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**Positive Train Control with Headway
Optimization on an Active Communication System-a case
study of Addis Ababa Light Rail Transit**

A Thesis for Master's Program

A Thesis Submitted to the School of Graduate Studies of Addis Ababa
University in Partial Fulfillment of the Requirements for the Degree
of Masters of Science in Railway Engineering (Traction and Train
Control)

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UNDERTAKING

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ABSTRACT

Reducing rail transit's headway effectively is of enormous practical value since it plays an increasingly significant part in the public transportation system. Some of the most important goals in railroad operations include safety, capacity, and timely schedules. The idea behind positive train control (PTC) is to use cutting-edge 2 information technologies to increase the safety and effectiveness of railroad operations. Except for increasing the average waiting time, headway irregularity may also result in additional energy consumption and more delay time. Active communications and other information technologies enable the deployment of a dynamic headway, which can increase track capacity and dispatching effectiveness while also enhancing safety. Minimum headway, which is the optima Interval time the following train can reach while tracking the lead train, is considered to be one of the main factors restricting operational capacity.

We can run with better headways without increasing the operational speed; for example, the Addis Ababa LRT currently uses 15 minutes of headway when the speed is averaging 20-70 km/h. The calculated results show that this significant headway can be reduced by up to 4 minutes without slowing down operation

As a result, dynamic headway control cannot be represented using existing modeling techniques that use fixed headways, especially when the dynamic headway only comprises a small portion of a single block. Minimum headway shall be a minimum period of time required for the station to carry out requisite train arrival and departure operations, which it is also essential that trains operating in this area are safe.

Key words:

Delays, Positive train control, headway, headway irregularity, capacity and safety.

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Addis Ababa, Ethiopia

Table of Contents

ABSTRACT.....	I
ACKNOWLEDGMENT.....	II
List of figures.....	VII <u>VIV</u>
List of tables.....	VIII <u>VIIIV</u>
List of abbreviations	VIII <u>VIIIIVH</u>
CHAPTER ONE	1
INTRODUCTION	1
1.1 Background of the study	1
1.2 Statement of the Problem.....	4
1.3 Objective of the Thesis	6
1.3.1 General objective	6
1.3.2 Specific objective.....	6
1.4 Methodology	6
1.5 Scope.....	9
1.6 Significances of the Thesis	9
1.7 Thesis Organization	9
CHAPTER TWO	10
THEORETICAL BACKGROUND AND LITERATURE REVIEW	10
2.1 Introduction.....	10
2.2 Alternatives in Train Control.....	11
2.2.1 First Generation Train Control.....	11
2.2.2 Second Generation Train Control	11
2.2.3 Third Generation Train Control	12
2.2.4 Fourth Generation Train Control	12

2.3 Technologies for Train Control Systems	13
2.3.1 Chinese Train Control System (CTCS)	13
2.3.2 European Train Control System (ETCS)	13
2.3.3 ERTMS (European Rail Train Management System)	14
2.3.4 Communication Based Train Control (CBTC)	14
2.4 Working of PTC.....	17
2.4.1 Units of PTC Control	18
2.4.2 Levels of Operations	20
2.4.3 Reliable communication system	21
2.4.4 Train Positioning System	21
2.4.5 Interoperability	22
2.4.6 Pros and Cons of Using PTC System.....	23
2.4.7 Research gaps identified	24
CHAPTER THREE	26
AA-LRT and Its Timetable	26
3.1 General Characteristics of AA-LRT System.....	26
3.2 Stations of the AA-LRT	27
3.3 Signaling System of AA-LRT.....	34
3.4 Block (Section) Safety of AA-LRT	35
3.5 Train Leaving/Entering the Depot Arrangement	36
3.6 Timetable of AA-LRT time specifications	36
CHAPTER FOUR.....	40
HEADWAY DESIGN MODEL FOR AA-LRT.....	40
4.1 Headway	40
4.2 Elements of headway	41

4.2 Braking Time (B_i)	48
4.3 Operating Margin Time (OMT).....	49
4.4 Release Time (R_i).....	49
4.5 Time Lock Switches	50
4.6 Travel Time.....	51
4.7 Dwell time.....	52
4.8 Capacity	55
Figure 4.5 Relationships between Speed and Capacity	57
4.9 Synchronizing Train Departure/Arrival	57
4.10 Comparison between the New Designed and Existing Headway	58
CHAPTER FIVE	60
CONCLUSIONS AND RECOMMENDATIONS	60
REFERENCES	61
Appendix.....	67

List of figures

Figure 1.1 generic positive train control system architecture[5]. 3

Figure 1. 2 Effect of Moving Block to Minimize Headway[8]. 4

Figure 1. 3 Headway control loop in PTC[2]..... 7

Figure 1. 4 Methodology 8

Figure 2.1 CBTC System Architecture[21]. 15

Figure 2.2 Train components for the Availability of the PTC System[25]. 18

Figure 3.1 Number of stations in each line 2827

Figure 3.2 Map of rail lines and stations of the AA-LRT phase-I[32]. 2928

Figure 4.1 Headway of three aspect signaling system[45]. 4039

Figure 4.2 Sample of the gradient for braking distance calculation[47]..... 4342

Figure 4.3 Sub-processes of train dwell time[48]. 5351

Figure 4.4 General workflow of UIC406 method[50]. 5654

Figure 4.5 Relationships between Speed and Capacity 5755

Figure 4.6 Relation between headway and approaching speeds 5957

List of tables

Table 3.1 Platform type and distance between stations of each station of the east-west line [43].	2928
Table 3.2 Platform station type and distance between stations of NS line [43].	3234
Table 3.3 Time list for first/last train and running interval for the AA-LRT NS line[43].	3837
Table 3.4 Time list for first/last train and running interval for the AA-LRT EW line[43].	3837
Table 4. 2 Intervals with a grade of 30‰ or above on the main track of the NS line [43].	43
Table 4.3 Intervals with a grade of 30‰ or above on the main track of the EW line[43].	4443
Table 4.4 Sample stations their speed and grades [43].	4544
Table 4.5 Calculated braking distance between the stations of EW line	Error!
<u>Bookmark not defined.45</u>	
Table 4.6 Calculated braking distance between the stations of NS line	4745
Table 4.7 Calculated braking distance between the stations in the common line....	4746
Table 4.8 Braking times of NS line.....	4847
Table 4.9 Braking times of EW line.....	4847
Table 4.10 Braking times of common line.....	4947
Table 4.11 Release time	5048
Table 4.12 Travel time for the average distance between the stations of NS line ...	5149
Table 4.13 Travel time for the average distance between the stations of EW line..	5150
Table 4.14 Travel time for the average distance between the stations of EW line..	5250
Table 4.15 Headway of NS line at different speeds.....	5352
Table 4.16 Headway of EW line at different speeds.....	5452
Table 4.17 Headway of common line at different speeds.....	5452

Table 4.18 Arrival and departure times of trains in each station 5856

List of abbreviations

ACPES	Advanced Civil Speed Enforcement System
ATO	Automatic Train Operation
ATP	Automatic Train Protection
BOS	Back office Server
BART	Bay Area Rapid Transit
CASC	Chinese-American Signal Company
CBTCS	Communication based train control system
ETCS	European train control system
ERTMS	European railway train management system
ERC	Ethiopian Railways Corporation
GPS	Global Positioning System
GIS	Geographical Information System
HSR	High Speed Rail
LD	Laser Diode
MAS	Maximum Authorized Speed
MBS	Moving-Block System
MARTA	Metropolitan Atlanta Rapid Transit Authority
TBTC	Transmission-Based Train Control
PTC	Positive Train Control
RSIA	Rail Safety Improvement Act
RSD	Revenue service demonstration
SCRRA	Southern California Regional Railroad Agency
WIU	Wayside Interface Unit
WMATA	Washington Metropolitan Area Transit Authority

Rx ID	Receiver identification
TCP/IP	Transmission control protocol/internet protocol
TIU	Train interface unit
TWC	Train wayside communication
TBTC	Transmission based train control
Tx ID	Transmitter Identification
UDP/IP	User Datagram Protocol/Internet Protocol
UTO	Unattended Train Operations
WLAN	Wireless Local Area Networks
DCC	Dispatcher Control center
OCC	Operation control center
OMT	Operating margin time
AA-LRT	Addis Ababa Light Rail Transit
ZC	Zone Controller
GSM	Global System for Mobile Communications for railway

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

The current infrastructure of railways has been put under enormous pressure to improve efficiency and security as a result of the increasing demand for railway capacity in transport of people and freight. Under the constraints of safe operations, efficiency means shorter journey times, predictable schedules, increased track capacity and reduced congestion delays. On the other hand, by reducing train speed and conservative movements that give the train operator sufficient time to stop the train in case of emergency, safety can be improved at the expense of reduced capacity [1].

