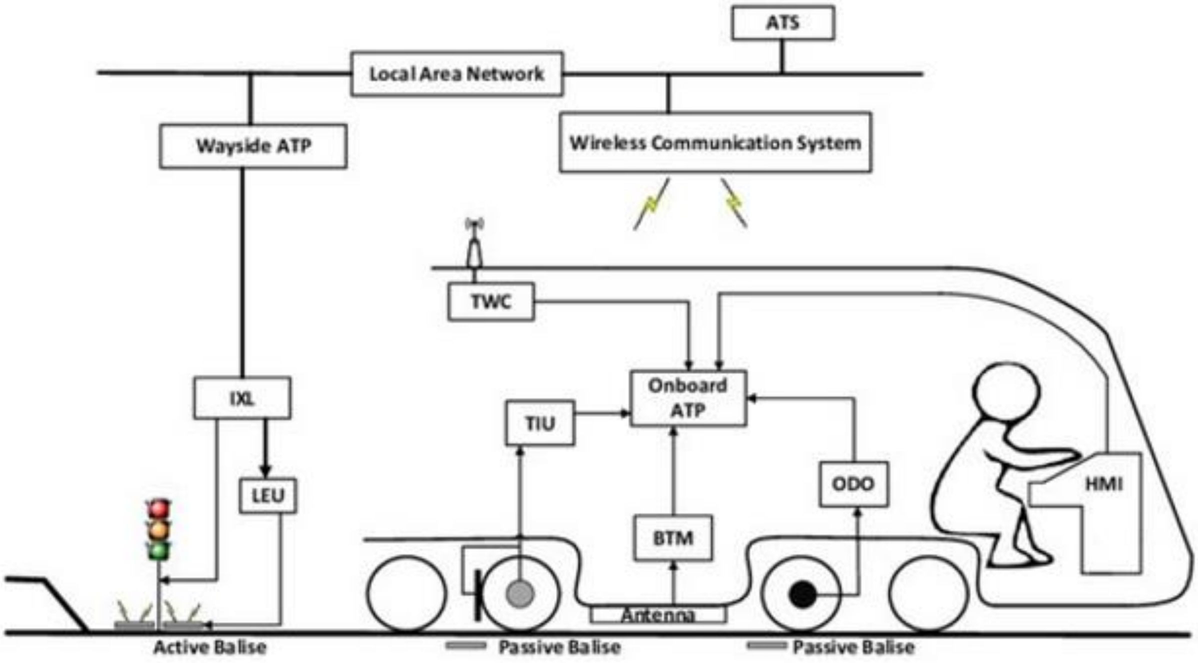


Figure 2.5 Train components for the Availability of the CBTC System [16]

3. Train–Ground Radio Communication Subsystem. It is one of the key technologies in CBTC systems. Wireless networks, such as Global System for Mobile Communications Railway and wireless local area networks (WLANs) are commonly used to provide bidirectional train–ground communications [16]. The modern CBTC systems use continuous and high capacity radio communication between the train and the wayside infrastructure to transmit train control information.

4. Zone Controller (ZC). The ZCs are located in the technical rooms. They are responsible for calculating and providing the MAL (movement authority limit) to the Car-borne Controller based on the information received from the trains and from other subsystems such as the interlocking. There are several ZCs per project to provide coverage for the full line. They exchange information with the onboard controllers in their territory and control, directly or through an external signal system, field equipment such as switches [16].

Failures occurring in any of the described devices may affect the system availability.

2.7.2 Working of CBTC

The goal of a CBTC system is the same as the traditional systems, for example, safe train separation; however, it also has the challenge of minimizing the amount of wayside and trackside equipment. This means the elimination of traditional train detection devices like track circuits. The reliable and safe mobile communication system become the key technology of a CBTC system. The accurate position system and the accurate speed measurement system are also the key technologies of CBTC systems [16].

The train continuously sends its current speed, direction, and location to the wayside over the radio connection. Based on this information received from all trains currently on the track, as well as a train's braking capability, the traffic control center at the wayside calculates the maximum speed and distance the train is permitted to travel, collectively known as "limit of movement authority" (LMA), and sends it to the train [13].

The main feature which differentiates a CBTC system from conventional signaling is the ability to determine the location of a train independent of track circuits [20]. The speed and location of a train is determined using a combination of devices such as speedometers, tachometers, transponders ("balises"), Doppler radar, odometers, and geolocation systems such as Global Positioning System (GPS). Location accuracy in particular is highly critical. Transponders or balises are fixed reference points mounted between rails. As a train passes over a balise, the location information is transmitted from the balise to the train using an antenna mounted under the train. Between the balises, location is continuously estimated using onboard odometer measurements. Any inaccuracies accumulated over distance are corrected when train passes the next balise.

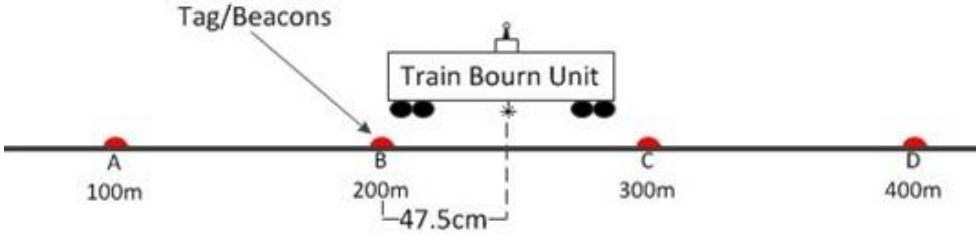


Figure 2.6: Transponders or Balises as a Reference Point [20]

As the train crosses tag/beacon B (Figure 2.6), the train borne unit is aware that it's located at the 200-meter mark (course position). As the train moves away, the tachometers will count how far the train has moved (fine position). Taking the course and fine position together, the train borne unit will be able to determine that the center of the train is located 247.5m away from the zero reference point [20].

There are a number of problems associated with using a geolocation system such as GPS as the primary means for localization. The location accuracy of geolocation systems might not be high enough, e.g. to differentiate trains traveling closely to each other. Satellite signals cannot be reliably received inside tunnels. Furthermore, CBTC suppliers are generally reluctant to depend on a system that is controlled by an external authority. Therefore, the use of a geolocation system in CBTC is normally supplementary.

Once the train is able to accurately determine its location, this information must be relayed to the wayside unit in a timely fashion. There are various methods to accomplish this. In the past inductive loop was utilized as a communication medium but recently over the past ten years, radio has become the technology of choice for the majority of suppliers. As the technology matures, radio will become the default standard for the rail industry. In the moving block operation employed in CBTC, thanks to the real-time communication between the train and the wayside, the train location is continuously updated. As a result, the occupancy block moves with the train and reflects its actual location. There are no fixed blocks boundaries.

For a railroad application, access points are installed along the track. As the train comes within range of an access point, the train borne radio will lock onto its signal and disconnect from the previous access point

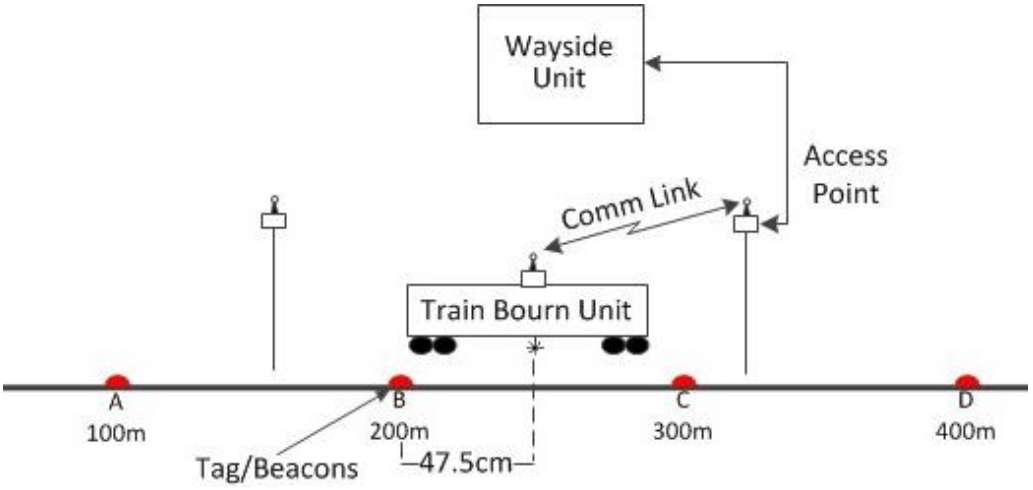


Figure 2.7: Train to Wayside Communication [20]

The communication protocols utilized in this medium is usually the standard Ethernet TCP/IP or UDP/IP protocols. This gives the solution flexibility and expandability. All data (vital and non-vital) is sent through this medium but this link is considered non-vital (TCP/IP and UDP/IP are not considered vital protocols). The train borne and wayside unit must guarantee the information they receive is not corrupted or stale through various mechanisms (sequence numbers, Tx ID, Rx ID etc.) [20].

It's not enough that a CBTC system is able to accurately determine the location of a train it also has to protect that train from all types' failures. It must also include these three vital functions collision avoidance, over speed protection and miscellaneous protections.

Based on this information, the train onboard ATP and ATO equipment's continuously adjusts the train speed and maintains the safety distance to any preceding trains.

CBTC systems offer the greatest operational flexibility and can support the maximum train throughput, constrained only by the performance of the rolling stock and the limitations of the physical track alignment. In particular, the high level of control provided by CBTC systems makes this the technology of choice for driverless/unattended train operations (UTOs).

2.7.3 Data Communication System

The modern CBTC systems use continuous and high capacity radio communication between the train and the wayside infrastructure to transmit train control information. The high resolution and highly accurate train location enables the "moving block" operation. The result is short headways and increased line capacity. A typical headway in CBTC systems is 90 seconds or less [13]. Furthermore, it enables advanced features such as driverless and unattended train operations. The first radio-based CBTC system was supplied by Bombardier and was installed at San Francisco airport in 2003[13].

Data communication systems are primarily designed to connect each component of CBTC systems: ZCs, APs along a railway, and train aboard equipment [21]. In CBTC system, continuous bidirectional wireless communications between each station adapter (SA) on the train and the wayside AP are adopted instead of the traditional fixed block track circuit. The railway line is usually divided into areas. Each area is under the control of a zone controller (ZC) and has its own wireless transmission system. The identity, location, direction, and speed of each train are transmitted to the ZC [16].

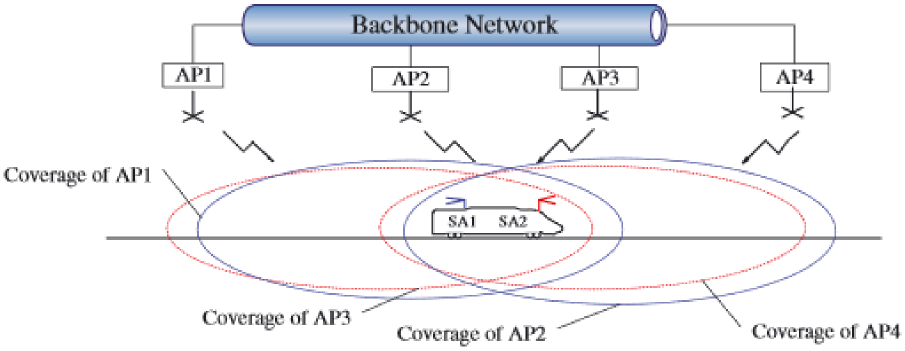


Figure 2.8: Data Communication System with Redundancy and Backup Link [21]

The wireless link between each train and the ZC must be continuous to ensure that the ZC knows the locations of all the trains in its area at all times. The ZC transmits to each train the location of the train in front of it, and a braking curve is given to enable it to stop before it reaches that train as well. Theoretically, two successive trains can travel together as close as a few meters in between them, as long as they are traveling at the same speed and have the same braking capability. Data communication systems are primarily designed to connect each component of CBTC systems: ZCs, APs (access points) along a railway, and train aboard equipment's.

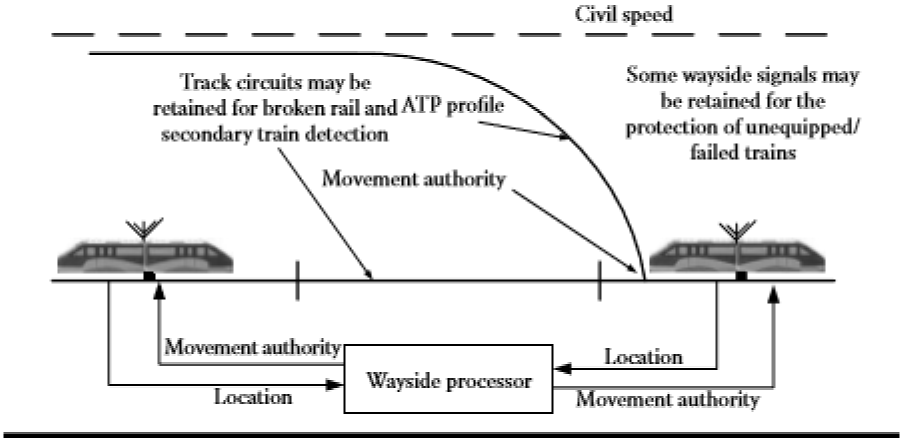


Figure 2.9: Communication Between CBTC Wayside and Onboard Components [16]

In radio-based CBTC systems, the radio network comprises the train borne radio and antenna equipment and trackside radio access points. Two alternative scenarios are possible for the transmission and reception of the wireless signal by the trackside radio access points [13]:

- The waveguide scenario: radio waveguides or leaky cables are installed along the track
- The free propagation scenario: antennas are positioned at distinct points along the track

The radio networks typically operate in the 2.4 GHz or 5.8 GHz frequency ranges. There are different advantages to using these microwave frequencies: First of all, microwaves propagate very well in tunnels, and, secondly, these frequency bands are globally available [13].

The low reliability of the wireless portion of the data communication system is mainly caused by the following [16]

1. Transmission errors due to dynamic channel fading in railway environments.
2. Handoffs that take place every time the train crosses the border of two successive APs's coverage areas. The communication link will be lost for a short period of time during the handoff process.

A typical configuration of the trackside backbone network is star-topology, as shown in Fig. 2.10, where each AP is connected directly to the wayside infrastructure using fiber optic cables as shown below.

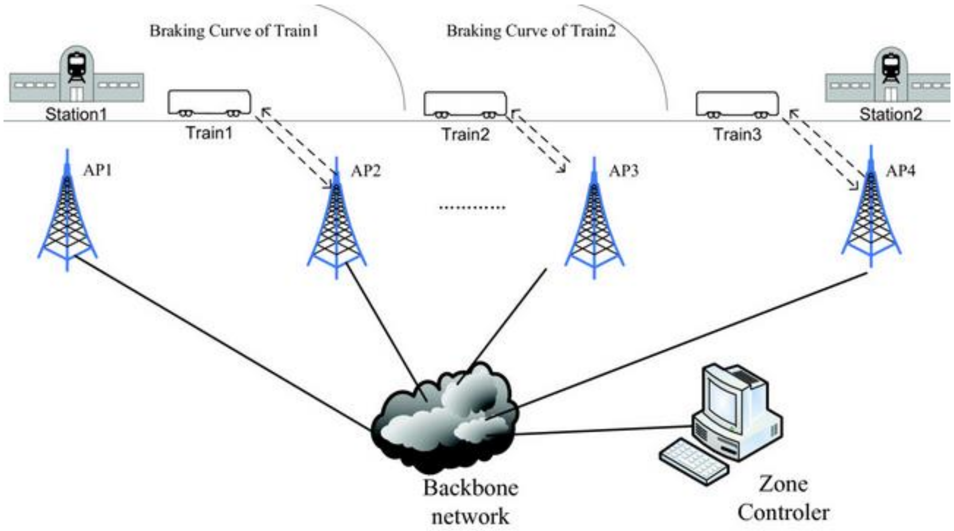


Figure 2.10: Star-Topology Trackside Network [22]

An advanced alternative is ring-topology, configuration minimizes cabling, as the distance between an AP and the backbone network is usually much larger than the distance between two adjacent APs.

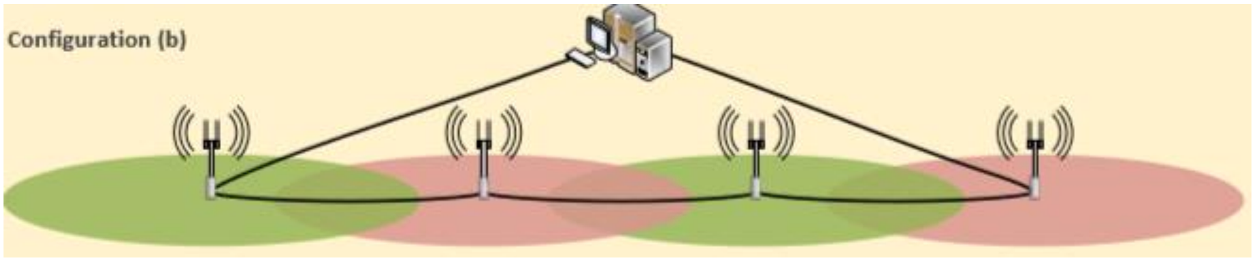


Figure 2.11: Ring Based Trackside Network [13]

An inherent limitation of a ring-based network is that a single failed node can disrupt the whole network. However, a number of Ethernet ring redundancy protocols, such as Media Redundancy Protocol (MRP), exist to mitigate this problem. Additionally, multiple rings can be employed to enable excessive redundancy, or to keep the number of nodes in a ring network under the limit.

2.7.4 Pros and Cons of Using CBTC System

CBTC has been deployed for more 30 years all over the world and is now a proven technology. Let us consider the reason why transit agencies decide to use CBTC for new lines or for upgrading their signaling system [16].

2.7.4.1 Pros of CBTC

The first advantage of using CBTC system is minimizing headway and increasing capacity. CBTC uses a moving or fixed virtual block system that allows trains to follow each other very closely resulting in improved headway performance.