PTC systems employ wireless communication and global positioning system (GPS) technologies to properly monitor train separation or headways, avoid possible collisions, enforce speed limits and improve the safety of wayside workers. In order to prevent possible train collision, active communications between the central control and trains will allow for frequent exchange of information concerning train dynamics and characteristics along with speed and position within the PTC system. Using the detailed information, it could be possible to come up with smaller but safer journeys on a given track by taking into account main train location, speed, deceleration and acceleration capabilities etc. The train control system shall receive information from the dispatch center, wayside equipment and leading trains with regard to speed limits, acceleration rates, position and deceleration parameters as well as intentions of stopping or braking at a stop within this environment. It uses this information to compute its optimal safe headway from the leading train ahead or upcoming track obstacle. As such progress changes with time, it is referred to as dynamic progress. The possibility of loss of communication due to bad weather or other failures should

also be taken into account in the dynamic headway approach, which should gracefully and safely return to a more conservative approach without putting any trains in danger. The performance and reliability of the PTC system with a dynamic headway depends on the reliability of the active communication system[2].

The locomotive computer is an onboard piece of equipment that accepts speed restriction information and movement authority, so that these data can be compared against the train's location to ensure compliance. The wayside device on the side of the track is capable of monitoring and reporting switch position and signal status to locomotive computers and the back office[3]. The back office is a centralized office for the communication and coordination of train orders, speed restrictions, train information, track authorities, crew sign-in and sign-off, and bulletins, as well as specialized data to and from the wayside and train operational and safety data. Three main parts of the back-office system (the back office server (BOS), the geographical information system (GIS), and the dispatch office) interface with other components of the PTC systems[4].

For various information systems that support train operation, such as track composition, train consist, and speed limits, the BOS acts as a data storage facility.. Overall, the back office provides the proper speed restriction information and movement authority to the locomotive computer. Advanced Civil Speed Enforcement System (ACSES), transponders are used for location tracking, permanent speed restriction (location, speed, and prevailing grade), maximum authorized speed (MAS) restriction, and telling the train when to communicate with the Wayside Interface Unit (WIU) at the interlocking ahead.

Apart from these components, PTC systems have a communication network capable of transmitting and receiving the data necessary to support an interoperable PTC network. Communications technologies (e.g., 220 MHz radio, Wi-Fi, or cell

modems) are commonly used to communicate train locations, speed restrictions, and movements [2].

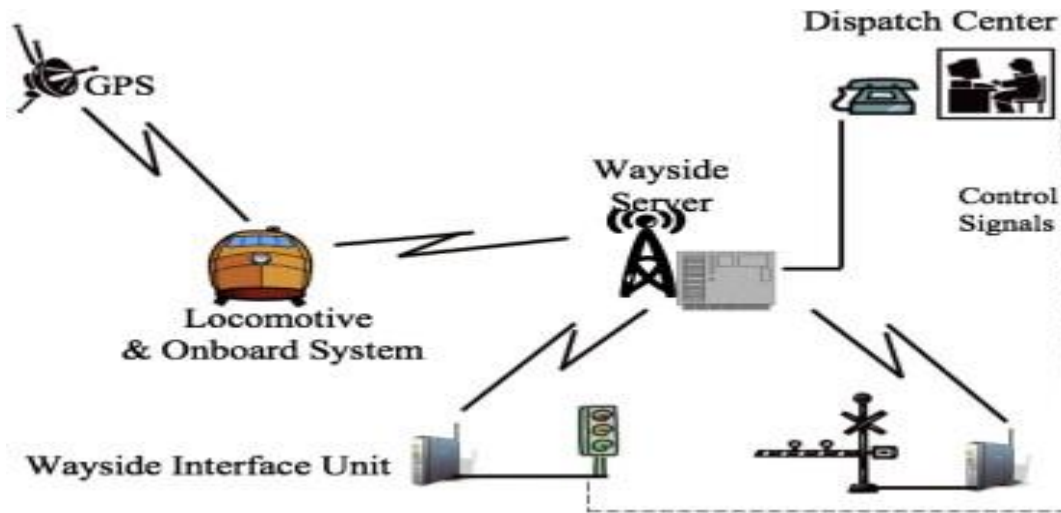


Figure 1.1 generic positive train control system architecture[5].

The headway policy for trains developed rapidly along with the improvement of communication technology and location technology. To ensure safety, the headway should be large enough in real time during the trip to avoid collisions. Originally, timetable policy was used to ensure the enough headway distance to prevent collisions. This method obviously puts a limitation on the capacity of the railway with large timetable headway. Different from the timetable policy, the fixed block system was presented and applied in railway operations widely. In this policy the headway depends on the block signals. However, it still cannot meet the growing demand of higher capacity[6]. In recent years the dynamic headway under MBS(Moving-Block System) gradually developed, especially in the subway system and HSR(High Speed Rail), where the following train's tracking target point is moving forward continuously with the leading train's operation. In solving conflicts encountered by train dispatcher, a reliable and cost effective approach or steps needs to be employed

to achieve this goal. This approach or steps will help the dispatchers in making reliable decisions that will give better or best way of solving conflicts encountered[7].

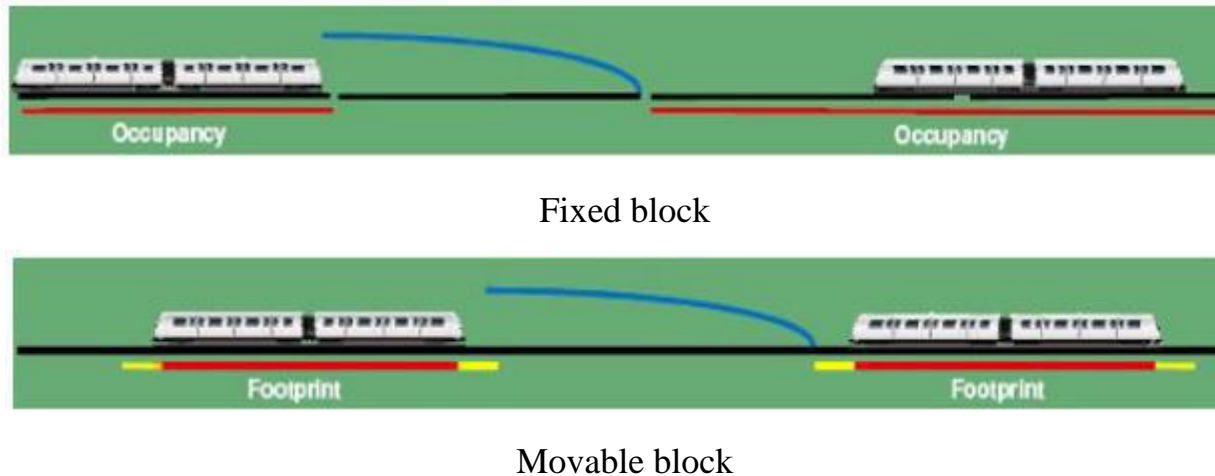


Figure1. 2 Effect of Moving Block to Minimize Headway[8].

1.2 Statement of the Problem

Trains run with little headway in order to meet passenger demand.. New communication technologies have the potential to improve railway operations, especially through more efficient train scheduling and dispatching. Positive Train Control (PTC) is introduced as a system of monitoring and controlling the movement of trains to increase safety by reducing human operation. PTC allows trains to speak with one another and exchange information.. Previously trains are ‘blind’ and controlled by the signals which are operated by experienced human dispatchers. With PTC, each train can be informed about other trains both locally and worldwide, depending on the location of the train.

In reality, trains are controlled by signals in order to avoid collision As a result, the section of track between two successive signals serves as headway between two trains. As a result, the railway track is often represented as a series of blocks, each of which can only accommodate one train at a time.. As a consequence, headway

between two consecutive trains is represented as a block with fixed length in most of the modeling approaches. The addition of a PTC system expands the meagre control that the signals previously provided. Dynamic headway between two successive trains is achieved by controlling the trains' deceleration, acceleration, and speed in real time at any moment.. As a result existing modeling approaches using fixed headways cannot be used to represent dynamic headway control, especially when the dynamic headway contains only a fractional of one single block.

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.

This Thesis focuses on a optimizing headway system for PTC which improves safety and increases track capacity. It employs an active communication system and is designed without compromising on reliability, safety and performance.

1.3 Objective of the Thesis

1.3.1 General objective

The aim of this work is to propose optimized headway system for PTC which improves safety and increases track capacity.

1.3.2 Specific objective

The specific objective of this thesis is to:

- Optimize the headway between the trains that lead to much smaller headways than existing ones.
- Analyze the effect of positive train control in train scheduling
- Compute a minimize headway time

1.4 Methodology

Different studies on this topic have been examined in the literature review .Having brief understanding of the problem, collection of necessary information, which is essential to achieve the objective of this thesis, is done.

The necessary timetable design requirement for communication based train control system and positive train control system are studied and selected from different literatures. However, due to unavailability of the required documents, assumptions and information from international railway manufacturing companies is used.

For the dynamic headway implementation in PTC we have the following two control loops: (1) driver control loop; (2) headway selection loop. The driver control loop determines the train acceleration/deceleration operations based on track speed limits and desired headway. The headway selection loop calculates the dynamic headway to be followed by the train by taking into account the following information: 1) communicated characteristics and acceleration/deceleration intentions of the leading train (target train to follow) based on an active communication system; 2) its own

characteristics and status; 3) condition of tracks, communication delays, train operator reaction times etc. Since the characteristics of the trains involved vary with time so is the headway and for this reason is referred to as dynamic headway policy.. It proposes a train dispatching model which serves to narrow down the identified gaps above and zero in the delays incurred during the train operations as a result of other factors relative to train routine operations such as dwell time delays, power outages, mechanical failures in order to improve the efficiency of the track utilization, recover the time wasted due to delays and improve the general efficiency of the train and track utilization and operations.

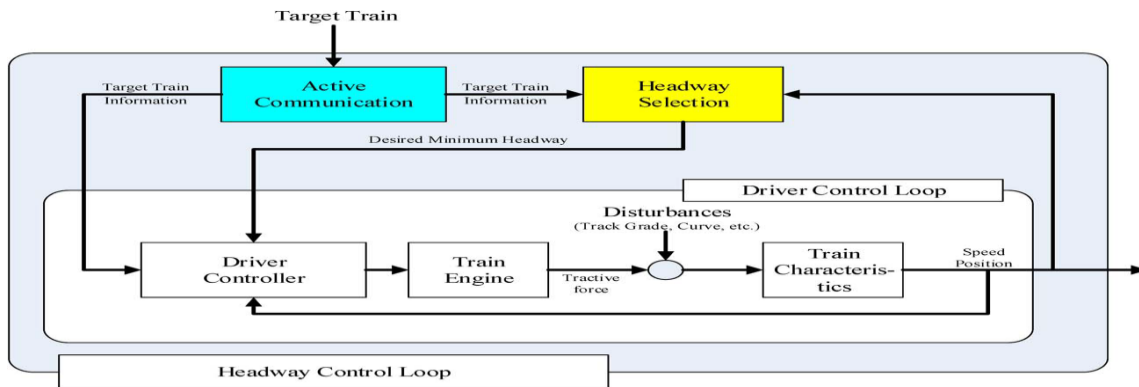


Figure1. 3 Headway control loop in PTC[2]

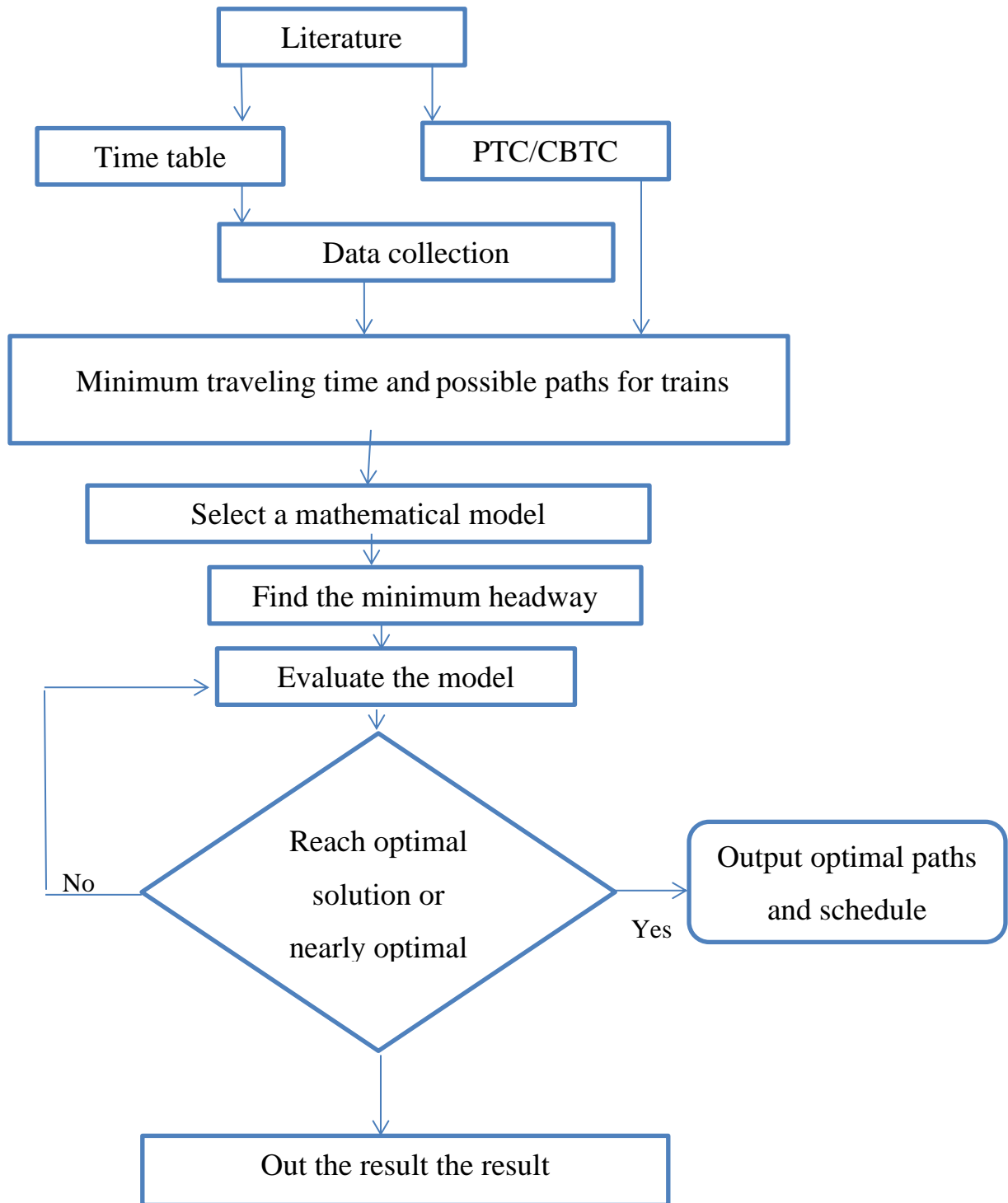


Figure1. 4 Methodology

It is essential to find the correct mathematical model to design the new minimum Headway to achieve the appropriate headway.