The safety of a CBTC system is high. CBTC includes continuous automatic train protection (ATP). Many conventional signaling systems enforce the speed of the train only at certain locations using grade time signals. After the train engineer accepts such signal, the train may then be operated to its maximum speed until the next red signal. This results in intermittent speed control that relies on human intervention not supervised by any system [16].

The CBTC system includes an ATO mode that enables the control center to control the movement of the train without the train engineer controlling the rolling stock master controller. The ATO mode provides a smoother ride for passengers, results in more predictable operation, and enables energy saving. ATO operation can be associated with driverless operation for additional benefits. ATO is also possible with other types of train control implementations.

The main feature of a CBTC system is its high system availability. CBTC includes redundancy and built-in diagnostic systems which report the status of most equipment to the automatic train supervision (ATS). These functions are also possible with other types of train control implementations.

CBTC has less equipment than conventional signaling systems, in particular on the trackside. As a result, the maintenance cost of a CBTC system is less compared to the fixed signaling system.

2.7.4.2 Cons of CBTC

CBTC technology also comes with several challenges for transit agencies. Initial investment cost of deploying the technology may be higher than other types of train control. Design, hardware, installation, and testing of CBTC require years of effort and usually take longer than expected [16].

The system is not modifiable by the transit agency for different reasons. The first reason is the computer skills required for CBTC system may not be available within the agency. Secondly the original equipment manufacturer (OEM) is liable to provide a safe system to the transit agency. Transit agencies do not want to accept the responsibility for changing such complex system. Any change has to be carried out by the OEM [16].

CBTC technology is very different from traditional relay-based signaling system, and, therefore, the transit agency must adapt to it. It requires new skills for engineering and maintenance personnel as well as a new organization in the transit agency[16].

CHAPTER THREE

SIGNALING SYSTEM AND TIMETABLE OF AA-LRT

3.1 Introduction to AA-LRT

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 42 trains. Out of these 42 trains, 20 trains are allocated to the East-west line (EW), 20 are to North-South line (NS) and the rest 2 are engineering trains which are used only for maintenance purpose.

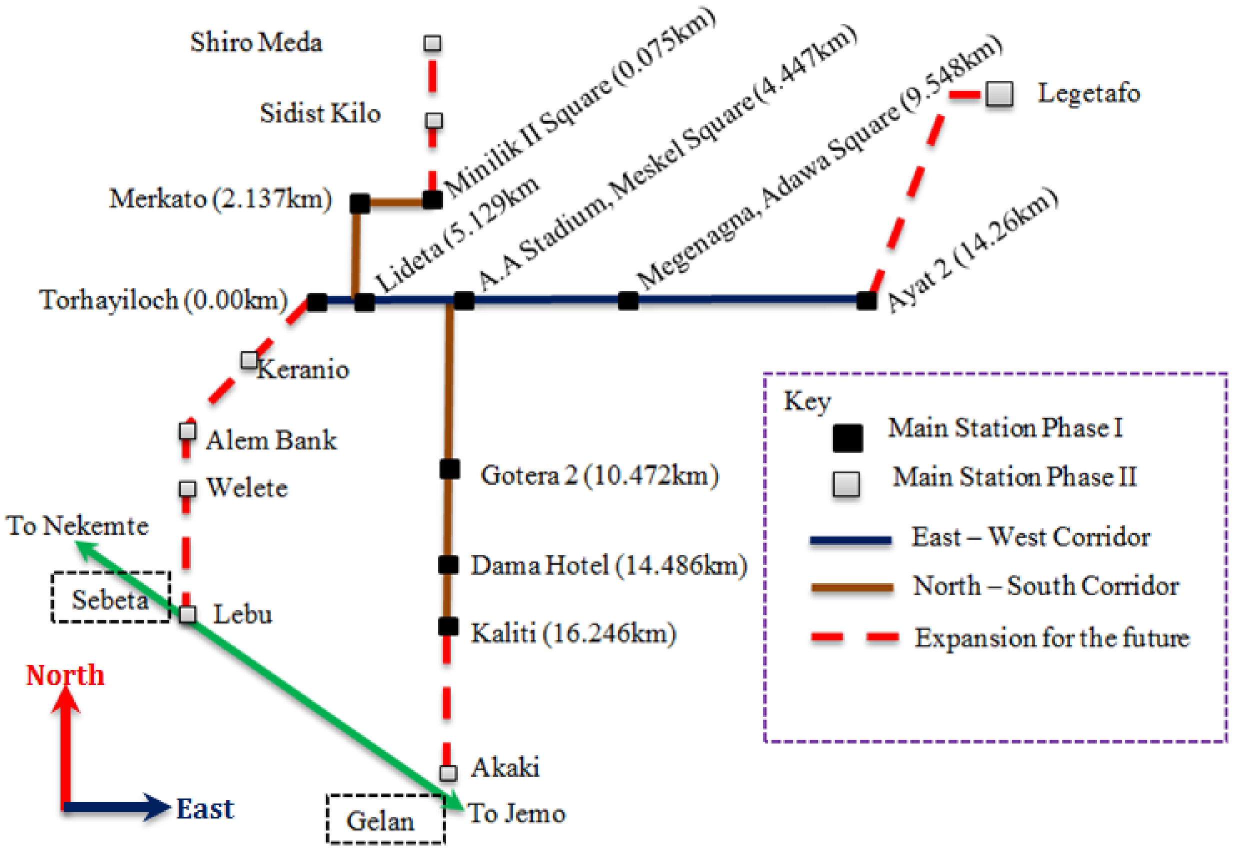


Figure 3.1: Addis Ababa LRT Rough Topology Including Future Expansions[23]

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. Since, It is fully electrified LRT ,it is environmental friendly . 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 [24].

The Addis Ababa light rail transit vehicles technical specification implies that operational speed of the AA-LRT is 20-70kmph with maximum speed of 80kmph whereas the maximum regression speed of a passenger train is 10km/h. The operation of train adopts the mode of manned visual driving .Average acceleration for startup is $1m/s^2$,Average deceleration for normal braking with rated load is greater than or equal to $1.0m/s^2$ and the average deceleration of emergency braking including the control response time is greater than or equal to $2m/s^2$ [24].

Its infrastructure line comprises tunnels, bridges, ground level and negotiates steep gradient(50‰) and sharp curves. AA-LRT use Standard Gauge of 1.435 meters with all the main,auxiliary tracks and the depots use 50kg/m steel rails with cut-length of 25m. The Sleeper arrangement of 1,600pairs/km for main tracks and 1,440pairs/km for tracks inside and outside the garages in rolling stock depots. Minimum Curve Radius is 50m for mainlines and 30m for parking garage [24].

3.2 Existing Train Control System of AALRT

3.2.1 Signaling System of AA-LRT

Signaling is one of the most important components of the many which make up a railway system. Train movement safety, control and management of trains depends on the signaling system of the railway operator. The main track of AA-LRT uses CASCO signal system, which consists of the following five subsystems.

1) IATP subsystem
2) Interlock subsystem (CBI subsystem)
3) ATS subsystem
4) DCS subsystem
5) MSS subsystem

The objective IATP is to calculate the track description and status according to inputs given by the CBI. Train can get trackside information either when it passes the switchable beacon or when it enters the radio area (this area is considered as a safe braking distance and time for radio establishment). IATP can get trackside information through CBI by radio. IATP subsystem consists of track side equipment and on-board equipment. Track side equipment consist of Beacons including mobile train initialization beacon (MTIB), relocation beacon (RB) and rapid location beacon, etc.

The on-board IATP equipment installed in each train can provide ATP functions like Excessive speed protection, jaywalk protection, backward sliding protection, Interval protection, train door monitoring, driving mode shifting, DMI (driving mode interface) and continuous monitoring of permanent speed limit.

Interlock equipment's basic interlock function can guarantee train operation safety. It connects with signal machine on the track side through safe relay to realize correct interlock relation and route control of the track section, turnout, and signal machine in the train route. The interlocking subsystem also is in charge of interface with line side electronic unit (LEU). The interlocking equipment mainly include turnouts, signals, axle counters and interlock control terminals.

Interlocking subsystem plays the most important role in signaling system. Without it, we can no longer ensure the operation safety and efficiency. Once, the worst situation occurs, only manual organization is available. In manual organization by ATS network, interlock device and ATS Signaling Devices provide status information and receive route ATS system control commands. Interlock device in combination with the ATS system control functions to achieve Approach control, approach to establish, approach locking and Unlock.

CBI block is one of the eight centralized station subsystem equipment CBI. In AA-LRT there are eight CBIs on the main line at stations EW1, EW7, EW16, EW20, EW22, NS6, NS10, NS27)

ATS-Automatic Train Supervision subsystem works with interlocking system, trackside integrated signal transfer point equipment, and other signal systems to implement centralized. monitoring of signal equipment and control of 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.

DCS data transmission subsystem consists of cable parts and wireless parts. This subsystem mainly including backbone network, a rail-side wireless access point (AP), on-board DCS antenna, onboard wireless modem and onboard Ethernet, etc. DCS cable network is the transmission platform of the whole signal system. DCS wireless network provides reliable, continuous and stable bidirectional communication channel for track side CBI and on-board CC system in order to understand point and continued IATP function.

IATP, Interlock, ATS, DCS, Level crossing signal equipment, and Power supply equipment can possess self-diagnosis and monitoring alarm function. MSS (Maintain and support subsystem**)** will maintain and support subsystem interlock, ATS, DCS, power supply to collect alarm information to realize remote concentrate monitoring and centralized supervising.

3.2.2 Cab Signaling

The cab signal system is an improvement over the wayside signal system, where visual signals beside or above the right-of-way govern the movement of trains, as it provides the train operator with a continuous reminder of the last wayside signal or a continuous indication of the state of the track ahead. [26]

Cab signaling systems in the AA-LRT 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.

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 [10].

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 counter point (no axle counter point will be set at the end of dead end tracks) [10].

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.

3.2.3 Block (Section) Safety of AA-LRT

Trains cannot collide with each other if they are not permitted to occupy the same section of track at the same time, so railway lines are divided into sections known as blocks. In normal circumstances, only one train is permitted in each block at a time. This principle forms the basis of most fixed block railway safety systems [26].

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) [10].

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 [10].

3.3 Timetable of AALRT

Timetable of AA-LRT have its own time specifications like trip time, dwell time and the headway. Hence because of this importance here is their definition with their specified time.

Running Interval: This is the headway time for both line of AA-LRT system. The system currently uses headway of 15 minutes in NS-line and 12 minutes in EW- line. But, the designed headway time (expected for the future) is 6 minutes with a capability of reducing to 90 seconds.

Return Time: this is the time taken by the trains to change direction at the end of track for example for NS line the return time for NS27 in NS27 is 5 minutes and 04 seconds.

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 40 seconds and in average 32.5 seconds.

3.3.1 Train Leaving/Entering the Depot Arrangement

3.3.1.1 Train Leaving Depot Arrangement

1) In peak hours, when the trains leave depot, the operation dispatcher should strictly control the trigger time of the depot-leaving route and return route to ensure train operation in accordance with train diagram.

2) Train leaving depot should base on planned route; OCC makes flexible adjustment under special circumstances.

3.3.2.2 Train into the Depot Arrangement

1) 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.

2) Train entering depot should base on planned route.

OCC makes flexible adjustment under special circumstances.

1)OCC and DCC need to strengthen contact, to ensure that the train leaving depot according to the plan;

2)Every day before 2 pm. the trains of NS line respectively turn back in the NS6 down ward platform and NS27 upward platform; the train of EW line turn back in the EW22 upward platform; After 2 p.m. the trains of NS line respectively turn back in the NS6 upward platform and NS27 downward platform; the trains of EW line turn back in the EW22 downward platform. the train turn back in ew1 platform the whole day

3) 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 the next day;

4) Every morning before 4:30am, DCC provides trains number scheduling to OCC.

According to the data collected from operation control center of AA-LRT there are two summarized technical detail schedule plans for trains of NS-line and EW-line.

3.3.2 Technical Details for NS-line

130 Commercial Train in Running

1. NS6～NS27：65 Upward commercial train in N-S line: 65trains
2. NS6～NS27：65 Downward commercial train in N-S line: 65 trains

8 Uncommercial Train in Running

1. NS6～NS27：4 Upward trains leaving depot: 4 trains
2. NS6～NS27：4 Downward trains entering depot: 4 trains

Table 3.1: Time for First/Last Train and Running Interval

Station / Time		N-S line			
		NS6		NS27	
First train		06:00	20502	06:00	20101
Last train		22:00	20518	22:00	20117
Route plan		NS6～NS27			
Running interval	15 min	06:00～22:00			

Table 3.2: Technical Details for Operation Timetable

Stop time for middle station	NS7--NS8 NS12--NS15 NS21--NS23	NS6，NS9，NS11 EW16--EW20 NS24--NS26	NS27 NS10
	25	30	35
NS6 Return time in NS6	8 min 38 s		
NS27 Return time in NS27	5 min 04 s		
（NS6～NS27） (NS6-NS27) Operation time for upward one-way (including stop)	**54 min 57 s**		

（NS27～NS6） (NS27-NS6) Operation time for downward one-way	**50 min 22 s**	
Numbers of train's groups for operation	Running interval	N-S line
	15 min interval	8
NS6～NS27 NS6-NS27 Running period (min)	120 min	
Running speed (km/h)	Upward	Downward
	17.6	**19.2**

3.3.3 Technical Details for EW-line

155 Commercial Train in Running

1. EW1～EW22：77 Upward commercial train in E-W line:77 trains
2. EW1～EW22：78 Downward commercial train in E-W line: 78 trains

7 Uncommercial Train in Running

1.EW1～EW22： 4 Upward trains leaving depot: 4 trains

2.EW1～EW22： 3 Downward trains entering depot:3 trains

Table 3.3: Time for First/Last Train and Running Interval

Station / Time		E-W line			
		EW1		EW22	
First train		06:00	10502	06:00	10103
Last train		22:00	10918	22:00	10819
Route plan		EW1～EW22			
Running interval	15 min	06:00～07:00/19:00～22:00			
	12 min	07:00～19:00			

Table 3.4: Technical Details for Operation Timetable

Stop time for middle station	EW16 -- EW20	EW5—EW9 EW12--EW15	EW3, EW4 , EW21	EW1,EW2	EW1, EW10
	30	45	50	55	60
Return time in EW1	10 min 35 s				
Return time in EW22	5 min 54 s				
(EW1-EW22) Operation time for upward one-way (including stop)	45 min 11 s				

(EW22～EW1) Operation time for downward one-way	46 min 25 s	
Numbers of train's groups for operation	Running interval	E-W line
	15 min interval	8
	12 min interval	9
EW1～EW22 EW1-EW22 Running period (min)	108 min	
Running speed (km/h)	Upward	Downward
	19.9	**19.2**

CHAPTER FOUR

TIMETABLE DESIGN MODEL FOR AA-LRT USING CBTC

Automatic train control system for Ethiopian context has been studied by a researcher based on topography, economy of the country (cost of the control system), interoperability future development of the railway system of the country, capacity of the control system, level of safety, culture of the people and different literature reviews. Moreover, a Communication Based Train Control System is one of the recommended Automatic train control system for Ethiopia [27].

4.1 Model Formulation

Before modeling timetable to AA-LRT, the following considerations and assumptions are made for Addis Ababa LRT system. The track is divided into different length of segments which are separated by intermediate stations; trains are assumed to stop at each station while moving from route starting point to the route terminal; tags/ balise are placed at regular intervals of 65m along the track; errors resulting from tachometer errors are given with typically 1% of the distance from the last Tag / balise and all the speed values are track speed limits which are collected from AA-LRT rolling stock department.

Here below (Figure 4.3) is the map of the sample stations and route of movement taken for this thesis. In order to find a good sample section for this new timetable model, it is a must to take in to account the common sections. It is known that the common sections have great impact on headway and also on synchronizations of trains.

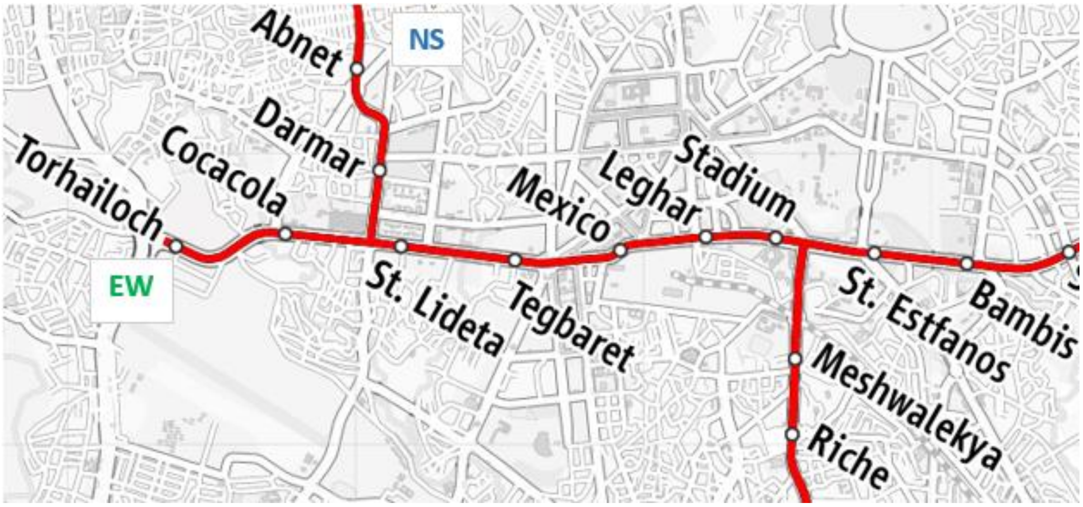


Figure 4.1: Map for the Sample Route Taken for the Thesis

4.2 Key Parameters of a Communication Based Train Control Timetable

4.2.1 Train Speed

One of the main parameters for a railway timetable is Train speed. It has a lot of effects in most of the other parameters to be considered. The train speed will affect the required headway between trains which will directly affect the capacity of the line.

On fixed block system if two trains operating at the same speed on unequal blocks, the maximum block length defined the minimum headway. Shorter block lengths and a strategic train order affected rail line capacity on a fixed block system. The maximum capacity of two trains can be achieved when two trains operated at the same speed in a moving block system. In this way, the route capacity is highly affected by the headway.

In the AA-LRT the speed designed ranges from 20-70km/h and the maximum regression speed of the trains is 10km/h [24].

4.2.2 Dwell Time

Dwell time is a main parameter of system performance, service quality and reliability in the rail passenger service. With known factors affecting dwell time, the dwell time at critical stations could be minimized, thus reducing the headway variations and enhancing service quality and reliability. Reduction in a dwell time can often result in a reduced headway. A variety of different factors determine how long dwelling time takes, including the size of the door on the train, the number of passengers waiting to board, or the step height from the platform to the floor of the car of the vehicle.

Train dwelling time (D_T) has two components [28]: -

- A fixed time for opening and closing doors T, and
- Door utilization time T, for boarding and alighting passengers

In the case of AA-LRT stations like Lem-Hotel(EW10), Hayahulet 1 (EW11), Autobus Tera (NS24), and Adey Ababa (NS9) have a lot of passenger movement hence they need longer dwell time than others which have few number of passenger movements. Currently, the AA-LRT has a dwell time ranging from 25 to 40 seconds. The proportion of dwell time productively used for passenger movements ranges from 31 to 64% of the total dwell time [27].

Table 4.1: Dwelling time, Speed and Gradient of Sample Sections

Station (From ~ to)	Section/Route Name (From ~ to)	Speed (km/hr)	Speed (m/s)	Gradient (‰)	Dwelling time (Sec)
EW Line					
EW15 - EW14	St.Estfanos to Bambis	60	16.667	-49	25
EW16 - EW15	Stadium to St.Estfanos	35	9.722	-47	30
EW21 - EW20	CocaCola to Lideta	35	9.722	-49.13	30
EW22 - EW21	Torhailoch to CocaCola	50	13.889	-55	35
Common Line					
EW17 - EW16	Leghar to Stadium	55	15.278	-46	30
EW18 - EW17	Mexico to Leghar	45	12.500	20.73	30
EW19 - EW18	Tegbared to Mexico	45	12.500	46	30
EW20 - EW19	Lideta to Tegbared	31.86	8.850	-55	30
NS Line					
NS15 - NS14	Meshwalkya to Riche	23.4	6.500	-43	25
NS16 - NS15	Stadium to Meshwalkya	20	5.556	-47	30
NS21 - NS20	Darmar to Lideta	35	9.722	-48.866	25
NS22 - NS21	Abnet to Darmar	20	5.556	-46	25

4.2.3 Movement Authority (MA)

A Movement Authority is defined as the authority for a train to safely proceed up to a certain point where it has to stop. In fixed block systems, the Movement Authority consists of a locked train route starting at a certain signal with a proceed aspect and ending at another signal with a stop aspect, passing through one or more track sections.

In a CBTC moving block system the Movement Authority is set from the exact point where the train is to a ‘conflict point’ in the track ahead of the train. In a CBTC system with constant update of information about the train’s position and constant renewal of the MA the train will be allowed to proceed without braking as long as there is no conflict point within braking distance ahead of it [14].

4.2.4 Conflict Points (CP)

A Movement Authority for a train always ends at a 'conflict point' ahead of the train. A 'conflict point' is defined as a location along the track beyond which a train NOT permitted to enter.
A CBTC system utilizes these conflict points to properly and safely manage the movement of trains throughout any metro line. A conflict point can either be static, meaning that its location in the track is fixed or dynamic, which means that its location is a moving train. An example of a static conflict point is a buffer stop at the end of the line and an example of a dynamic conflict point is the end of the train in front [14].

4.2.5 Calculating 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.

Stopping a train requires work. This work equals the change in the train's kinetic energy plus the change in its potential energy (change in height due to the gradient of the track).
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 acceleration rate (a) (deceleration is negative acceleration) and the stopping distance (S) [30].

The change in 'kinetic' energy relates to the change in the train's speed i.e. the difference of the speed at which deceleration began (U) and the 'at stop' speed i.e. 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 the its height at the stopping point (h_2).
Mathematically this can be expressed as [30]:

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

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‟

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

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 below). For small α, which is the case for railways, tanα equals sinα. Sin α is the change in height (h2– h1) over the stopping distance(s) which is given as follows [30].

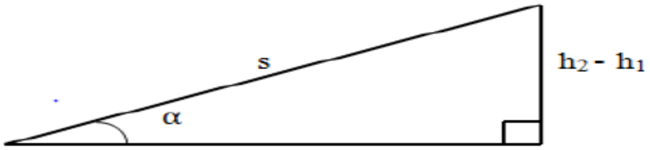


Figure 4.2: Sample of the gradient for braking distance calculation

$$(h_2 - h_1) = s(\sin\alpha) = s(\tan\alpha) \qquad \text{...}(4.3)$$

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

Now substituting equation and then putting final speed v=0, gives

Where "a‟ is the deceleration, hence it is negative.

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

$$(h_2 - h_1) = s(\sin\alpha) = s(\tan\alpha)$$

$h_2 - h_1 > 0$ and $h_2 - h_1 < 0$

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

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. In the AA-LRT the maximum grade of the main track is 55‰, and the minimum grade is 0‰ [24].

Here below is the calculation of service braking distance on sample stations for the case of this thesis using Equation 4.4. The blocks used here are selected based on the restricted speed allowed which can show the different speed ranges (minimum, average and maximum speeds).

EW direction: EW15-EW14, EW16- EW15, EW21- EW20, EW22- EW21 and the speed of each station is 60km/hr, 35km/hr, 35km/hr and 50km/hr respectively

For EW15 - EW14 here u = 60km/h = 16.667m/s, $\alpha = -49/1000 = -0.049$

$S = -u^2 / (2\,(a - g\,(\tan\alpha))) = -(16.667)^2 / [2(-1 - 9.8\tan(-0.049))] = 140.063\text{m}$

For EW16 - EW15 here u = 35km/h =9.72222m/s, $\alpha = -47/1000 = -0.047$

$S = -u^2 / (2\,(a - g\,(\tan\alpha))) = -(9.72222)^2 / [2(-1 - 9.8\tan(-0.047))] = 47.644\text{m}$

For EW21- EW20 here u = 35km/h = 9.72222m/s, $\alpha = -49.13/1000 = -0.04913$

$S = -u^2 / (2\,(a - g\,(\tan\alpha))) = -(9.72222)^2 / [2(-1 - 9.8\tan(-0.04913))] = 47.661\text{m}$

For EW22 - EW21 here u = 50km/h = 13.889m/s, $\alpha = -55/1000 = -0.055$

$S = -u^2 / (2\,(a - g\,(\tan\alpha))) = -(13.889)^2 / [2(-1 - 9.8\tan(-0.055))] = 97.367\text{m}$

Common stations: EW17 - EW16, EW18 - EW17, EW19 - EW18, EW20- EW19 with the speed of 55km/hr, 45km/hr, 45km/hr, and 31.86km/hr respectively.

For EW17- EW16 here u = 55km/h = 15.278m/s, $\alpha = -46/1000 = -0.046$

$S = -u^2 / (2\,(a - g\,(\tan\alpha))) = -(15.278)^2 / [2(-1 - 9.8\tan(-0.046))] = 117.63\text{m}$

For EW18- EW17 here u = 45km/h = 12.5m/s, $\alpha = 20.73/1000 = 0.02073$

$S = -u^2 / (2\,(a - g\,(\tan\alpha))) = -(12.5)^2 / [2(-1 - 9.8\tan(0.02073))] = 77.849\text{m}$

For EW19- EW18 here u = 45km/h = 12.5m/s, $\alpha = 46/1000 = 0.046$

$S = -u^2 / (2\,(a - g\,(\tan\alpha))) = -(12.5)^2 / [2(-1 - 9.8\tan(0.046))] = 77.515\text{m}$

For EW20- EW19 here u = 31.86 km/h = 8.85m/s, $\alpha = -55/1000 = -0.055$

$S = -u^2 / (2\,(a - g\,(\tan\alpha))) = -(8.85)^2 / [2(-1 - 9.8\tan(-0.055))] = 39.533\text{m}$

NS direction: NS15-NS14, NS16-NS15, NS21- NS20, NS22- NS21, and with the speed of 23.4km/hr, 20km/hr, 35km/hr and 20km/hr respectively.

For NS15-NS14 here u = 23.4km /h = 6.5m/s, α = -43/1000= - 0.043

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (6.5)^2 / [2(-1-9.8\tan (- 0.043))] = 21.304m$

For NS16-NS15 here u = 20km/h = 5.556m/s, α = -47/1000= - 0.047

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (5.556)^2 / [2(-1-9.8\tan (- 0.047))] = 15.557m$

For NS21- NS20 here u = 35km/h = 9.722m/s, α = -48.866/1000= - 0.048866

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (9.722)^2 / [2(-1-9.8\tan (-0.048866))] = 47.653m$

For NS22- NS21 here u = 20km/h = 5.556m/s, α = -46/1000= - 0.046

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (5.556)^2 / [2(-1-9.8\tan (-0.046))] = 15.554m$

4.2.6 Emergency Braking distance

A following train must know at any time the speed, position and braking capacity of its front train to calculated its own control speed curve. Once the communication is interrupted, the following train must be actuated by emergency braking to ensure train operation safety.

EW direction: EW15-EW14, EW16- EW15, EW21- EW20, EW22- EW21 and the speed of each station is 60km/hr, 35km/hr, 35km/hr and 50km/hr respectively

For EW15 - EW14 here u = 60km/h = 16.667m/s, α = -49/1000= -0.049

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (16.667)^2 / [2(-2-9.8\tan (-0.049))] = 69.737m$

For EW16 - EW15 here u = 35km/h =9.72222m/s, α = -47/1000= -0.047

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (9.72222)^2 / [2(-2-9.8\tan (-0.047))] =23.726m$

For EW21- EW20 here u = 35km/h = 9.72222m/s, α = -49.13/1000= - 0.04913

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (9.72222)^2 / [2(-2-9.8\tan (-0.04913))] = 23.730m$

For EW22 - EW21 here u = 50km/h = 13.889m/s, α = -55/1000= -0.055

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (13.889)^2 / [2(-2-9.8\tan (-0.055))] = 48.453m$

Common stations: EW17 - EW16, EW18 - EW17, EW19 - EW18, EW20- EW19 with the speed of 55km/hr, 45km/hr, 45km/hr, and 31.86km/hr respectively.

For EW17- EW16 here u = 55km/h = 15.278m/s, α = -46/1000= - 0.046

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (15.278)^2 / [2(-2-9.8\tan (-0.046))] = 58.583m$

For EW18- EW17 here u = 45km/h = 12.5m/s, α = 20.73/1000= 0.02073

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (12.5)^2 / [2(-2-9.8\tan (0.02073))] = 38.993m$

For EW19- EW18 here u = 45km/h = 12.5m/s, α = 46/1000= 0.046

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (12.5)^2 / [2(-2-9.8\tan (0.046))] = 38.909m$

For EW20- EW19 here u = 31.86 km/h = 8.85m/s, α = -55/1000= - 0.055

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (8.85)^2 / [2(-2-9.8\tan (- 0.055))] = 19.673m$

NS direction: NS15-NS14, NS16-NS15, NS21- NS20, NS22- NS21, and with the speed of 23.4km/hr, 20km/hr, 35km/hr and 20km/hr respectively.

For NS15-NS14 here u = 23.4km /h = 6.5m/s, α = -43/1000= - 0.043

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (6.5)^2 / [2(-2-9.8\tan (- 0.043))] = 10.607m$

For NS16-NS15 here u = 20km/h = 5.556m/s, α = -47/1000= - 0.047

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (5.556)^2 / [2(-2-9.8\tan (- 0.047))] = 7.747m$

For NS21- NS20 here u = 35km/h = 9.722m/s, α = -48.866/1000= - 0.048866

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (9.722)^2 / [2(-2-9.8\tan (-0.048866))] = 23.728m$

For NS22- NS21 here u = 20km/h = 5.556m/s, α = -46/1000= - 0.046

$S = -u^2 / (2 (a-g (\tan\alpha))) = - (5.556)^2 / [2(-2-9.8\tan (-0.046))] = 7.747m$

4.2.7 Braking Time (Bt)

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 [10]:

B_t = Braking distance/Speed ……………………………………………..(4.5)

Here below is the calculated Service braking time and Emergency Braking time using the formula

Table 4.2: Service and Emergency Braking Time

Stations	Gradient (‰)	Speed (m/s)	Service Braking Distance(m)	Emergency Braking Distance(m)	Service Braking Time(sec)	Emergency Braking Time(sec)
EW15 - EW14	-49	16.667	140.063	69.737	8.404	4.184
EW16 - EW15	-47	9.722	47.644	23.726	4.901	2.440
EW21 - EW20	-49.13	9.722	47.661	23.730	4.902	2.441
EW22 - EW21	-55	13.889	97.367	48.453	7.010	3.489
EW17 - EW16	-46	15.278	117.631	58.583	7.699	3.835
EW18 - EW17	20.73	12.500	77.849	38.993	6.228	3.119
EW19 - EW18	46	12.500	77.515	38.909	6.201	3.113
EW20 - EW19	-55	8.850	39.533	19.673	4.467	2.223
NS15 - NS14	-49	6.500	21.304	10.607	3.277	1.632
NS16 - NS15	-47	5.556	15.557	7.747	2.800	1.394
NS21 - NS20	-48.1	9.722	47.653	23.728	4.901	2.441
NS22 - NS21	-46	5.556	15.554	7.747	2.800	1.394

4.2.8 Operating Margin Time (OMT)

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 [10].

4.2.9 Release Time (Rt)

The release time is the time required for the entire length of a train to cross a signal at a station or to fully leave a station and enter to another station. Mathematically it is given as [10]:

Rt = Length of train /Speed

In the case of AA-LRT when two trains are coupled they make a total length of about 59 meters. In this thesis we are going to take this value as our length of train.

Hence Rt = 59m/speed …………………………………… …. (4.6)

Using the formula shown above we can calculate the numerical values of the release times for the sample stations.

- $Rt_{(EW15 - EW14)}$ = 59m/60kmph = 59/16.667 = 3.540 seconds
- $Rt_{(EW16 - EW15)}$ = 59m/35kmph = 59/9.722 = 6.069 seconds

- $Rt_{(EW21 - EW20)}$ = 59m/35kmph = 59/9.722 = 6.069 seconds
- $Rt_{(EW22 - EW21)}$ = 59m/50kmph = 59/13.889 = 4.248 seconds
- $Rt_{(EW17 - EW16)}$ = 59m/55kmph = 59/15.278 = 3.862 seconds
- $Rt_{(EW18 - EW17)}$ = 59m/45kmph = 59/12.5 = 4.720 seconds
- $Rt_{(EW19 - EW18)}$ = 59m/45kmph = 59/12.5 = 4.720 seconds
- $Rt_{(EW20 – EW19)}$ = 59m/31.86kmph = 59/8.850 = 6.667 seconds
- $Rt_{(NS15 - NS14)}$ = 59m/23.4kmph = 59/6.5 = 9.077 seconds
- $Rt_{(NS16 - NS15)}$ = 59m/20kmph = 59/5.556 = 10.620 seconds
- $Rt_{(NS21 – NS20)}$ = 59m/35kmph = 59/9.722 = 6.069 seconds
- $Rt_{(NS22 – NS21)}$ = 59m/20kmph = 59/5.556 = 10.620 seconds

4.2.10 Time Lock Switches

Time lock switches are manual switches found in t-rail on the mainline. Like all other mainline t-rail switches, they are padlocked for safety. However, these have an additional lock built in where the switch cannot be thrown until a timer has counted down, hence the name. They will have a sight glass on the switch machine that displays the status of the lock; it'll show the word padlocked, under normal operating conditions while the padlock is in place and display locked which is that status after the padlock was removed but before the timer is up. On the other hand, Unlocked means that the padlock has been removed and the timer has run out, so the switch can now be thrown [31].

If there is no train detected in the approach circuit where the switch is, the timer takes 17 seconds before the switch can be thrown. If there is a train in the circuit approaching a time lock switch, it takes 4 minutes and 17 seconds before the time lock timer runs out and the switch can be thrown this is done as a safeguard to give the train time to get out of the circuit before the switch is thrown [31]. This is the same case of the switches found main line of AA-LRT and this safety lock time must be considered when analyzing the headway between two trains. This 420 second is the time taken for trains coming from two directions (EW and NS) but for two consecutive trains coming from the same direction (which is either from NS or EW direction) the switch will create path after 840 seconds.

4.2.11 Positional Uncertainty

The basic premise behind a CBTC system is its ability to determine the location of a train independent of axel counters. Transponder tags or beacons (tag will be used for the remainder of the post) installed along the track provide coarse position and speed sensors installed on the axle provide fine position. CBTC train's ability to report an accurate position depends on the design of the train and the track it's running on [32].

Positional uncertainty is the area of track where the train might be located. The magnitude depends on the track characteristics and train parameters. If a train reports a position of 147.5m, the actual position may be 150m or 145m (+/- 2.5m for example). This extra 2.5 meters in front and behind the train is called the positional uncertainty and must be considered occupied. Several factors affect positional uncertainty and they are broken into two components, the static and dynamic uncertainty [32].

Position uncertainty =Static uncertainty + Dynamic uncertainty

$$P = S + D \qquad \text{(4.7)}$$

4.2.11.1 Static Uncertainty (S)

The static uncertainty is present from the moment the train borne unit is powered on. It's fixed and does not change when the train moves and it's composed of factors like transponder tag footprint and transponder tag installation error.

The lobes that radiate out from the tag create a footprint which is called transponder tag footprint. When the train passes over the tag, the tag antenna (on the train) may detect the tag earlier (or later) then it should [32]. Usually, when a train passes over a beacon, its BTM emits electromagnet wave to power the beacon. A 20 Won-board antenna, a BTM emits a continuous electromagnetic wave at frequency 27.095 MHz (±5 kHz) to power a beacon up to a distance of 60 cm. The downlink uses an amplitude modulation on the 27.095 MHz frequency. This frequency is used to power the passive beacon. The uplink uses frequency-shift keying with 3.951 MHz for a logical

'0' and 4.516 MHz for a logical '1'. The data rate of 564.48 Kbit/s is enough to transmit 3 copies of a telegram to a train passing at 500 km/h.