1.5 Scope

The scope of this thesis point towards developing an looks into development a new modeling for headway control rule taking the train's dynamics into consideration, through applying suitable technique or analytical method and software simulation by adapting a positive train control (PTC).

1.6 Significances of the Thesis

This thesis work is able to provide documented findings and recommendations related optimization of headway on positive Train Control specifically

1.7 Thesis Organization

This thesis has five 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.

Chapter three is about AALRT time tabling and its headway

Chapter four is about headway modeling and

Chapter five is conclusions and recommendation

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

The Southern California Regional Railroad Agency (SCRRA) that operates the Metro link regional commuter rail plans to implement a positive train control (PTC) system by 2012, ahead of the deadline set for the end of 2015. Implementation of the PTC system is required by the Rail Safety Improvement Act (RSIA) of 2008. The RSIA requires all Class I railroads, intercity passenger and commuter railroads to implement a PTC system on all main-line tracks where intercity passenger railroads and commuter railroads operate and where toxic-by-inhalation hazardous materials are transported[9].

The five county members of the SCRRA are jointly funding the development of an interoperable PTC system to improve safety for freight and commuter railroads in the region. PTC is designed to prevent train collisions using GPS tracking to remotely monitor train movements. In a typical PTC system, onboard equipment on the train uses GPS satellites to transmit speed and location data over wireless or hard line communications links to an operations center. A back office system at the operations center analyzes the data using software that determine the likelihood of a collision or derailment[10]. An advance alert is sent by the dispatch center to the locomotive and brakes are automatically engaged if the warnings are not acted on by the train engineer. Federal regulations does not prescribe the type of technology a PTC system uses as long as it can accomplish the following functions: preventing train-to-train collisions, derailment from over speeding, incursions into designated work zone areas and train movements caused by switches left in the wrong position.

2.2 Alternatives in Train Control

There have essentially been four generations of train control philosophy in the development of railway signaling for mass transit applications, with each generation offering a small gain in operational performance.

2.2.1 First Generation Train Control

The first generation of train control systems adhere to a set of principles that include track circuits for train recognition, roadside signals to provide train operators with movement authority cues, and trips stops to force a train to stop if a signal is passed at risk (intermittent ATP). This train control concept restricts the usage of train borne equipment to trip stops and abandons nearly all train control machinery and logic[11]. The track circuit configuration, associated wayside signal features, and fixed-block features have an effect on the feasible train throughput and operational flexibility. Manual driving modes are the only train operating modes that are currently available.[12].

2.2.2 Second Generation Train Control

The second generation of train control technology, which is track circuit-based and uses in-cab signals in place of roadside signals to replace the wayside signals, provides a continuous ATP. Utilizing speed codes, which are broadcast to the train from the roadside, is how this is accomplished. This railway control philosophy enables the display of movement authority information (signal aspects) to the train operator as well as the detection and response to speed codes by moving some of the train control machinery and logic to the train itself[13]. With this generation of train control technology, automatic driving modes are conceivable, but train throughput and operational flexibility are still limited by the layout of the track circuit and the number of usable speed codes.[14].

2.2.3 Third Generation Train Control

The next development in train control philosophy carried on the trend of offering more accurate control of train movements by increasing the quantity of data provided to the train. Instead of only responding to a few different speed codes, the train could now be controlled to follow a certain speed/distance profile. This generation of railway control technology, which also permits automated driving modes, offers increased train throughput. However, under this train control philosophy, the limits of a train's movement authority continue to be determined by track circuit occupancies.[15].

2.2.4 Fourth Generation Train Control

Communications-based train control (CBTC) is the common name for the fourth generation of train control concept. CBTC allows autonomous driving modes and regulates train movements in line with a specified speed/distance profile, just like the previous generation of train control technology. Instead of being restricted by actual track circuit borders, CBTC systems' movement authority restrictions are created using train position reports, which might support "virtual block" or "moving block" management philosophies[16]. More control and status information may be transmitted than with earlier generation systems thanks to a geographically continuous train-to-wayside and wayside-to-train RF data communications network. Therefore, CBTC systems provide the greatest operating flexibility and can support the most trains per hour, with the only restriction being the efficiency of the physical track alignment[17].

2.3 Technologies for Train Control Systems

2.3.1 Chinese Train Control System (CTCS)

The concept of CTCS was put forward in 2002 for the Chinese railways by the Ministry of Railway. A few years ago, the CTCS working programme was launched.. This system aims at ensure maximum efficiency, safety and reliability and guides the Chinese railway construction. Many signaling systems used in Chinese railways are not interoperable due to the reasons of historical and technical development. The issue of Chinese railways' lack of a standardized signaling system will be resolved by CTCS. The existing signaling systems cannot be interoperable, and the direction of the new signaling systems is not clear. Due to the challenge of interoperability, the CTCS provides signaling standards for the Chinese railways so that the current and future signaling system can be interoperable. The problem of incompatibility was common in Europe some years back before the European Train Control System (ETCS) project started in 1992[18].

2.3.2 European Train Control System (ETCS)

This system began in 1992 as a requirement of the European railway network development, this was mainly to ensure interoperability between tracks and existing systems as there was at least 15 different Automatic Train Protection (ATP) systems in operation(these ATP systems were incompatible as they were made and supplied by different companies with their own unique operation standards) and also as a result of development of high speed train, train cross border became unavoidable and therefore to enable for smooth operations, a standard system was coined[19]. ETCS is a subsystem of ERTMS (the European Rail Traffic Management System) and can also a time be referred to as ERTMS/ETCS. ERTMS includes Euro-interlocking, ETCS (Euro-cab), GSM-R (Euro-radio), Euro-balise. With the assistance of European researchers and the European Union, a group of European railway signalling vendors

known as UNISIG started working for ETCS ten years ago.. The goals of ETCS can be described further in[20].

2.3.3 ERTMS (European Rail Train Management System)

The European Union supports the European Rail Traffic Management System (ERTMS), a project that aims to improve cross-border interoperability and the purchase of signaling equipment by establishing a unified Europe-wide standard for train control and command systems.

ERTMS has two basic components

1. ETCS, or the European Train Control System, is a national ATP system that will take the place of the current ones;
- 2- GSM-R is a radio technology that uses standard GSM and frequencies designated for rail applications to provide voice and data communication between the track and the train specific and advanced functions.

Across Europe many ERTMS based signaling schemes have been introduced most of them at level 1 (which retains the basic signaling but adds automatic train protection by a spot transmission system), or level 2 (also fixed block but which introduces radio based signaling)[21].

The various national rail control and command systems in Europe are intended to be replaced by ERTMS. The implementation of ERTMS will enable the development of a unified European railway system and boost the competitiveness of European railroads. [22].