The beacon induced voltage is variable with the distance between BTM and beacon center point. If the induced voltage becomes higher than a threshold value Vth (e.g., 3.3 V), the beacon is activated to send the telegram to the train, and will transmit the telegram repeatedly as long as the induced voltage is higher than Vth. Therefore, the moving train may receive a multiple of telegram copies at different positions [33] [34].

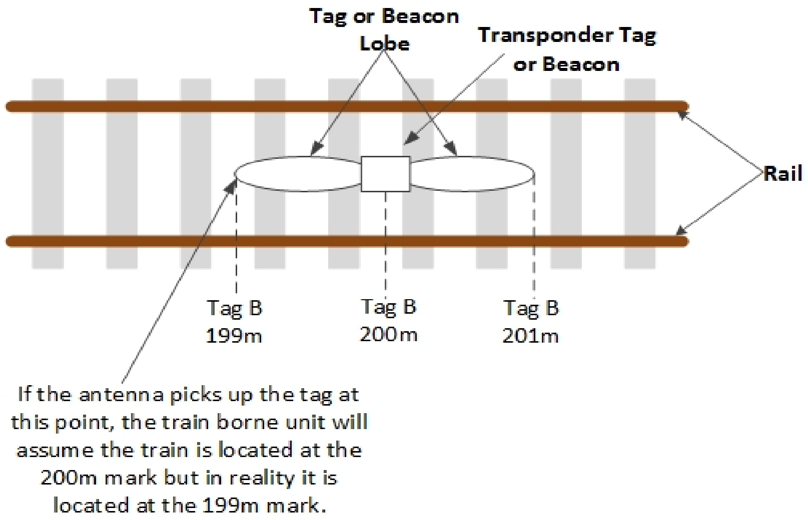


Figure 4.3: Tag or Beacon Lobe [32]

If the tag or beacons is shifted to either side by a small margin, the train borne unit will still consider the train is located at the same mark but in fact the train is located plus or minus the installation error (transponder tag installation error). According to Addis Ababa E-W and N-S LRT project(p1) signaling system beacon installation specification Beacons must be installed in transversal or longitudinal direction relative to the train traffic direction. The beacons found in AA-LRT are euro beacon which are installed under the STF-DL antenna with the transversal installation tolerance of maximum offset ± 5mm on the Z axis and ± 40mm horizontal offset relative to the track center axis if the curve radius is greater than or equal to 1000m, and maximum speed is less than or equal to 180Km/hr. The distance between the beacon and the top of the rail should be ensured at 65mm and the distance from the bottom of antenna to the top of rail is between 170mm and 290mm in order to ensure correct transmission.

4.2.11.2 Dynamic Uncertainty (D)

The dynamic uncertainty is related to train movement. It’s based on the distance the train has travelled since a known reference point; as the train moves the error increases. The dynamic uncertainty consists of wheel slip, wheel slide, Speed Sensor Granularity and wheel calibration.

Wheel slipping occurs when tractive effort exceeds adhesive weight .If the speed sensor is installed on a powered axle, error will occur on the reading of the odometer when the wheel slip. This is similar to a car spinning its wheels when it accelerates suddenly; the odometer detects movement but the car did not move. Most suppliers have a mechanism to detect wheel slip but undetected micro slips around curves will not be detected [32]. However, in the case of AA-LRT the speed sensors are installed in the TP module (trailer without driver’s cab) [24].

If the speed sensor is installed on a braked axle there is a chance the axle will lock and the train will slide. From the speed sensor perspective, the train stopped but in reality it’s still moving (Wheel sliding). If a supplier does not have a mechanism in place to detect wheel slide, the dynamic uncertainty will be higher. In AA-LRT there is automatic systems used to detect and prevent wheel-slide during braking.

The speed senor is a device connected to the axle of the train. It determines the speed and distance the train has travelled based on the number of pulses per revolution. This device has its own error that builds up over the distance travelled. the speed sensor which is installed in AA-LRT is called Hasler IP68 known by its high accuracy. In this thesis Speed sensor granularity is assumed to be 1% of the distance from the last Tag / balise.

The diameter of the wheel changes over time. The train must run a wheel calibration test to determine the actual wheel diameter which is used to calculate the distance the train travels every revolution. If the wheel calibration test fails, this will add to the dynamic uncertainty. The Wheel calibration test is done regularly in AALRT. Wheel diameter for new wheel ≤660 mm and max wear Wheel diameter ≤600 mm [24].

Unless there is a mechanism to reset the dynamic uncertainty, the error will grow indefinitely causing the length of the train to increase indefinitely. To control this behavior, the tag is used to reset the dynamic error because it’s an established reference point; the installation is guaranteed within a certain margin of error. When the train detects the tag, the dynamic error is reset (but not the static error).

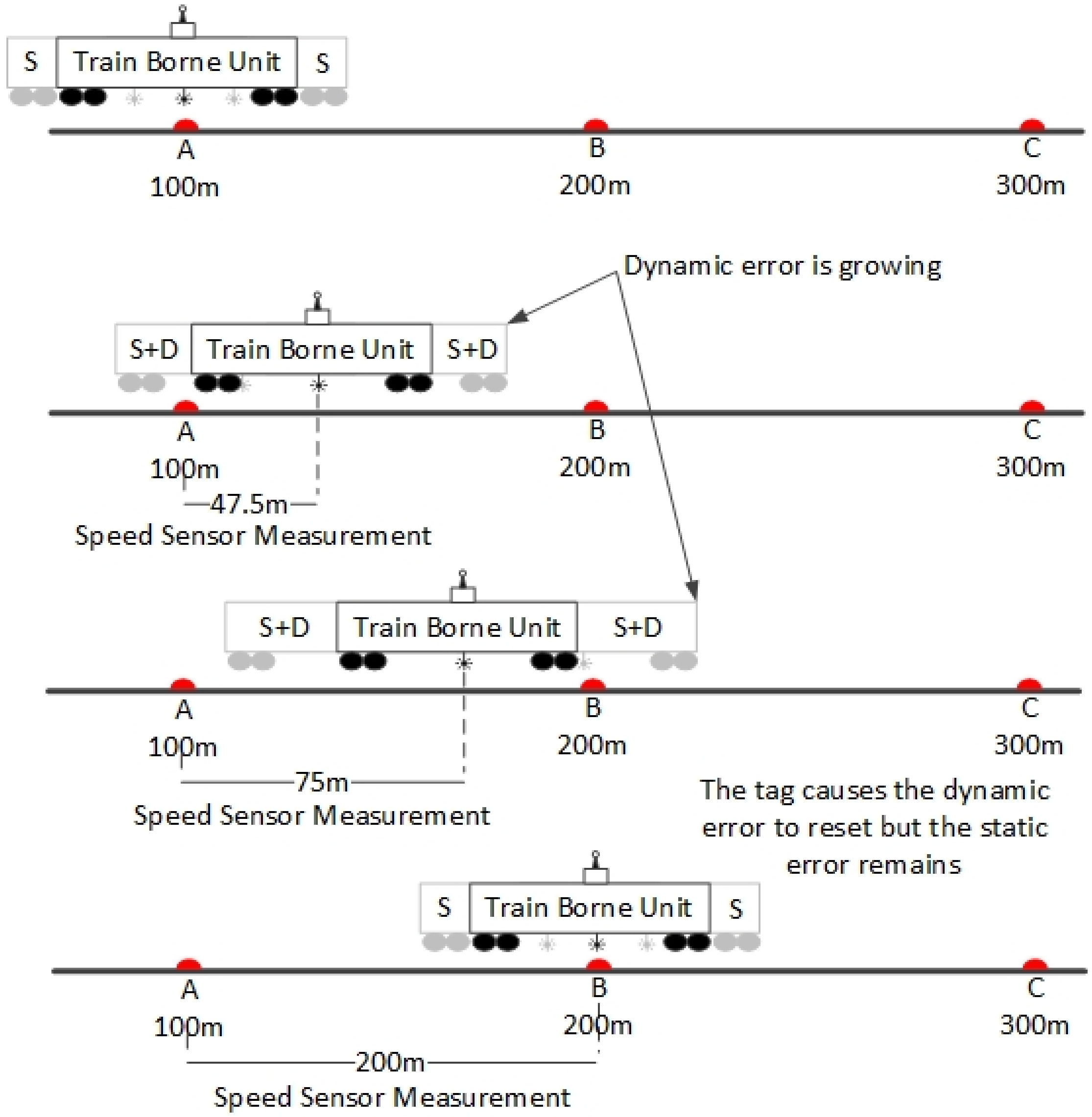


Figure 4.4: Dynamic Error Reset at New Reference Point [32]

The general rule is, the tags are spaced out one to two hundred meters in between the stations and as close as 10 meters apart leading into the station stopping point.

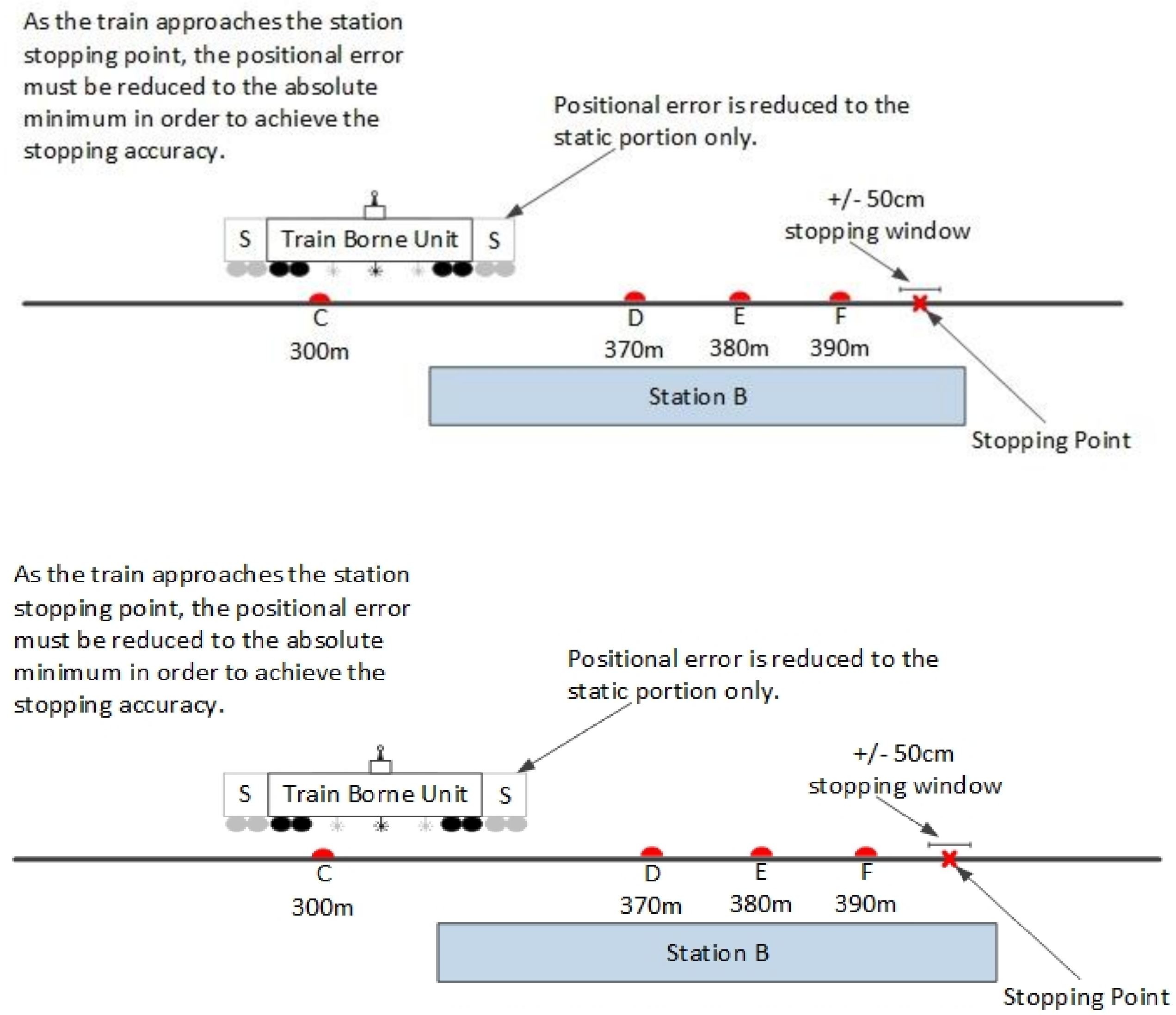


Figure 4.5: Tag Placement Near Station [32]

Putting all together; The position uncertainty of AA-LRT which is calculated for the case of this thesis equal to (for the front and the rare part):

$$P = 2(S + D) = 6.5cm + 30cm + 60\ cm = 96.5cm = 2*0.965m = 1.93m$$

Train board unit precision = Tachometer errors are assumed with typically 1% of the distance from the last Tag =1% of 65 m= 6.5cm

Stopping accuracy = 30cm

Transponder Tag footprint = 60 cm

4.2.12 Minimum Headway Calculation

Headway is defined as the time interval between the successive trains moving along the same track in the same direction through the same point. Minimum Design Headway is defined as the shortest headway at which the CBTC system is able to operate trains at its maximum ATO speed continuously [35] [20].

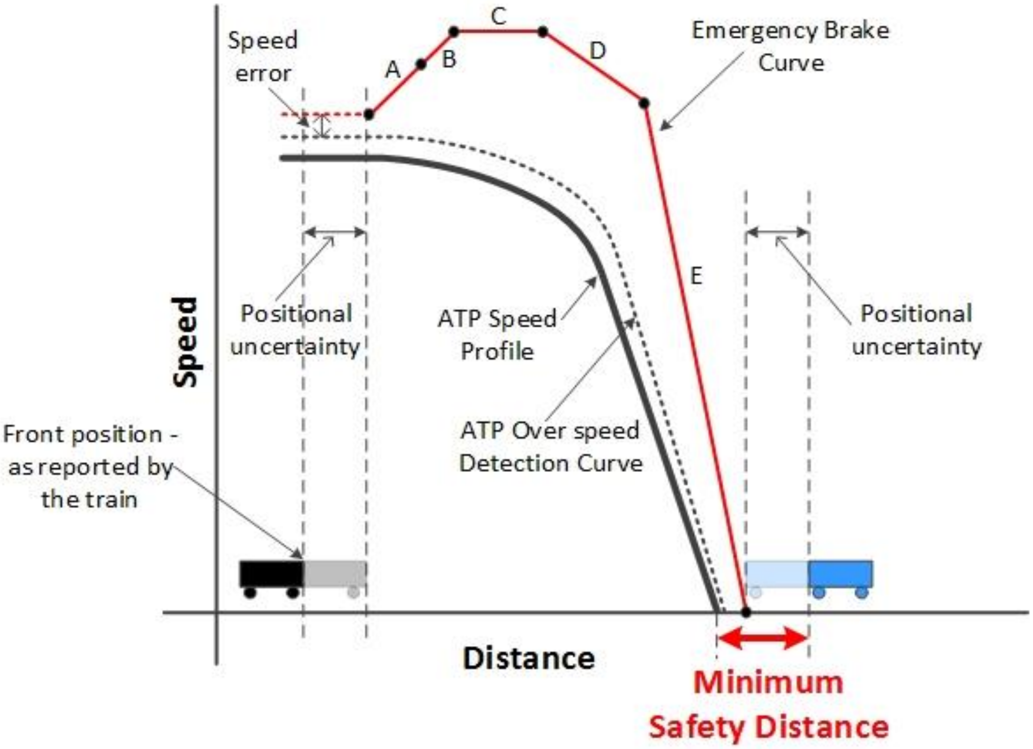


Figure 4.5: Minimum Headway of CBTC [36]

A modern CBTC system with moving block operation where the train ‘footprint’ or part of the track considered to be ‘occupied’ by the train is the train length plus a speed dependent ‘buffer’ area around the train. Moving and variable block, by its nature allows the trains to circulate closer to each other than fixed block system [35].

$$T_{Headway} = \frac{S_{servicebreak} + S_{safetydis\tan ce} + S_{Trainlength} + S_{uncer\tan ity}}{V_{Max-ATO}} \qquad \text{………….………….(4.8)}$$

Where T $_{Headway}$, is the minimum headway;

S $_{Service\ Brake}$, is the service brake distance for train 2 at the maximum ATO speed;

S $_{safety\ Distance}$, is the safety distance calculated by the brake model;

S $_{Train\ Length}$, is the length of train;

D $_{uncertainty}$, is the position uncertainty of the proceeding train;

V $_{Max\ -ATO,}$ is the maximum ATO speed of train

The figure below (Figure 4.9) is the model to determine the minimum intermediate station headway. According to this model, the constraint for the non-interfering train separation requires that Train 1 has cleared the station by a SD beyond the station stopping point (Position uncertainty of the proceeding train is taken into consideration), at the time that Train 2 is a braking distance away from the station stopping point (i.e. the disturb point). System can be configured to use the full service brake rate or a certain constant brake rate to calculate the braking distance [35].