2.3.4 Communication Based Train Control (CBTC)

The Comprehensive, Integrated and Intelligent Train Control System for Railway Systems including Major Line Trains, Light Rail or Underground Lines in Cities is commonly referred to as the CBTC systems also known as Transmission Based Train

Control(TBTC). CBTC is expected to become a very reliable tool for controlling most railway operations such as speed control, etc in the near future due to its continued development and evolution of more autonomous computers, communication system and data controls and analytical systems. It has proven to be a very useful tool for ensuring railway security, efficiency and reliability as it is capable of optimizing the capacity of the existing rail network when used in combination with CBTC; this will make the dispatching system flexible and efficient. It can be said that CBTC is the nerve brain of the railway system[16] .

CBTC system comprises of the following four major subsystems:

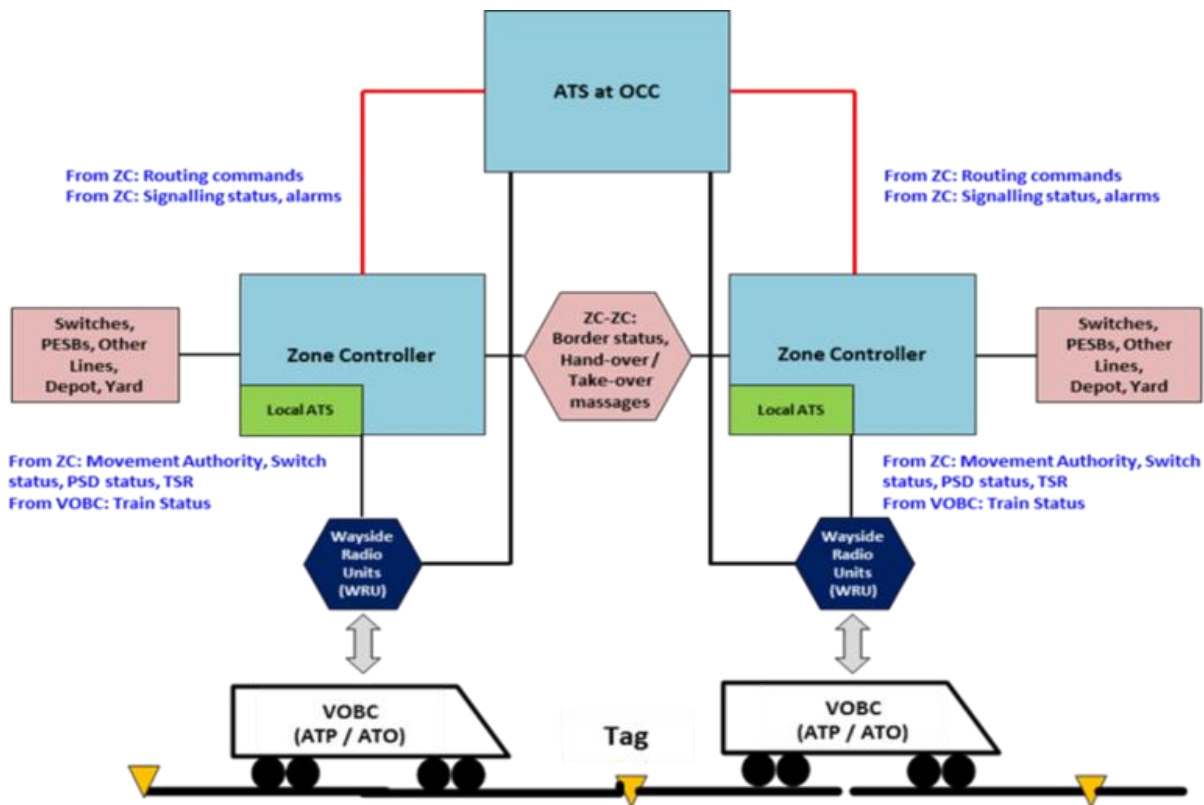


Figure 2.1 CBTC System Architecture[23].

1. CBTC-ATS equipment
2. CBTC Wayside Equipment
3. CBTC Train-borne Equipment

4. CBTC Data Communications Equipment.

In order to carry out the functions of automatic train control, such as identifying, maintaining operational schedules, tracking and displaying trains or regulating rail movement in general, CBTC equipment shall include devices placed at central stations or wayside locations. The CBTC wayside system is composed of a network of processor based controllers installed at central and side locations. The CBTC wayside system may interface with an external separate interlocking subsystem or, alternatively, the interlocking functions may be integrated into the CBTC wayside equipment. With the help of a CBTC data communication device, each roadside controller can connect to any CBTC system with regard to rail borne equipment and may also interoperate with outside Interlocking CBTC-ATS[24] .A computer based controller and related speed measurement and location determination sensors are integrated into CBTC's train loading equipment. The CBTC train-borne equipment interfaces to the train subsystems and also interfaces to the CBTC wayside equipment and the CBTC-ATS equipment via the CBTC data communication equipment[25].

The fundamental guidelines for a CBTC system's operation include:

- ❖ High resolution train position determination independent of track circuits using CBT train-borne equipment.
- ❖ Communication between the interlocking about the status and the wayside equipments and from the wayside equipments to the interlocking equipment to support CBTC operations.
- ❖ Transmission of this train's location information and other train status data over the CBTC train-to-wayside data communications link to CBTC wayside equipment.
- ❖ Communication of movement authority information and other train control data to the appropriate train over the CBTC wayside-to-train data communications link.

- ❖ The CBTC train-borne equipment determines and upholds the ATP profile..
- ❖ Conveyance of information between wayside controllers which are neighboring each other to facilitate the hand-off of train control.
- ❖ Sharing of vital information amongst a number of the CBTC train borne equipments so as to enhance the CBTC operations.
- ❖ Determination of movement authority information for each CBTC-equipped train, by the CBTC wayside equipment, based on train location information and inputs from interlocking.

Other than the existing communication modes and CBTC technologies through GSM and GSMR also proposes a new ground-to-train communication system using free-space optics between a train and the ground. In the proposed system, a cylindrical concave lens spreads the incoming beam from transmitter (Laser Diode, LD) horizontally to form a wide fan-shaped beam. The fan-shaped beam is projected onto a train, and its breadth is equal to the length of a standard bullet-train vehicle.. In this concept, horizontally spread beams are received continuously from the transmitter with cylindrical concave lens by a corresponding receiver (Avalanche Photo Diode, APD) which are installed on a train and the ground. This spread beam allows the train to maintain a constant communication link with the ground.[26].

2.4 Working of PTC

The train's speed and location shall be monitored using a GPS system or transponder and the information shall be transmitted between the wayside signals installed on the track and the Central Train Control and this information shall be transmitted to the train and displayed as a cab signal. The integrated system ensures that there is easy monitoring and control of train movements on the track. In order to give guidance and instructions about what the train is supposed to do, positive train control uses both

hardware such as wayside signals and software[27]. A good example of how it works is that if a train is running at a prohibited speed or trespassing through an area which it should not be, then a warning signal is sent to the crew, and if the crew doesn't respond then the train applies brakes automatically stopping further movements.

Currently, two main implementing methods of the PTC system are under development. It takes advantage of the fixed communications networks, such as circuits on rail lines and wireless transponders, in order to communicate with its onboard speed control unit. Another way to do this is by transmitting dynamic information using radio data radios that are distributed on the line. This approach of wireless information makes the use of variable or linear blocks possible if the train continues to communicate its position. In this way, a virtual block can be created. The installation of wireless networks is complex and requires a high level of sophisticated communication network, even though the cost analysis reveals that this is perfectly justified to achieve increased capacity utilization[28].

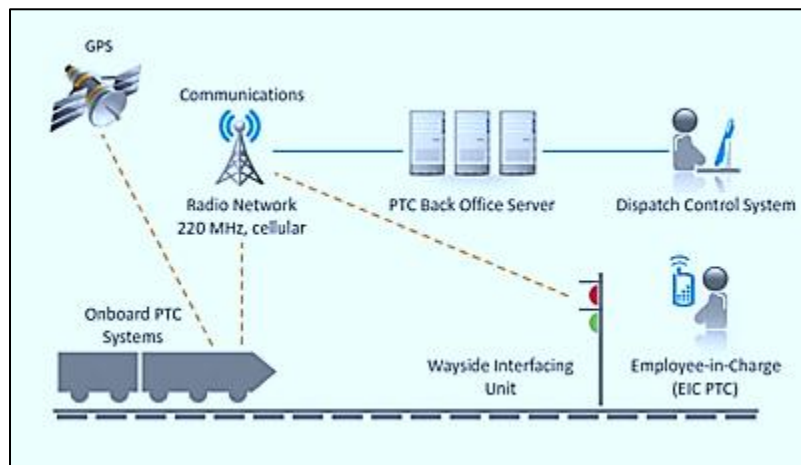


Figure 2.2 Train components for the Availability of the PTC System[29].

2.4.1 Units of PTC Control

The PTC system consists of train systems, equipment installed on the track and a central control unit, also known as a back office server, which can be described on the

basis of three common units, which are considered to be the building blocks of the system.

- i. Onboard or locomotive systems: they shall be located on board the train and shall monitor its speed and position, allowing it to control the operation of the train, such as braking, in order to prevent any further movement.
- ii. Trackside/Wayside system: They are located along the track line and are responsible for monitoring of switches, track signals and general track status and it relays data or information needed to permit the onboard system to allow or stop the train movement.
- iii. Centralized control unit/ back-office server: This is the unit that receives and stores all the data and information about a rail network and the information about the trains in that network i.e information about the speed restrictions, position of the trains with respect to each other, train compositions, train movement authorization etc, and relays this information to individual locomotive onboard enforcement systems[30] .

PTC integrated system has to identify the precise location, the speed and the direction of the train and warn the train crew accordingly by comparing that information with the same data from the other trains using the same track and other track restrictions from the wayside equipment. Should the operator fail to take action as may be required, the PTC system must be able to stop the train

The fundamental operations of a PTC system should meet the operational requirements set in place by the Rail Safety Improvement Act (RSIA) of 2008 in terms of its ability to prevent accidents or collisions incase the train operator fails to take the required action. PTC is a group of a number of technologies serving to ensure safety of the train[31].Rail tracks are allowed to use various PTC technologies once

approved by the federal Railroad authority, a body which is in charge of performance standards. Various units namely the locomotive computer, wayside device, communication network, and back office the locomotive computer is an onboard piece of equipment that accepts speed restriction information and movement authority and integrated into the PTC system, so that these data can be compared against the train's location to ensure compliance. The wayside equipments are located along the track and they are responsible for communicating the status of the switches and signal status. Back-office is for communication and coordination of trains relative status i.e speed and its position. The back office can be categorized into three main parts: (the control/back office server (BOS), the geographical information system (GIS), and the dispatch office) interface with other components of the PTC systems. The BOS stores the information such as the composition of the track, speed limits, and the general track status to aid in operations of the trains, in a nut shell the Back office provides information regarding the movement authority and speed restrictions to the loco computers. There are however a number of communication technologies being researched on presently to make the PTC system more efficient[32].

2.4.2 Levels of Operations

The primary operations of a PTC system can be categorized into levels as shown below depending on the control action it offers: Each level has a distinct role it does to ensure proper efficiency of the PTC system.

PTC Level 1: Responsible for prevention of train collisions, protecting track workers and enforcing speed limits.

PTC Level 2: Does the roles of level 1 and in addition responsible relay of train information i.e the position and speed and also responsible for digital transmission of authorities.

PTC Level 3: Does the roles of level 2 and in addition to that it also monitors the wayside equipments i.e signals, protective devices in traffic control territory and the status of all switches.

PTC Level 4: Does the roles of level 3 and also wayside monitoring for all mainline switches, signals and protective devices [33].

2.4.3 Reliable communication system

A number of possible communication technologies are currently being used and are being explored for future use of the PTC system, which are very important for continuous, reliable and efficient communication between the operational blocks of the PTC, i.e. locomotives on board, wayside equipment and back office. It is stated that radio transmission, common in 2.4 GHz ISM band and able to reduce the likelihood of interference between systems by using a spectrum propagation technique, constitutes one suitable communication system for today's CBTC networks[30].

The communication medium chosen can be based on 'line of sight, or leaky coax using a RADIAX cable, or both depending on the application. However, proposes a dynamic headway system for PTC which improves safety and increases track capacity. It employs an active communication system and is designed without compromising on reliability, safety and performance[34].

2.4.4 Train Positioning System

Any (advanced) moving block system must have an accurate positioning system as a component. Typically, trackside tools like axle counters or track circuits are used to find trains in the conventional fixed block arrangement. Accurate train position information must be updated frequently and in real-time to provide dynamic headways in a moving block system[35].

Real-time railway positioning is possible everywhere thanks to the Global Positioning System (GPS) by satellite. Dynamic headways are possible because to Positive Train Control (PTC), a widely utilized signaling system that employs GPS to track train locations. GPS has only been utilized for non-safety-critical subsystems in Britain due to the difficulty that some regions, such as underground tunnels and areas with high-rise buildings, cannot readily be covered by GPS signals. In order to assure precision and reliability when using moving blocks, stationary block placement system equipment like track circuits may be kept around as a backup. Signal loss in tunnels and other radio-inaccessible regions can be resolved by switching the operated signaling system's moving block and stationary block configurations via on-board control units[36].

2.4.5 Interoperability

It defines interoperability as the state of compatibility in which the PTC must be able to communicate with each other in order for trains to be able to move smoothly across the tracks owned by different railroads with potentially different PTC technologies. Interoperability shall be achieved by locomotives from any host or tenant railroad that operates on one of the tracks in a single track segment, where it is possible for them to efficiently communicate with and interact with other rail PTC systems which permit continuous operations over land borders[37]. A good example is if a train crosses into another territory in which it operates as tenants, where the train requires information about that line, such as temporary speed limits due to maintenance work or any other relevant information. The term interoperability can best be used to describe this aspect of the tenant train[38].

Railroads must take a number of actions to achieve interoperability, including::

- 1) Additional installation work (such as installing equipment on a tenant railroad's locomotives) and scheduling.

- 2) Laboratory testing.
- 3) Field testing.
- 4) Operations of a RSD or revenue service: By the time a number of railroads are beginning to take steps towards interoperability with other railway lines, they will already have completed much implementation work for their own Passenger Transport Computer Systems, like initiating RSDs in some or all sections of track. At the same time, a railway may take steps to overcome interoperability with other railroads and complete field testing or other phases of tests which it itself has in place for its PTC system[39].

2.4.6 Pros and Cons of Using PTC System

Pros

- i. PTC systems are focused on achieving zero accidents in their operations.
- ii. The PTC plays a crucial role in accident prevention due to the tracking related errors
- iii. Driverless trains which are automatically controlled by PTC systems are the trains of the future

Cons

- i. Resource constraints:-The cost of initial implementation of the PTC is very high, given that it uses advanced technology.
- ii. Interoperability: - PTC systems adopted by various railroads must have inter-train communication so that trains can move seamlessly between tracks controlled by different systems. The fact that there are networks available and the current system used may make it difficult to achieve PTC interoperability on some rail lines.
- iii. Technology availability: - PTC technology is sophisticated, which means that the current railway system needs to be equipped with technical modifications

and a number of suppliers have their own sets of standards i.e. China and Europe are both specialized in this area.