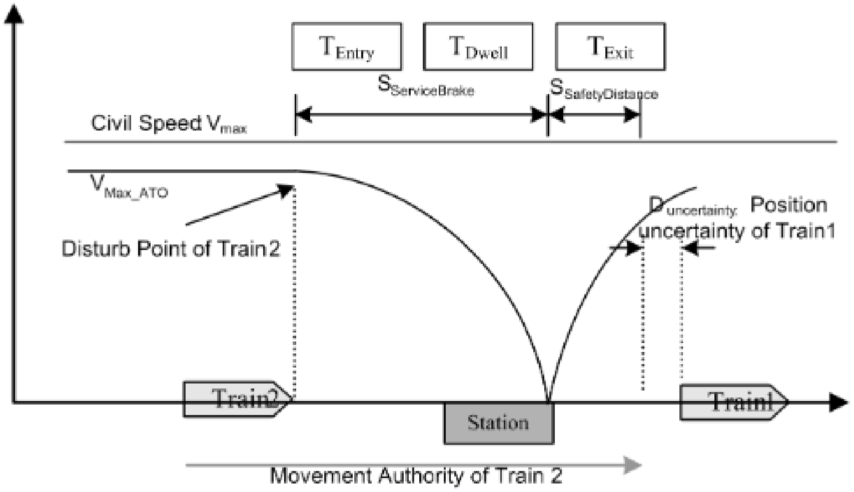


Figure 4.6: Minimum Intermediate Station Headway of CBTC [35]

From this model, we can have [35]

$$T_{Headway} = T_{Entry} + T_{Dwell} + T_{Exit} + T_{process} \qquad \text{………………. ……. (4.9)}$$

Expanding the above equation will give as:

$T_{\text{Headway}} = T_{\text{service braking}} + T_{\text{Emergency braking}} + T_{\text{dwell}} + T_{\text{release}} + T_{\text{uncertainty}} + T_{\text{Switch operating time}} + T_{\text{OMT}}$ ...(4.10)

where: -

T_{Entry}, is the time for the train to travel from the disturb point to the station stop point along with the ATO profile;

T_{Dwell}, is the station dwell time;

$T_{\text{Exit,}}$ is the time for the train to travel from the station stop point to its rear is a safety distance plus the position uncertainty beyond the station stopping point;

T_{process}, is the system process delay time.

Using the calculated parameters previously it is easy to find headway time between two consecutive trains

Table 4.3: Calculated Headway of Sample Stations

Station	Section/Route Name	Speed	Release time	Dwelling time	Service braking Time	Emergency Braking Time	OMT	Safety lock time	(P)Position uncertainty for two Consecutive trains	Headway	Headway
(From ~ to)	(From ~ to)	(m/s)	(Sec)	(Sec)	(sec)	(sec)	(sec)	(sec)	(sec)	(sec)	(min)
EW15 - EW14	St.Estfanos to Bambis	16.667	3.54	25	8.404	4.184	7	480	0.114717706	528.2427	8.804045
EW16 - EW15	Stadium to St.Estfanos	9.722	6.069	30	4.901	2.44	7	480	0.196667352	530.6067	8.843445
EW21 - EW20	CocaCola to Lideta	9.722	6.069	30	4.902	2.441	7	480	0.196667352	530.6087	8.843478
EW22 - EW21	Torhailoch to CocaCola	13.889	4.248	35	7.01	3.489	7	480	0.137662898	536.8847	8.948078
EW17 - EW16	Leghar to Stadium	15.278	3.862	30	7.699	3.835	7	480	0.12514727	532.5212	8.875353
EW18 - EW17	Mexico to Leghar	12.5	4.72	30	6.228	3.119	7	480	0.15296	531.22	8.853666
EW19 - EW18	Tegbared to Mexico	12.5	4.72	30	6.201	3.113	7	480	0.15296	531.187	8.853116
EW20 - EW19	Lideta to Tegbared	8.85	6.667	30	4.467	2.223	7	480	0.216045198	530.5731	8.842884
NS15 - NS14	Meshwalkya to Riche	6.5	9.077	25	3.277	1.632	7	480	0.294153846	526.2802	8.771336
NS16 - NS15	Stadium to Meshwalkya	5.556	10.62	30	2.8	1.394	7	480	0.34413247	532.1581	8.869302
NS21 - NS20	Darmar to Lideta	9.722	6.069	25	4.901	2.441	7	480	0.196667352	525.6077	8.760128
NS22 - NS21	Abnet to Darmar	5.556	10.62	25	2.8	1.394	7	480	0.34413247	527.1581	8.785969
										Average Headway time	8.837567

4.2.13 Synchronizing Arrival and Departure of Trains

Creating a timetable with maximal synchronization enables the transfer of passengers from one route to another, with minimum waiting time at the transfer nodes. This problem is a major concern to the public transportation designers, taking into account the satisfaction and convenience of the system's users. Timetable synchronization can reduce the transfer waiting times so that improve the service quality. If two trains, routes have a headway time of 't' time at the separate route, and then they will have headway time of half of 't' (t/2) at the common line if they are well synchronized [10]. By adjusting the trains' run-times and station dwell-times during their trips, and their dispatch times, turnaround times and headways at the terminals, our system can construct high quality timetables that optimize the objective of minimizing passenger transfer waiting-times.

The time taken to reach at the intersection can be given as:

$$t = \sum_{i=m}^{n} \frac{S}{V} + \sum_{i=m}^{n} dt \qquad \text{……………………………………. …. (4.11)}$$

m=Starting Station

n= Common station

t=Time taken to reach at the intersection (Common station)

S=Distance from the starting point to the intersection node

V=Speed of the train at each station

dt =Total dwelling time of each station until the intersection node

For the Upward Direction:

The time taken from Ayat to Stadium is given as, the summation of all the dwelling times plus the time taken to travel from Ayat to Stadium (section distance per speed of the section from Ayat to stadium). Using equation (4.11) the travel time taken for this line will be: -

$$t = \sum_{i=m}^{n} dt + \frac{S_{EW1-EW2}}{V_{EW1-EW2}} + \frac{S_{EW2-EW3}}{V_{EW2-EW3}} + \frac{S_{EW3-EW4}}{V_{EW3-EW4}} + \frac{S_{EW4-EW5}}{V_{EW4-EW5}} + \frac{S_{EW5-EW6}}{V_{EW5-EW6}} + \frac{S_{EW6-EW7}}{V_{EW6-EW7}} + \frac{S_{EW7-EW8}}{V_{EW7-EW8}} + \frac{S_{EW8-EW9}}{V_{EW8-EW9}} + \frac{S_{EW9-EW10}}{V_{EW9-EW10}} +$$

$$\frac{S_{EW10-EW11}}{V_{EW10-EW11}} + \frac{S_{EW11-EW12}}{V_{EW11-EW12}} + \frac{S_{EW12-EW13}}{V_{EW12-EW13}} + \frac{S_{EW13-EW14}}{V_{EW13-EW14}} + \frac{S_{EW14-EW15}}{V_{EW14-EW15}} + \frac{S_{EW15-EW16}}{V_{EW15-EW16}}$$

$$t = 7.25 + \frac{1260}{9.0647} + \frac{1092}{13.1566} + \frac{863}{9.0842} + \frac{860}{7.5438} + \frac{724.82}{9.2925} + \frac{970}{6.2179} + \frac{1083.6}{7.9676} + \frac{829}{8.8191} + \frac{776}{8} + \frac{746}{8.7764} + \frac{758}{9.5949} + \frac{963}{5.6982} + \frac{675}{8.766} + \frac{593}{18.055} + \frac{640}{6.8085}$$

t=24.25min

Similarly, the Time Taken from Kality to Stadium is given as:

$$t = \sum_{i=m}^{n} dt + \frac{S_{NS\,6\,-\,NS\,7}}{V_{NS\,6\,-\,NS\,7}} + \frac{S_{NS\,7\,-\,NS\,8}}{V_{NS\,7\,-\,NS\,8}} + \frac{S_{NS\,9\,-\,NS\,10}}{V_{NS\,9\,-\,NS\,10}} + \frac{S_{NS\,10\,-\,NS\,11}}{V_{NS\,10\,-\,NS\,11}} + \frac{S_{NS\,11\,-\,NS\,12}}{V_{NS\,11\,-\,NS\,12}} + \frac{S_{NS\,12\,-\,NS\,13}}{V_{NS\,12\,-\,NS\,13}} + \frac{S_{NS\,13\,-\,NS\,14}}{V_{NS\,13\,-\,NS\,14}} + \frac{S_{NS\,14\,-\,NS\,15}}{V_{NS\,14\,-\,NS\,15}} + \frac{S_{NS\,15\,-\,NS\,16}}{V_{NS\,15\,-\,NS\,16}}$$

$$t = 4.583 + \frac{950}{9.0278} + \frac{845}{8.333} + \frac{535}{7.229} + \frac{995}{5.7514} + \frac{861}{8.1226} + \frac{1971.66}{13.888} + \frac{555}{13.194} + \frac{610}{18.0556} + \frac{481.12}{7.0752} + \frac{908}{5.555}$$

t=21.4min

Now to synchronize each train coming from both lines to the upward direction, trains coming from Ayat arrives at Stadium according the following patterns [with headway of 8.84minutes] and assuming the first train starts at 00:00 o'clock]. The patterns are (in minutes): - 24.25, 33.09, 41.93, 50.77, 59.61, 68.45, 77.29…

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): - 21.4,30.24,39.08,47.92,56.76,65.6,74.44,83.28,92.12...

According to the pattern, the first train coming from Kality should be arrived earlier than its schedule by one minute and fifty-seven seconds earlier on the way to Stadium in order to have 4.42 minutes' headway time in the common route. Therefore, the trains coming from Kaliy will arrive at Stadium with a patterns (in minutes): 19.83, 28.67, 37.51, 46.35, 55.19, 64.03… and trains coming from Ayat will arrive at Stadium according the following pattern (in minutes): 24.25, 33.09, 41.93, 50.77, 59.61, 68.45, 77.29…

For the Downward Direction

Time Taken from Torhailoch 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:

$$t = \sum_{i=m}^{n} dt + \frac{S_{EW\,22\,-\,EW\,21}}{V_{EW\,22\,-\,EW\,21}} + \frac{S_{EW\,21\,-\,EW\,20}}{V_{EW\,21\,-\,EW\,20}}$$

$$t = 1.083 + \frac{769}{13.889} + \frac{732}{9.722} = 3.26 \text{ min}$$

Time Taken from Menelik II Square to St. Lideta**:** Using the formula given above (section 4.2.13), the time taken for the selected sections will be:

$$t = \sum_{i=m}^{n} dt + \frac{S_{NS\ 27\ -\ NS\ 26}}{V_{NS\ 27\ -\ NS\ 26}} + \frac{S_{NS\ 26\ -\ NS\ 25}}{V_{NS\ 26\ -\ NS\ 25}} + \frac{S_{NS\ 25\ -\ NS\ 24}}{V_{NS\ 25\ -\ NS\ 24}} + \frac{S_{NS\ 24\ -\ NS\ 23}}{V_{NS\ 24\ -\ NS\ 123}} + \frac{S_{NS\ 23\ -\ NS\ 22}}{V_{NS\ 23\ -\ NS\ 22}} + \frac{S_{NS\ 22\ -\ NS\ 21}}{V_{NS\ 22\ -\ NS\ 21}} + \frac{S_{NS\ 21\ -\ NS\ 20}}{V_{NS\ 21\ -\ NS\ 20}}$$

$$t = 3.3167 + \frac{743}{12.5} + \frac{945}{12.0759} + \frac{604.88}{18.056} + \frac{667}{5.556} + \frac{812.71}{7.5954} + \frac{739}{8.333} + \frac{591}{9.722}$$

t=12.45min

Similar calculation for downward direction as done before for the up direction trains coming from Torhailoch arrives at St. Lideta according to the following patterns (pattern in minutes): - 3.26, 12.1, 20.94, 29.78, 38.62, 47.46, 56.3, 65.14… [with a headway of 8.84 minutes and assuming the first train starts at 00:00:00 o'clock].

Doing the same for the first few trains coming from Menelik II Square arrives at St. Lideta according to the following patterns (in minutes): - 12.45, 21.29, 30.13, 38.97, 47.81, 56.65, 65.49, 74.33…

According to the pattern, the first train coming from Torhailoch should be arrived earlier than its schedule by 4.07 minute and on the way to St. Lideta in order to have 4.42 minutes' headway time in the common route. Hence, the trans coming from Torhailoch will arrive at St. Lideta as according to the following patterns (in minutes): -0.81, 8.03, 16.87,25.71, 34.55, 43.39, 52.23, 61.07… and trains coming from Menelik II Square will arrive at St. Lideta according the following pattern (in minutes): 12.45, 21.29, 30.13, 38.97, 47.81, 56.65, 65.49, 74.33…so on. Similarly, for the other speeds we can find the corresponding arrival time patterns using the same procedure.

4.2.14 Capacity

Considering capacity refers to two things, though they are related to each other. Those are Train capacity and Line Capacity [10].

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/m2 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:

$$L_c = \frac{60}{H_t} \qquad \text{…………………………………… …. (4.12)}$$

Where: L_c = Line Capacity

H_t = Headway time in minutes

Let's take the average headway of our new designed timetable which is 8.84 minutes

Lc= 60/Ht= 60/ 8.84= 6.787; which means 7 trains

Those trains are for a single direction only. So, for both directions, the number of trains should be doubled (14 trains).

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 [10].

$$C_{DP} = C_L \times C_T \qquad \text{…………………………………… …. (4.13)}$$

Where: CDP = 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.

$$C_{DP} = C_L \times C_T = 6.787 \times 317 = 2151.5 \text{ passengers/h}$$

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).

4.3 Comparison Between the New Designed and Existing Timetable

At present, the trains of the AA-LRT travel at a speed close to 20km/h, with a headway 12 minutes in EW line and 15 minutes in NS line the, but according to the details stated above, the headway can be reduced to 8.84 minutes. This result implies that the headway can be improved using a communication based train control which has a direct impact on capacity.

Finally, after calculating the values of the main parameters a comparison between the existing and calculated parameters is done. Therefore, the outcome indicates that the main parameters to design the timetable depends on signaling system used (Communication Based Train Control for this case), different values of the parameters can be achieved.

Table 4.4: Comparison of the Existing and New Timetable

Traveling direction (line)	Current Values			New values		
	Average Headway Time (min)	Number of trains	Line Capacity (Number of Trains in 1 hr. for one route)	Average Headway Time (min)	Number of trains	Line Capacity (Number of Trains in 1 hr. for one route)
EW-line	12	9	2853	8.84	14	4438
NS-line	15	8	2536	8.84	14	4438

In communication Based Train Control (CBTC) systems, with train detection by communication, the concept of block has been further refined and what is known as a moving block is used, which include a safety envelope behind and in front of a train, always moving along with the train. This helped to improve the headway further by reducing the length of safety block and also with boundaries (moving block) required for each train. CBTC is to increase capacity by reducing the time interval (headway) between trains which will minimize the waiting time of passengers at stations and also increase passengers satisfaction.

CHAPTER FIVE

SIMULATION AND DISCUSSION

5.1 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. In this thesis version 14.00.00 of Rockwell Arena simulation software is used.

Arena® software is designed for analyzing the impact of changes involving significant and complex redesigns associated with supply chain, manufacturing, processes, logistics, distribution 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. Typical scenarios include [37]:

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

Rockwell Automation offers a full suite of products to provide enterprise-wide simulation, optimization, and 3D model animation.

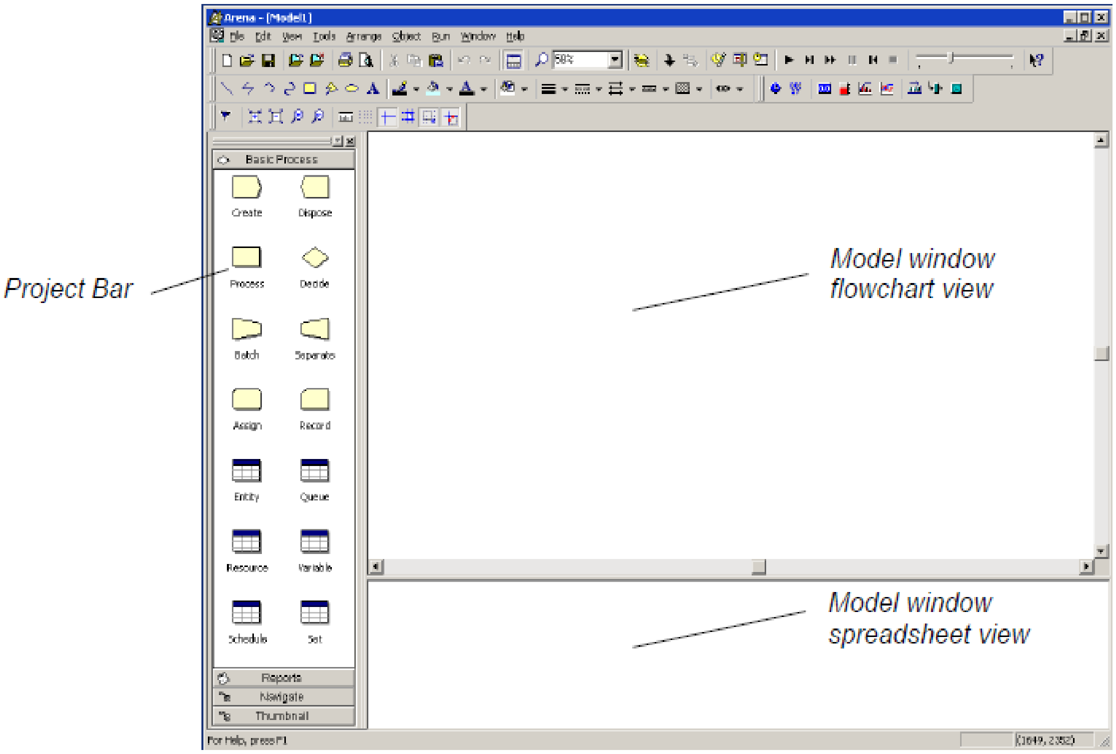
Arena offers several editions of the software, ranging from the entry-level Arena Basic Edition up to the Professional Edition and Enterprise Suite, which are the ultimate in functionality and flexibility.

In Arena, the user builds an experiment model by placing modules (boxes of different shapes) that represent processes or logic. Connector lines are used to join these modules together and to specify the flow of entities. While 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 made output as reports [38].

Arena can be integrated with Microsoft technologies. It includes Visual Basic for Applications so models can be further automated if specific algorithms are needed. It also supports importing Microsoft Visio flowcharts, as well as reading from or sending output to Excel spread sheets and Access databases. Hosting ActiveX controls is also supported [38].