- iv. PTC CYBER SECURITY:-PTC cyber security Cyber theft is a growing threat to our infrastructure. Any successful unauthorized entry into the system can pose serious safety risks, this may mainly be used by terrorists who are determined to cause havoc or security threats which could have a negative effect on economies or other areas of national security. These communication channels have their own risks, such as cyber-attacks, due to the digital connection of modern railway communications via Ethernet, Transmission Control Protocol HTTP TCPIP, or similar networking standards[40].
- v. Communication failure:-The entire system shall enter a failed safe state until the problem is resolved, if there are disturbances in radio transmission of trains to each other. Communication can be interrupted due to equipment failure, signal weakness, frequent handoff, interference with sound or overload of the communications medium. The performance of railway control can be seriously affected by wireless networks, owing to the lack of reliable wireless communication and train mobility[41].

2.4.7 Research gaps identified

- ❖ Headway is simply calculated from the running time calculation for the safe braking distance between two trains in the existing methodologies for headway optimization. The blocking time at movable parts, such as switches, crossings, and stops, has unique properties, though. The gap between two successive trains at movable elements exceeds the safe braking distance because signaling systems control train separation.
- ❖ The efficiency of railway operation and control is currently being improved through the use of train-to-train communication technologies. The properties of

relative distance braking can be used with the aid of real-time train information exchange. Complex infrastructure architectures cannot be handled by the analytical models for headway optimization.

- ❖ The headway is only established as a constraint for optimization in particular applications, such as energy-saving control or train movement regulation. The reduction of energy use or overall delays is the goal of optimization.

CHAPTER THREE

AA-LRT and Its Timetable

3.1 General Characteristics of AA-LRT System

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

The Addis Ababa railway line is double track and it is a homogeneous system, i.e. the trains are all the same as well as the track lines are uniform and all are electrified track lines.

The main characteristics of AA-LRT are:

- Its operational speed is 20-70kmph with maximum speed of 80kmph
- Its infrastructure line comprises tunnels, bridges, and the ground level.
- The battery capacity can support a failed train for at least 30 minutes for the functions of door control, emergency lighting, onboard equipment, and communication system.
- It has a total length of 34.25 km (North-South line 16.90 km and East-West line 17.35 km with about 2.662km common line to both routes.
- It negotiates steep gradient(50‰)1 and sharp curves
- It gives service 16 hours per day
- It is fully electrified LRT and hence environmentally friendly

- Standard Gauge (1.435 meters) and double track for the whole route
- Expected headway: 6 minutes with a potential of reducing to 90 seconds
- The fare system is passenger-km based

- Minimum Curve Radius: 50m for mainlines, 30m for parking garage
- Minimum vertical curve Radius: 1000m
- Steel rail: all the main and auxiliary tracks and the depots use 50kg/m steel rails with cut-length of 25m.
- Sleeper arrangement: the arrangement is 1,600pairs/km for main tracks and 1,440pairs/km for tracks inside and outside the garages in rolling stock depots.
- The operation of train adopts the mode of manned visual driving
- Average acceleration for startup: 1m/s²
- Average deceleration for braking :-
 - The average deceleration of normal braking with rated load (including control response time): $\geq 1.0\text{m/s}^2$
 - The average deceleration of emergency braking with rated load (including control response time): $\geq 1.5\text{m/s}^2$

3.2 Stations of the AA-LRT

The platforms at AA-LRT stations are 60 metres long. The AA-LRT has a total of 39 stations on both routes, with five stations shared between the EW line's 22 stops and the NS line's 22 stations. The first method the names of the stations are written is by using the local name of the city. The other, more orderly name (i.e., one that is simple to remember) utilises the letters EW after a number of east-west stations and the letters NS after a number of north-south stations. The station names for the EW direction are EW1, EW2, EW3 and EW22, which stand for Ayat, Meri, CMC,...., and Torhailoch, respectively.

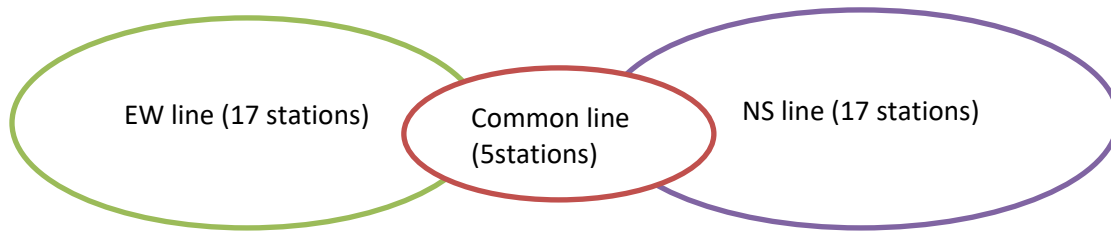


Figure 3.1 Number of stations in each line

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

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

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

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

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



Figure 3.2 Map of rail lines and stations of the AA-LRT phase-I[42].

Table 3.1 Platform type and distance between stations of each station of the east-west line [43].

N o.	Station name	Distance between stations	Station type
1	Origin	52	Ground station
2	EW22	769	
3	EW21		

		732	Ground station
4	EW20	735	Elevated common rail station
5	EW19	688	Elevated common rail station
6	EW18	560	Elevated common rail station
7	EW17	445	Elevated common rail station
8	EW16	640	Elevated common rail station
9	EW15	593	Elevated station
10	EW14	675	Ground station
11	EW13	963	Semi-underground station

12	EW12		Ground station
		758	
13	EW11		Ground station
		746	
14	EW10		Ground station
		776	
15	EW9		Semi-underground station
		829	
16	EW8		Ground station
		1083.6	
17	EW7		Ground station
		970	
18	EW6		Ground station
		724.82	
19	EW5		Ground station
		860	
20	EW4		Ground station
		863	
21	EW3		Ground station
		1092	
22	EW2		Ground station
		1260	

23	EW1		Ground station
		182	
24	Terminal		

Table 3.2 Platform station type and distance between stations of NS line [43].

Station name	Distance between stations	Station type
Origin	196	
NS27	743	Underground station
NS26	945	Ground station
NS25	604.88	Ground station
NS24	667	Elevated station
NS23	812.71	Ground station
NS22	739	Elevated station

NS21		Elevated station
	591	
EW20		Elevated common rail station
	735	
EW19		Elevated common rail station
	688	
EW18		Elevated common rail station
	560	
EW17		Elevated common rail station
	445	
EW16		Elevated common rail station
	908	
NS15		Ground station
	481.12	
NS14		Ground station
	610	
NS13		Ground station
	555	

NS12		Ground station
	1971.66	
NS11		Ground station
	861	
NS10		Ground station
	995	
NS9		Ground station
	535	
NS8		Ground station
	845	
NS7		Ground station
	950	
NS6		Ground station
	269	
Terminal		

3.3 Signaling System of AA-LRT

Signaling is a mechanism whereby the stationmaster gives information to the train driver that he must stop or proceed with caution. When planning the timetable, it is best to use a signaling system which will be guided by signals when train tries to break out of its schedule or attempt to enter an occupied path ahead. Safe separation of trains from one another and the protection of specific corridors through interlocking at junction or crossing points are essential functions for signaling.

Cab Signaling

The cab, crew compartment, or driver's compartment of a locomotive, railcar, or multiple units can receive information from a railway safety system about the state and condition of the track. The information is continually updated giving an easy to read display to the train driver or engine driver [44]

Both Kaliti and Ayat rolling stock depots use CASCO intelligent computer interlocking system and the signal devices are under the centralized control of the signal building of the depot. AA-LRT signaling system uses axle counter and has 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.

3.4 Block (Section) Safety of AA-LRT

A section shall be defined as the scope of the lines between two adjacent end walls of two adjacent stations. 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).

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). Under normal circumstances, the operation of the train must ensure spacing of one station matching with one Section allows only one train to operate between two

adjacent signals in the same direction within a single route, except for a train that helps other trains in trouble, and the train operates with a display of the ground signal.

3.5 Train Leaving/Entering the Depot Arrangement

3.5.1 Train Leaving Depot Arrangement

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

3.5.2 Train Entering Depot Arrangement

In peak hours, when trains enter depot, the operation dispatcher should strictly control the trigger time of the depot-entering route to ensure train operation in accordance with train diagram/timetable.