5.2 Main Parts of the Arena Software Modeling

5.2.1 Project Bar: The Project Bar provides a mechanism for displaying the panels used for model-building, the Reports panel used for launching reports, and the Navigate panel used for easy navigation through the different views and hierarchical levels of any model or drawing window.



Project Bar

Model window flowchart view

Model window spreadsheet view

Figure 5.1: The Main Parts of Arena Software [37]

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 [37].

5.2.2 Model Window Flowchart: The model window contains two main regions: the flowchart view and the spreadsheet view. The flowchart view contains all of your model graphics, including the process flowchart, animation, and other drawing elements. The lower, spreadsheet view displays model data, such as times, costs, and other parameters [37].

5.2.3 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.

5.3 Main Elements of the Simulation Design

5.3.1 Create module-This module is intended as the starting point for entities in a simulation model. Entities are created using a schedule or based on a time between arrivals. Entities then leave the module to begin processing through the system. The entity type is specified in this module [37].

5.3.2 Leave: The Leave module is used to transfer an entity to a station or module. An entity may be transferred in two ways. It can be transferred to a module that defines a station by referencing the station and routing, conveying, or transporting to that station, or a graphical connection can be used to transfer an entity to another module. When an entity arrives at a Leave module, it may wait to obtain a transfer device (resource, transporter, or conveyor). When the transfer device has been obtained, the entity may experience a loading delay. Finally, the entity is transferred from this module to a destination module or station [37].

5.3.3 Enter: The Enter module defines a station (or a set of stations) corresponding to a physical or logical location. When an entity arrives at an Enter module, an unloading delay may occur and any transfer device used to transfer the entity to the Enter module's station may be released. The station (or each station within the defined set) has a matching Activity Area that is used to report all times and costs accrued by the entities in this station. This Activity Area's name is the same as the station [37].

5.3.4 Decide: This module allows for decision-making processes in the system. There are two exit points out of the Decide module when its specified type is either 2-way by Chance or 2-way by Condition. There is one exit point for "true" entities and one for "false" entities, in this caseit is either Blue of Green train [37].

5.3.5 Transporter: The Transport module transfers the controlling entity to a destination station. After the time delay required for the transport, the entity reappears in the model at the Station module. In this thesis, simulation section the guided transporter is used. Guided transporters unlike the free transporter may be moved to a different network location than the entity's station destination using the guided train destination type [37].

5.3.6 Network: The Network module defines a system map that a set of guided transporters will follow. A network encompasses the set of links specified in its Network Links repeat group. The parameters of a network link (for example, length, intersections, directions) are defined in the Network Link module [37].

5.3.7 Network Link: The Network Link module defines the characteristics of a guided transporter path between an intersection pair Beginning Intersection Name and Ending Intersection Name. The Network module then references a set of network links to define a network that guides transporters follow for movement [37].

5.4 The Simulation Design

In the simulation design, each block will take input parameters like the distance between each station, the velocity of the train, the dwell time at each station, the headway, acceleration, deceleration etc.

Table 5.1: Inputs for the Simulation Tool

Simulation Parameters	Typical values for AA-LRT
Speed	Operation Speed 20-70km/h, but for this part the speed is selected at each station depending on the speed restrictions
Headway time	calculated Headway value have been used which is 8.84
Dwelling Time	Varies according to the station (25-30seconds)
Distance	The distance between each adjacent stations in meter
Type of transporter	Guided path
Type of Queue	First in first out (FIFO)
Acceleration	1m/s^2
Deceleration	2 m/s^2
Number of trains	Depending on the calculated Headway 7 trains can be used in each direction
Synchronization time	Based on the synchronized values in section 4.2.13 of chapter four values are added to the simulation tool

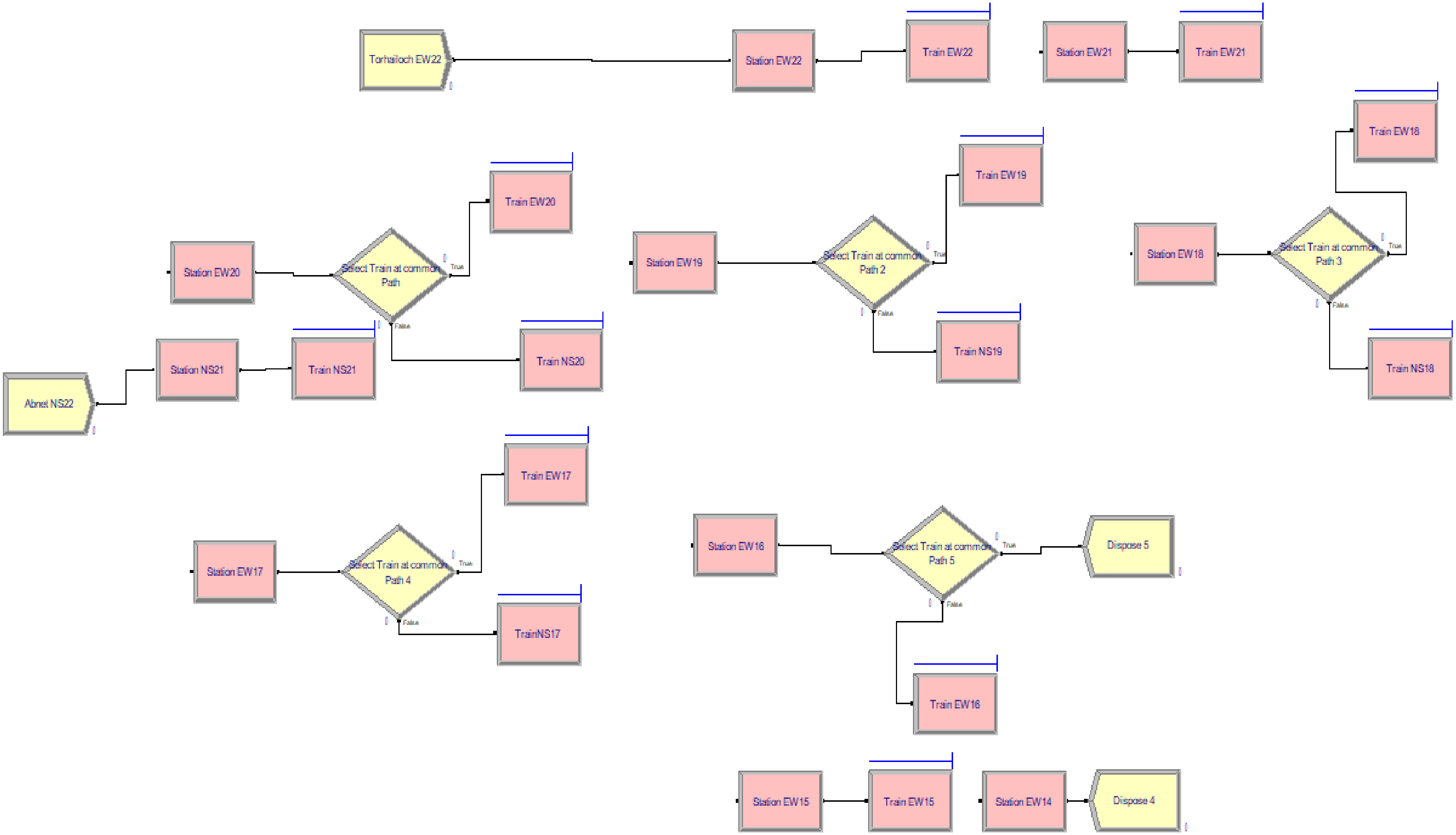


Figure 5.2: The Simulation Design for the Sample points of AA-LRT EW-Down Line

5.2.3 Output Analysis of the Simulation

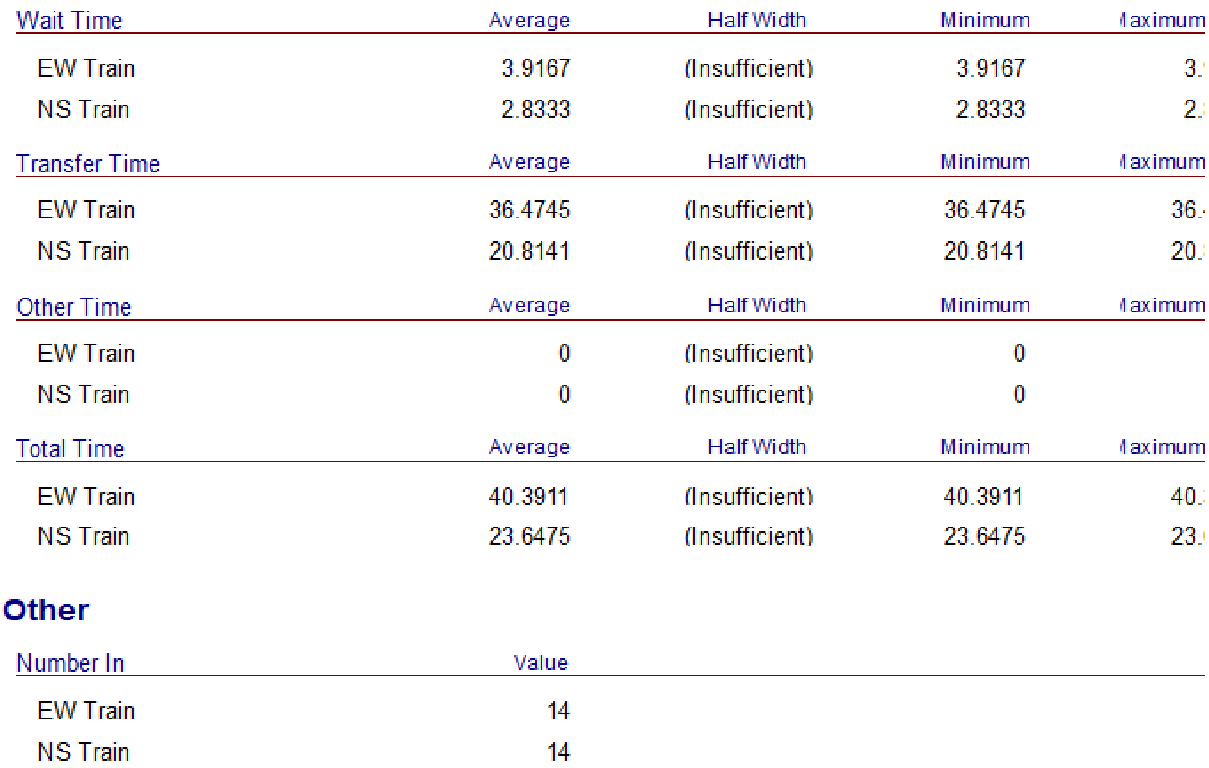
After giving the necessary inputs to the system model and ordered to run the system it gives the statistical analysis of the simulation result under some of the following sets according to our design model.

Entity

The simulation result gives the details of the time spending on the trip from the origin station to the destination station.

- **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. Hence based on the simulation result the waiting time is 3.92 min.
- **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 36.47min.
- **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.

Table 5.2: Output of Simulation for Different Process Times



Wait Time	Average	Half Width	Minimum	aximum
EW Train	3.9167	(Insufficient)	3.9167	3.
NS Train	2.8333	(Insufficient)	2.8333	2.

Transfer Time	Average	Half Width	Minimum	aximum
EW Train	36.4745	(Insufficient)	36.4745	36.
NS Train	20.8141	(Insufficient)	20.8141	20.

Other Time	Average	Half Width	Minimum	aximum
EW Train	0	(Insufficient)	0	
NS Train	0	(Insufficient)	0	

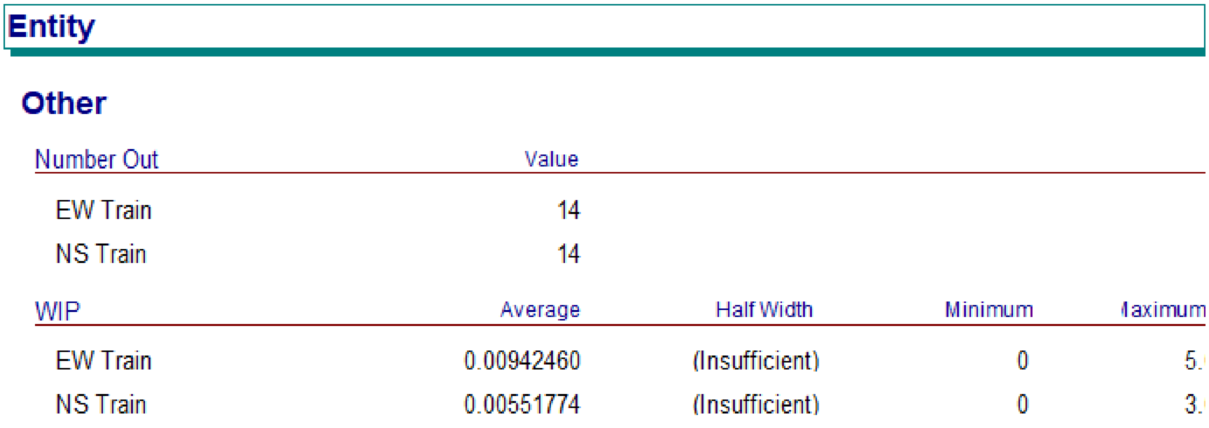
Total Time	Average	Half Width	Minimum	aximum
EW Train	40.3911	(Insufficient)	40.3911	40.
NS Train	23.6475	(Insufficient)	23.6475	23.

Other

Number In	Value
EW Train	14
NS Train	14

- **Number In**: This number imply the total number of trains (14 trains) to be used in the system which is similar to the calculated value in chapter four of the thesis.
- **Number Out**: This number imply the total number of trains (14 trains) processed in the whole processes and disposed at the end of the route.
- **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 5 trains for each direction are needed to give full service (which is Transfer time /Headway).

Table 5.3: Output of Simulation for Entity Number Out and WIP



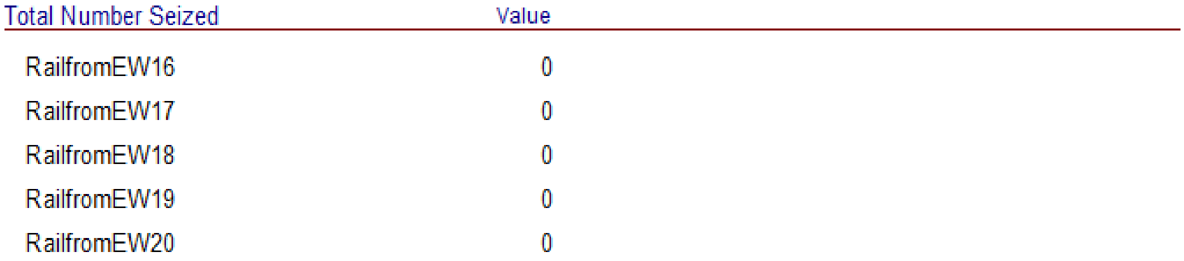
Entity

Other

Number Out	Value			
EW Train	14			
NS Train	14			
WIP	**Average**	**Half Width**	**Minimum**	**Maximum**
EW Train	0.00942460	(Insufficient)	0	5.
NS Train	0.00551774	(Insufficient)	0	3.

- **Total Number Seized:** 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.

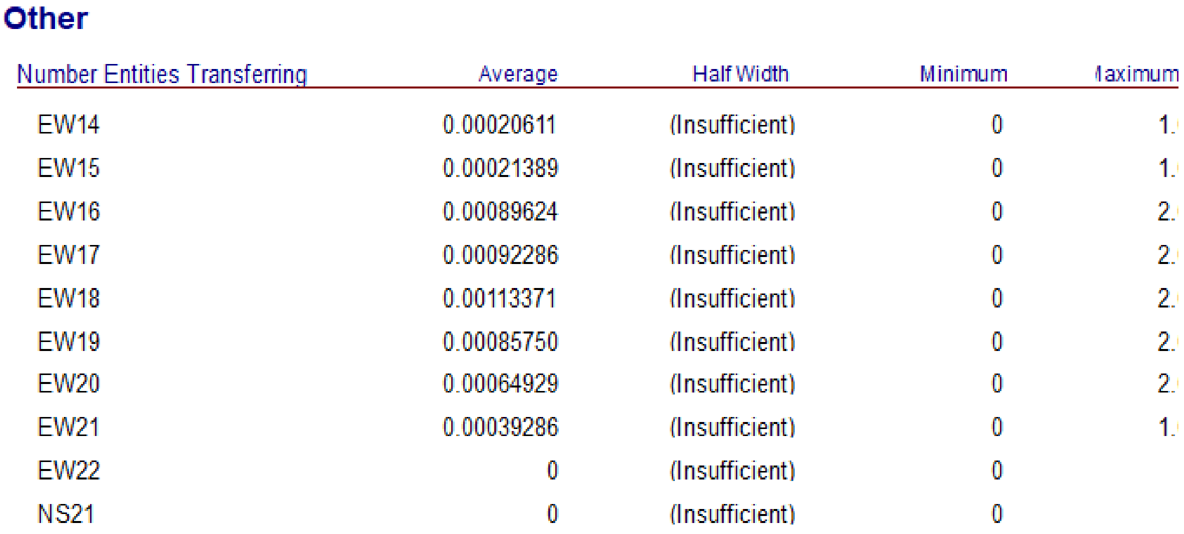
Table 5.4: Output of Simulation for Seized Trains



Total Number Seized	Value
RailfromEW16	0
RailfromEW17	0
RailfromEW18	0
RailfromEW19	0
RailfromEW20	0

- **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. It also displays the total accumulating waiting time in each station during the whole working day.

Table 5.5: Output of Simulation for Entity Transfer Time in the Process

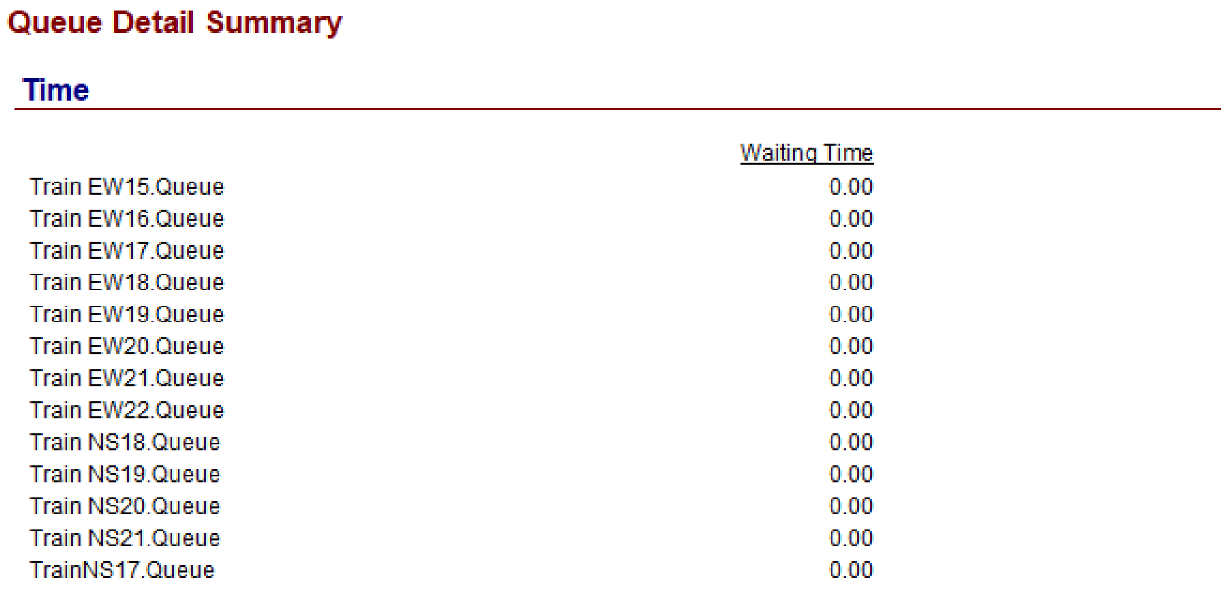


Other

Number Entities Transferring	Average	Half Width	Minimum	laximum
EW14	0.00020611	(Insufficient)	0	1.
EW15	0.00021389	(Insufficient)	0	1.
EW16	0.00089624	(Insufficient)	0	2.
EW17	0.00092286	(Insufficient)	0	2.
EW18	0.00113371	(Insufficient)	0	2.
EW19	0.00085750	(Insufficient)	0	2.
EW20	0.00064929	(Insufficient)	0	2.
EW21	0.00039286	(Insufficient)	0	1.
EW22	0	(Insufficient)	0	
NS21	0	(Insufficient)	0	

- 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.

Table 5.6: Output of Simulation for Queue Times



```
Queue Detail Summary

Time

                                          Waiting Time
Train EW15.Queue                                  0.00
Train EW16.Queue                                  0.00
Train EW17.Queue                                  0.00
Train EW18.Queue                                  0.00
Train EW19.Queue                                  0.00
Train EW20.Queue                                  0.00
Train EW21.Queue                                  0.00
Train EW22.Queue                                  0.00
Train NS18.Queue                                  0.00
Train NS19.Queue                                  0.00
Train NS20.Queue                                  0.00
Train NS21.Queue                                  0.00
TrainNS17.Queue                                   0.00
```

As expected the simulation output indicate number of trains used resemble with the calculated headway, the minimum waiting time, less delay 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. Therefore, the calculated values in chapter four of this thesis, as well as the simulation result demonstrate all the parameters are fulfilled.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusions

Passenger demand for urban rail transit systems increases dramatically and varies significantly along urban rail transit lines nowadays. In Addis Ababa, Railway transportation is becoming the main mode of public transportation for short to medium distances. Hence, the performance of railway transits as a whole depends largely on the performance of the railway signaling system as indicated so far in this thesis. The development on the signaling system to communication based train control will minimize the headway between two trains which have a direct effect on the waiting time of passengers at stations. According to the calculated values in chapter 4, the 15minutes headway of Addis Ababa light rail transit can be minimized up to 8.84 minutes without changing the parameters like speed, braking distance and so on. Subsequently, more trains can provide service with a headway of 8.84 minutes than the number of trains with the current 15 minutes headway hereafter the line capacity can be increased. Furthermore, it must be noted that this calculated headway can be minimized if the safety lock time for the time lock switches is minimized.

CBTC system can be easily upgraded with development of new technologies in the key technical areas. For the meantime, it is easier for the traditional train control system to be transited into CBTC systems. It makes the dispatching system more flexible and efficient. The safety and reliability of the system are high. The maintenance cost for CBTC is lower since axel counters are removed from the system. The control system of railway network will be towards intelligent, network and comprehensive system.

In general, the impact of an automatic train control system known Communication Based Train Control (CBTC) in train scheduling of Addis Ababa light rail transit has been studied using the parameters like headway, dwell time, trip time, speed, signaling system, braking distance, braking time and synchronization of trains in detail. Also their values are calculated and checked their validations using the Arena software simulation. This thesis analysis the effect of automatic train control (communication based train control) to improve the robustness of timetables for passenger train services in the case of Addis Ababa light rail transit which shows an improvement on timetable's headway by 58.93%.

6.2 Recommendation

On this thesis, the calculations on the headway of Addis Ababa light rail transit using a communication based train control does not consider the level crossings and switches in the depot. Although the Addis Ababa Roads Authority gives priority to the train, it may still have an effect on the headway and also on most of the parameters like line capacity, speed, and travel time etc. Therefore, it is recommended to involve the level crossing effect to obtain a better result on the calculated values.

The error values of the microprocessors of the speedometer in this thesis have been assumed to be 1% from the last tag but it is possible to study the correct value of this error which will help us to estimate the exact position of the train and give more accurate value.

The time lock switches found on the mainline of Addis Ababa light rail transit cannot be thrown to the other direction unless the timer has counted down, which affect the movement of trains on the common line. The productivity of Addis Ababa light rail transit is constrained by this time lock switches. In this thesis the safety lock time for two trains coming from different direction is found to be 480 seconds. Therefore, it is recommended to study the possible ways to minimize this safety lock time.

CBTC is used to improve energy efficiency in the traffic operation due to its capability to update the ATO (Automatic Train Operation) driving commands not only at stations but also along the journey. In this thesis the effect of CBTC on energy consumption is not studied or included and it is recommended for future work.

Even though the main aim of this thesis is to show the effect of communication based train control on timetable of Addis Ababa light rail transit but it is also possible to fully design the assumed communication based train control using the suitable design software which will help to understand and figure the signaling system in a better way.

REFERENCE

[1] Benoit Bienfait and Patrick Zoetardt, “*Automatic train operation: the mandatory improvement for ETCS applications*” Alstom Transport, Belgium Bob Barnard, Signaling Solutions Ltd, UK, pp. 1-2

[2] Yihui Wang, Bin Ning, Ton van den Boom, Bart De Schutter (auth.)” *Optimal Trajectory Planning and Train Scheduling for Urban Rail Transit Systems* “, 2014, pp. 9-16

[3] Neha Deotale, Manish Katkar, S.P.Khandait (Nagpur University, India) “*Automatic Train Operation, Scheduling, Simulation and Anti-Collision System with Terminal's Station Backup of Train's Schedule* “A Review, 2014,pp. 1-3

[4] Communication based train control, Retrieved 2018-12-17, from, http://www.railsystem.net/communications-based-train-control-cbtc

[5] Addis Ababa Light Rail, Retrieved on 2018-12-30, from, https://en.wikipedia.org/wiki/Addis_Ababa_Light_Rail

[6] Bernd Schittenhelm *“Quantitative Methods for Assessment of Railway Timetables”* Rail Net Denmark & Department of Transport, Technical University of Denmark, PhD-2013-02 Banedanmark, pp. 7-39

[7] David Cancaa, Eva Barrenaa, Encarnación Algabaa, Alejandro Zarzob “*Design and analysis of demand-adapted railway timetables*”, pp. 1-2

[8] Tomáš Robenek Yousef Maknoon, Michel Bierlaire, “*Railway Passenger Service Timetable Design*” Transport and Mobility Laboratory, EPFL April 2015, pp. 1-4

[9] Leon Willem Petrus Peeters “*Cyclic Railway Timetable Optimization*” 2003, L.W.P. Peeters, pp. 22-25

[10] Tekle Haylekiros Assefa “Investigation on the Performance of Train Timetable for the Case of Addis Ababa Light Rail Transit (AA-LRT)” Vol.7, No.2, 2017, pp. 35-53

[11] Yihui WANG, “*Optimal Trajectory Planning and Train Scheduling for Railway Systems*” 2014, pp.1-21

[12] Qing-Yuan Wang, Xiao-Yun Feng “*Automatic train operation based on adaptive terminal sliding mode control*” International Journal of Automation and Computing April 2015, Volume 12, pp 142–148

[13] Farooq, Jahanzeb; Soler, José, “*Radio communication for Communications-Based Train Control (CBTC)”*, IEEE Communications Surveys & Tutorials 2017, pp 1-10

[14] N. Bin, T. Tao, Q. K. Min & G. C. Hai,” *Computers in Railways X’* pp. 391-420

[15] The Institute of Electrical and Electronics Engineers, Inc. 3 Park Avenue, New York, NY 10016-5997, USA “1474.2 *IEEE Standard for User Interface Requirements in Communications Based Train Control (CBTC) Systems*” ,12 December 2003, pp.3

[16] F. Richard Yu “*Advances in Communications Based Train Control Systems*” pp. 5-10

[17] ISTI-CNR, Via G. Moruzzi 1, Pisa, ITALY, “*Model-based Evaluation of the Availability of a CBTC System*” pp. 5-8

[18] Bassam Mansour “*Towards Digital Railways – Signalling and Train Control System*” December 18, 2017

[19] The Institute of Electrical and Electronics Engineers (IEEE Std 1474.1), Inc. 3 Park Avenue, New York, NY 10016-5997, USA, USA," *IEEE Standard for Communications Based Train Control (CBTC) Performance and Functional Requirements*" 25 February 2005, pp.1-45

[20] What is CBTC? (IEEE 1474.1), Retrieved on 2018-12-10, from, https://www.cbtcsolutions.ca/

[21] L. Zhu, F. R. Yu and B. Ning “*Service availability in communication-based train control (CBTC) systems using WLANs”*, 18 October 2012, pp.17-19

[22] Fei Richard Yu, Bin Ning, Tao Tang” *Wireless Communications and Networking*” December 2012

[23] Yehualaeshet Jemere (MSc. CEng) “Ethiopian Railways Corporation (ERC) Addis Ababa Light Rail Transit Project” July, 2012

[24] East-West Line (Phase1) Project of Addis Ababa, Ethiopia “*Technical Specification of Vehicles”* China Railway Group Limited, July 2013, pp.1-14

[25] Cab signaling, Retrieved on 2018-7-2, from, https://en.wikipedia.org/wiki/Cab_signalling

[26] Railway signaling and safety; Retrieved on 2018-6-25, from, https://en.wikipedia.org/wiki/Railway_signalling

[27] Sintayehu Bezabih, “*Automatic train control standard for Ethiopia*”, (2014) pp. 106-107

[28] William H. K, Lam C.Y. Cheung Y.F Poon "*A Study of Train Dwelling Time at the Hong Kong Mass Transit Railway System*" Journal of Advanced Transportation, Vol 32, NO. 3, pp. 285-289

[29] Transit Cooperative Research Program (TCRP) "*Transit Capacity and Quality of Service Manual* 2^{nd} *edition*" Washington, D.C. 20418, January 1999, Chapter five pp.5-19

[30] David Barney, David Haley and George Nikandros "*Calculating Train Braking Distance*" pp. 1-4

[31] Time lock switches, Retrieved on 2018-12-10, from, https://maxfaqs.wordpress.com

[32] Positional Uncertainty in communication based train control, retrieved on 2018-12-10, from,https://www.cbtcsolutions.ca/blog/2017/4/26/what-is-positional-uncertainty-in-cbtc-applications

[33] Thomas Albrecht & Katrin L¨uddecke, "*A Precise and Reliable Train Positioning System and its Use for Automation of Train Operation*" @2013 IEEE pp. 1-3

[34] Zhuo WEI,Yongdong WU, Jian WENG, Robert H. DENG "*Position manipulation attacks to balise-based train automatic stop control*" pp. 1-7

[35] R. Chen & J. Guo," Computers in Railways XII' pp. 497-506

[36] Safe braking distance in communication based train control, retrieved on 2018-12-10, from,https://www.cbtcsolutions.ca/blog/2017/3/29/safe-braking-model-explained

[37] Supersedes publication arena-um001f-en-p pn-111648 "*GETTING STARTED WITH ARENA®*" January 2012, version: 14.00.00 pp. 1-119

[38] Arena simulation software from Wikipedia, Retrieved on 2019-5-15, from, https://en.wikipedia.org/wiki/Arena_(software)

APPENDIX

Here below are some important tables, which are used as a reference in this thesis.

Table 1. Length of central lines and distance between stations of each station of the east-west line.

No.	Station name	Length of central lines	Right line coordinates of the station center	Distance between stations	Distance between centers of tracks	Elevation of station center	Station type
1	Origin	YDK5+483.00	X-996862.2995 Y-469474.0755	52	5		
2	EW22	YDK5+535.00	X-996839.1058 Y-469520.6163	769	5.00 (side)	2357.930	Ground station
3	EW21	YDK6+304.00	X-996911.0019 Y-470225.6892	732	4.00 (side)	2344.895	Ground station
4	EW20	YDK7+036.00	X-996835.8709 Y-470953.7219	735	4.00 (side)	2368.193	Elevated common rail station
5	EW19	YDK7+771.00	X-996741.9782 Y-471682.7001	688	4.00 (side)	2354.928	Elevated common rail station
6	EW18	YDK8+459.00	X-996801.1117 Y-472358.4619	560	4.00 (side)	2366.198	Elevated common rail station
7	EW17	YDK9+019.00	X-996887.5591 Y-472906.9799	445	4.00 (side)	2359.776	Elevated common rail station
8	EW16	YDK9+464.00	X-996902.5663 Y-473348.1557	640	4.00 (side)	2350.067	Elevated common rail station
9	EW15	YDK10+104.00	X-996795.6393 Y-473978.9619	593	4.00 (side)	2350.033	Elevated station
10	EW14	YDK10+697.00	X-996726.4625 Y-474567.5919	675	4.00 (side)	2333.711	Ground station
11	EW13	YDK11+372.00	X-996789.6514 Y-475223.6982	963	8.45 (island)	2342.382	Semi-underground station
12	EW12		X-997201.6457		4.00	2362.002	

		YDK12+ 335.00	Y-476091.8807	758	(side)		Ground station
13	EW11	YDK13+ 093.00	X-997371.7463 Y-476830.3757	746	4.00 (side)	2351.348	Ground station
14	EW10	YDK13+ 839.00	X-997557.3654 Y-477552.2791	776	4.00 (side)	2365.876	Ground station
15	EW9	YDK14+ 615.00	X-997745.0504 Y-478303.7177	829	8.95 (island)	2371.893	Semi-underground station
16	EW8	YDK15+ 444.00	X-997812.0607 Y-479122.4389	1083.6	4.00 (side)	2378.329	Ground station
17	EW7	YDK16+ 530.00	X-997685.5967 Y-480196.9975	970	4.00 (side)	2371.315	Ground station
18	EW6	YDK17+ 500.00	X-997879.8411 Y-481125.6722	724.82	4.00 (side)	2380.134	Ground station
19	EW5	YDK18+ 225.00	X-997975.1137 Y-481831.3394	860	4.00 (side)	2387.226	Ground station
20	EW4	YDK19+ 085.00	X-997939.3444 Y-482690.5893	863	4.00 (side)	2381.913	Ground station
21	EW3	YDK19+ 948.00	X-997893.5336 Y-483552.3376	1092	4.00 (side)	2386.685	Ground station
22	EW2	YDK21+ 040.00	X-997849.2514 Y-484643.1008	1260	4.00 (side)	2401.463	Ground station
23	EW1	YDK22+ 300.00	X-997912.7097 Y-485901.1314	182	4.00 (side)	2403.268	Ground station
24	Terminal	YDK22+ 482.00	X-997923.4631 Y-486082.8134		4		

Table 2. Length of central lines and distance between stations of each station of the North-south line.

No.	Station name	Length of central line	Right line coordinates of the station center	Distance between stations	Distance between centers of tracks	Elevation of station center	Station type
1	Origin	YDK1+731.00	X-999889.0115 Y-472815.9335	196	4.5		
2	NS27	YDK1+927.00	X-999700.6192 Y-472762.1360	743	4.50 (side)	2462.805	Underground station
3	NS26	YDK2+670.00	X-999410.2998 Y-472165.5605	945	4.00 (side)	2443.945	Ground station
4	NS25	YDK3+615.00	X-999369.2328 Y-471230.2225	604.88	4.00 (side)	2452.019	Ground station
5	NS24	YDK4+228.00	X-999349.2542 Y-470634.6507	667	4.00 (side)	2467.723	Elevated station
6	NS23	YDK4+895.00	X-998744.4611 Y-470631.8092	812.71	4.00 (side)	2442.499	Ground station
7	NS22	YDK5+706.00	X-997936.5527 Y-470674.0686	739	4.00 (side)	2406.728	Elevated station
8	NS21	YDK6+445.00	X-997287.2727 Y-470816.1044	908	4.00 (side)	2376.051	Elevated station
14	NS15	YDK10+372.00	X-996122.2103 Y-473471.6420	481.12	4.00 (side)	2341.643	Ground station
15	NS14	YDK10+835.00	X-995641.5645 Y-473450.2915	610	4.00 (side)	2330.220	Ground station
16	NS13	YDK11+445.00	X-995052.7711 Y-473574.2988	555	4.68 (side)	2310.969	Ground station
17	NS12		X-994512.1123		4.00	2299.214	

		YDK12+ 000.00	Y-473512.3357	1971.66	(side)		Ground station
18	NS11	YDK13+ 969.00	X-992605.4106 Y-473681.0584	861	4.00 (side)	2285.645	Ground station
19	NS10	YDK14+ 830.00	X-991785.3588 Y-473921.5131	995	4.00 (side)	2275.680	Ground station
20	NS9	YDK15+ 825.00	X-990799.5069 Y-474019.5967	535	4.00 (side)	2244.587	Ground station
21	NS8	YDK16+ 360.00	X-990266.8328 Y-473969.7656	845	4.12 (side)	2230.767	Ground station
22	NS7	YDK17+ 205.00	X-989489.3270 Y-474284.5594	950	4.00 (side)	2210.650	Ground station
23	NS6	YDK18+ 155.00	X-988719.9841 Y-473930.0774	269	5.00 (side)	2190.960	Ground station
24	Terminal	YDK18+ 424.00	X-988497.5328 Y-474081.3269		5		

Table 3. Speed restriction of NS and EW lines

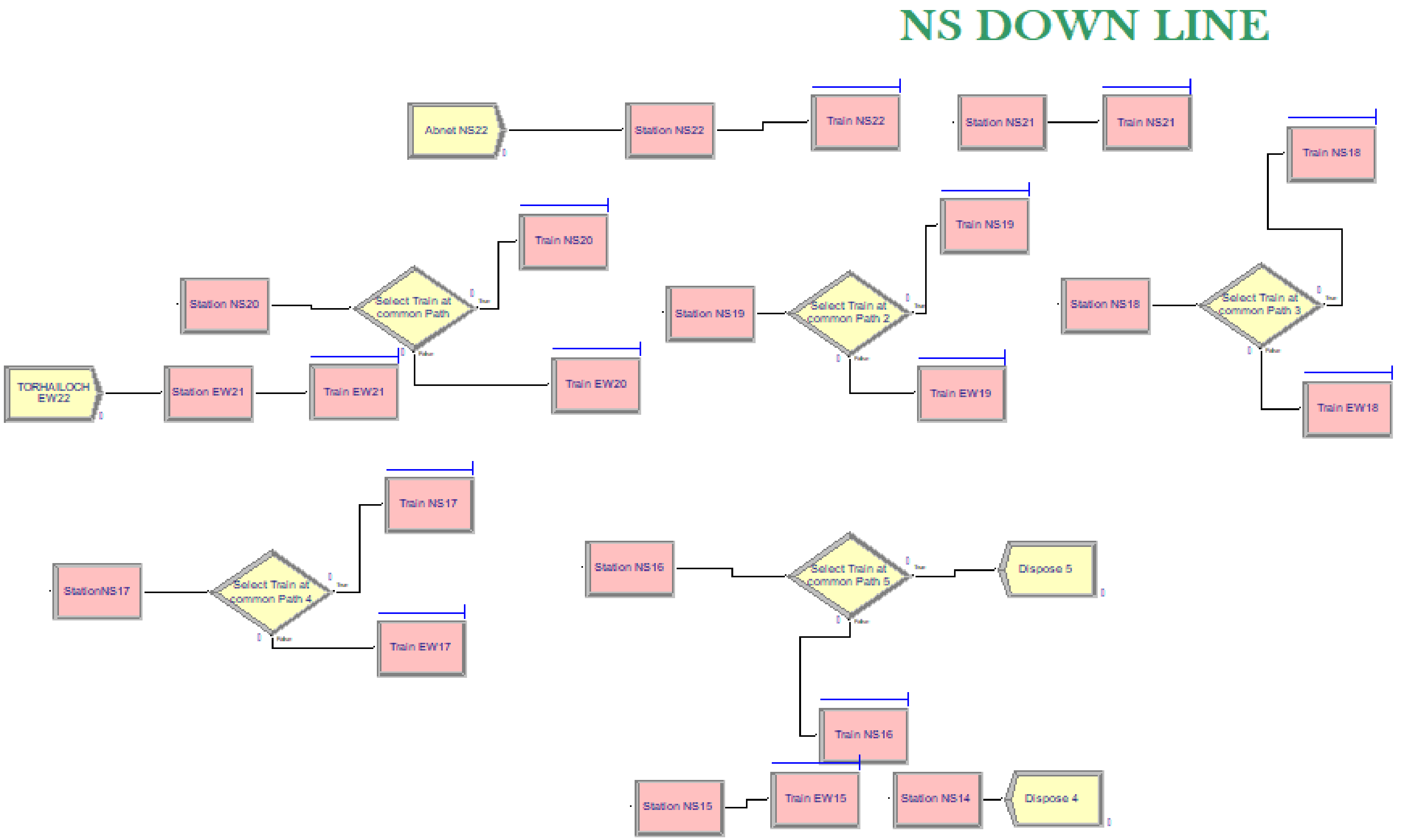
Interval	Track	Distance between stations	Curve radius	Length (m)	Speed restriction of curve	Reason for control
EW22〜EW21	Right	776	190	274.469	50	Road alignment
	Left	773.797	194	263.879		
EW22〜EW21	Right	776	240	235.413	60	Road alignment
	Left	773.797	236	252.490		
EW19〜EW18	Right	688.000	204	131.430	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		

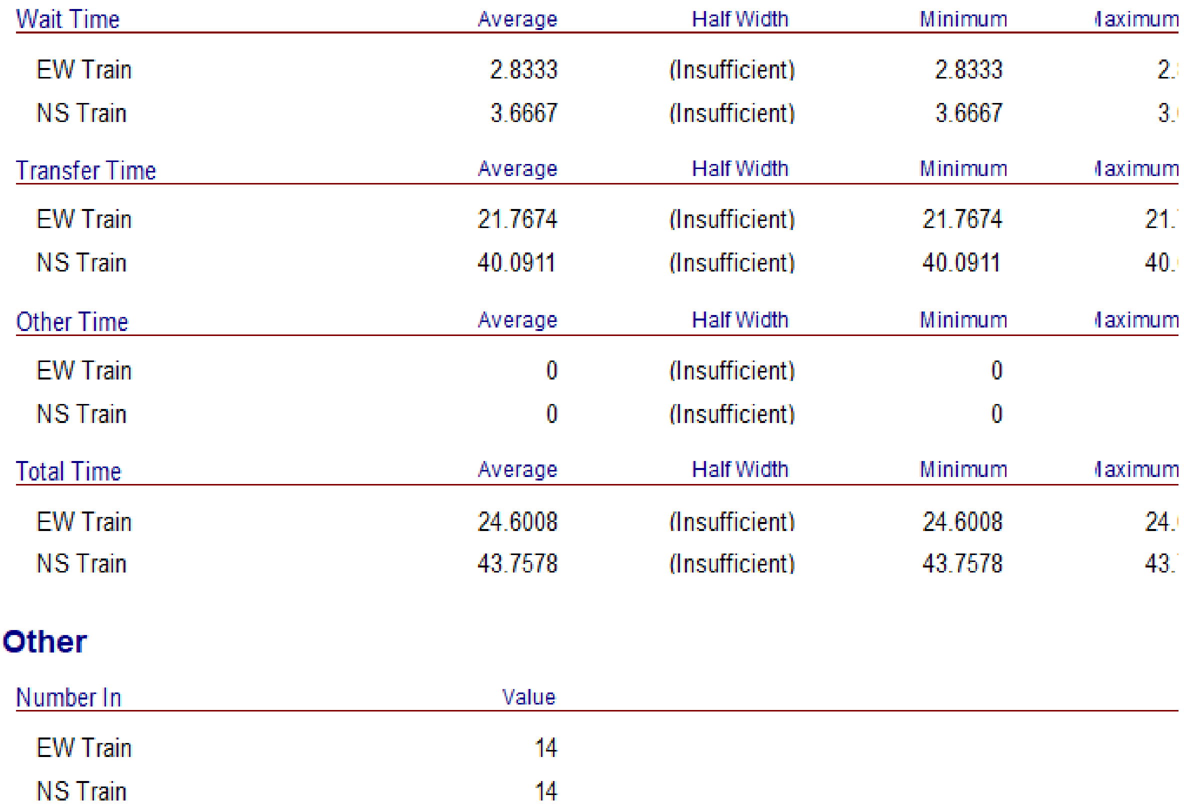
Interval	Track	Distance between stations	Curve radius	Length	Speed restriction of curve	Reason for control
NS27〜NS26	Right	741.000	304.5	95.550	45	Construction control
	Left	747.538	304	94.359		
NS27〜NS26	Right	741.000	65	137.366	20	Road alignment
	Left	747.538	70	124.163		
NS27〜NS26	Right	741.000	305	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
NS19〜NS18	Right	688.000	204	131.430	45	Road alignment
	Left	685.124	200	149.637		
NS18〜NS17	Right	571.965	200	150.783	45	Road alignment
	Left	571.965	204	127.499		
NS17〜NS16	Right	435.000	250	140.660	55	Road alignment
	Left	436.224	254	127.030		
NS16〜NS15	Right	908.000	300	19.821	35	Rail joint scheme
NS16〜NS15	Right	908.000	50	93.480	20	Road alignment
	Left	915.388	55	97.194		
NS14〜NS13	Right	610.000	290	201.946		
	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		

Simulation Diagram for NS-Down Line



Simulation output for NS-Down Line



Wait Time	Average	Half Width	Minimum	Maximum
EW Train	2.8333	(Insufficient)	2.8333	2.
NS Train	3.6667	(Insufficient)	3.6667	3.

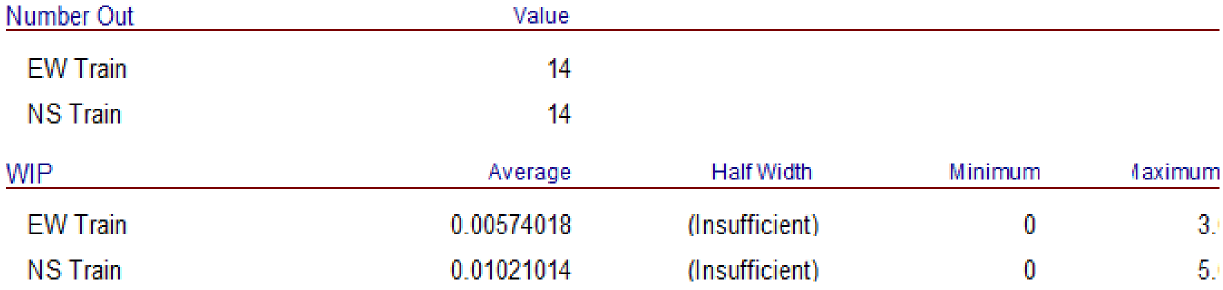
Transfer Time	Average	Half Width	Minimum	Maximum
EW Train	21.7674	(Insufficient)	21.7674	21.
NS Train	40.0911	(Insufficient)	40.0911	40.

Other Time	Average	Half Width	Minimum	Maximum
EW Train	0	(Insufficient)	0	
NS Train	0	(Insufficient)	0	

Total Time	Average	Half Width	Minimum	Maximum
EW Train	24.6008	(Insufficient)	24.6008	24.
NS Train	43.7578	(Insufficient)	43.7578	43.

Other

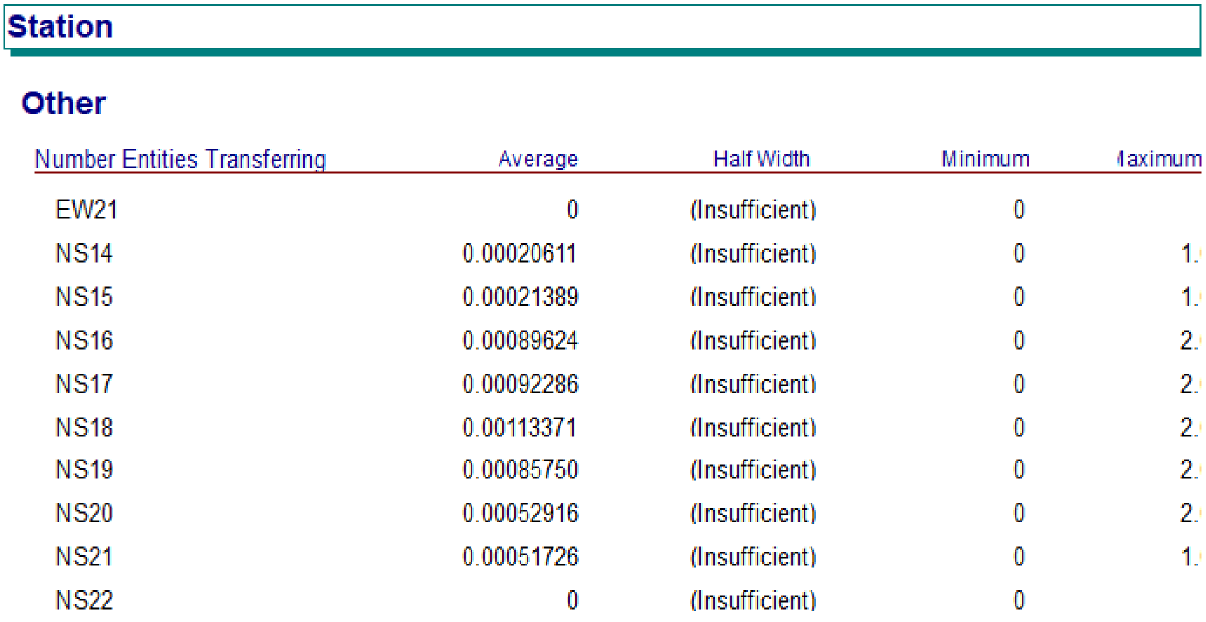
Number In	Value
EW Train	14
NS Train	14



Number Out	Value
EW Train	14
NS Train	14

WIP	Average	Half Width	Minimum	Maximum
EW Train	0.00574018	(Insufficient)	0	3.
NS Train	0.01021014	(Insufficient)	0	5.

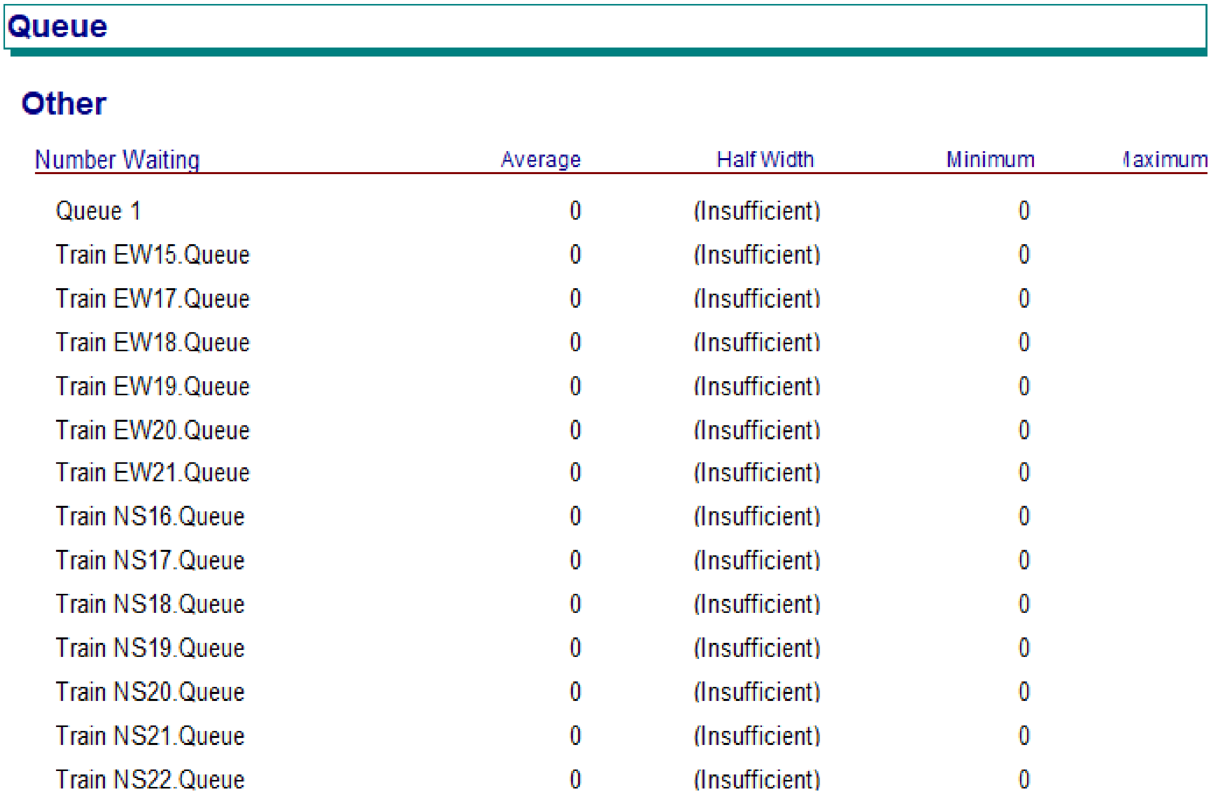
Simulation output for NS-Down Line



Station

Other

Number Entities Transferring	Average	Half Width	Minimum	aximum
EW21	0	(Insufficient)	0	
NS14	0.00020611	(Insufficient)	0	1.
NS15	0.00021389	(Insufficient)	0	1.
NS16	0.00089624	(Insufficient)	0	2.
NS17	0.00092286	(Insufficient)	0	2.
NS18	0.00113371	(Insufficient)	0	2.
NS19	0.00085750	(Insufficient)	0	2.
NS20	0.00052916	(Insufficient)	0	2.
NS21	0.00051726	(Insufficient)	0	1.
NS22	0	(Insufficient)	0	



Queue

Other

Number Waiting	Average	Half Width	Minimum	aximum
Queue 1	0	(Insufficient)	0	
Train EW15.Queue	0	(Insufficient)	0	
Train EW17.Queue	0	(Insufficient)	0	
Train EW18.Queue	0	(Insufficient)	0	
Train EW19.Queue	0	(Insufficient)	0	
Train EW20.Queue	0	(Insufficient)	0	
Train EW21.Queue	0	(Insufficient)	0	
Train NS16.Queue	0	(Insufficient)	0	
Train NS17.Queue	0	(Insufficient)	0	
Train NS18.Queue	0	(Insufficient)	0	
Train NS19.Queue	0	(Insufficient)	0	
Train NS20.Queue	0	(Insufficient)	0	
Train NS21.Queue	0	(Insufficient)	0	
Train NS22.Queue	0	(Insufficient)	0	