- Train entering depot should base on planned route, and OCC can make a flexible adjustment under special circumstances. Additionally:
- Under special circumstances, the trains cannot come back to the depot according to the plan, OCC should contact DCC immediately, and DCC makes the plan to ensure trains leave depot according to the plan.
- OCC and DCC need to strengthen contact, to check as the plan works accordingly.

3.6 Timetable of AA-LRT time specifications

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.

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 is 5 minutes and 04 seconds.

Total Trip Time: This amount of time is required to perform a single journey. A journey from Kality station to Menelik II station and returning to Kality station is an example. Currently, the AA-LRT requires two hours to complete a single trip. Naturally, the overall trip time includes both the time spent moving between stations and the dwell times at each station.

Dwell Time: The amount of time a train stays in a station is known as the dwell time. This restriction links a train's arrival and departure events. Dwell periods ought to be lengthy enough to allow for the boarding of fresh passengers as well as potential loading, unloading, or train maintenance. Given that passengers want to continue their journey and that a station's platform capacity may be limited, it shouldn't be much longer than necessary. The dwell duration for the AA-LRT is specifically between 25 and 40 seconds, with an average of 32.5 seconds.

The North-South Line (NS-Route)

The working time 16 hours per a day that is from 6:00 in the morning to 22:00 at noon.

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

- ✓ Downward trains entering depot (NS6-NS27) are 3 trains. The trains will go empty after finishing their task to go from Menelik II square to Kality depot at the end of the day.

Table 3.3 Time list for first/last train and running interval for the AA-LRT NS line[43].

station		NS line			
		NS6		NS 27	
time		06:00	20502	06:00	20101
First train					
last train		22:00	20518	22:00	20117
Route plan		NS6~NS27			
Routing interval	15 minutes	06:00~22:00			

Table 3.4 Time list for first/last train and running interval for the AA-LRT EW line[43].

station		EW line			
		EW1		EW 22	
time					
First train		06:00	10502	06:00	10103
last train		22:00	10918	22:00	10819
Route plan		EW1~EW22			
	12 minutes	07:00~19:00			

CHAPTER FOUR

HEADWAY DESIGN MODEL FOR AA-LRT

It is important to evaluate and minimize headway, which is defined as the time interval calculated from “head to head” between two successive trains. With existing approaches for headway optimization, the headway for moving block systems is often calculated based on the safe braking distance. However, the blocking time at movable elements (e.g., switches and crossings) and stops has special characteristics. Since train separation is dominated by a signaling system, the distance between two successive trains at movable elements and stops exceeds the safe braking distance

4.1 Headway

Headway of a system is the minimum spacing between two trains so that the second train can maintain identical speed to the first train. Headways can be expressed in terms of distance and time, but the headway time is significant term as it can be related to a system capacity.

Headway of a train depends on

- ❖ Train speed
- ❖ Dwell time
- ❖ Communication between the trains travelling in single route

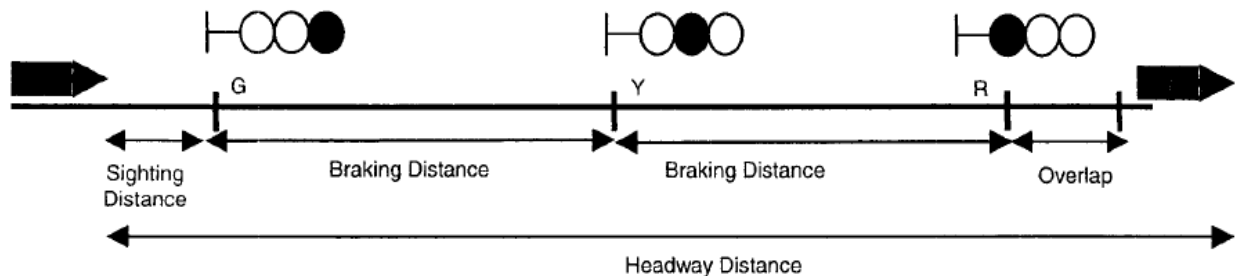


Figure 4.1 Headway of three aspect signaling system[45].

4.2 Elements of headway

Before considering headways as whole, elements that make up headways should be considered. These are:-

4.2.1 Sighting Distance

Although adequate braking distance is allowed from the first warning signal to stop a signal it is generally recognized that the driver will take some action to reduce his speed at the point before a warning signal rather the signal itself. The point is known as sighting point and its sighting distance from the warning signal. The point at which the driver takes the first action will differ from driver to driver and from railway to railway. Table below shows sighting distances from different speeds

Table 4.1 Sighting distances in different operating speeds[46].

Operating speed(km/hr)	Sighting distance(m)
60	100
80	140
100	170
115	200
160	260

4.2.2 Braking distance

Braking distance (sometimes called as service braking distance) is the distance the train travels from when the train driver makes a full-service brake application to when the train stops. The braking distance depends on the speed of the train, geography of the track (gradient and curve) and on the response of the brake. The change in braking rate affects both the braking time and the safe separation time (distance).

As the driver applies the brake 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 change in 'kinetic' energy relates to the change in the train's speed difference of the speed at which deceleration began (U) and the 'at stop' speed.

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:-

$$m * (a) * S + \frac{1}{2} * m * (U^2) + m * G(h_1 - h_2) = 0 \quad (3.1)$$

Where:-

m = mass of the train

u = speed of the train when it starts decelerating

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

As the mass of the train kept constant we can cancel out it then it can be simplifies the equation as

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. $\tan\alpha$, where α is the angle of the slope (refer figure below). For small α , which is the case for railways, $\tan\alpha$ equals $\sin\alpha$. $\sin\alpha$ is the change in height ($h_2 - h_1$) over the stopping distance(s) which is given as follows

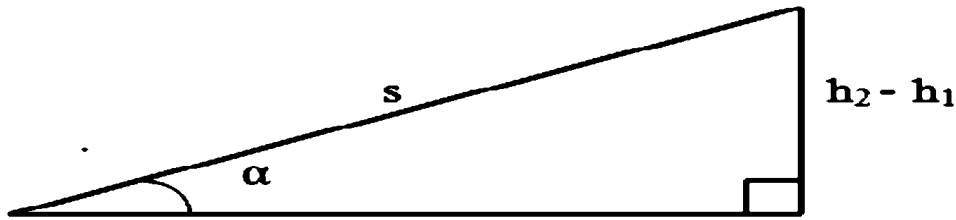


Table 4.2 Sample of the gradient for braking distance calculation[47].

Substituting Eq(2) into Eq(1) and rearranging

$$S = \frac{U^2}{2(a-g*\tan \alpha)} \text{ for } a < 0 \quad (3.2)$$

$h_2 - h_1 > 0$ and $h_2 - h_1 < 0$. The term " $-g*\tan \alpha$ " is the gravitational acceleration. For upward track gradients i.e. $h_2 > h_1$, gravity assists deceleration.

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.

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

The AA-LRT the maximum grade of the main track is 55‰, and the minimum grade is 0‰. For intervals with a grade of 30‰ or above on the main track summarized as tables below

This distance is the minimum distance that needs to be provided. Other factors that will further increase this distance are:

- ❖ Other design constraints e.g. the track layout arrangement, level crossings etc.
- ❖ Access to the physical location for installation and future maintenance;
- ❖ Suitability of the site to erect its supporting structure.

Table 4. [12](#) Intervals with a grade of 30‰ or above on the main track of the NS line [43].

Interval	Grade (‰)	Length of grade section (m)
NS27-NS26	-50	225
NS26-NS25	47	295
NS25-NS24	55	150
NS24-NS23	-54	370
NS23-NS22	-46	420.171
NS23-NS22	55	326
NS22-NS21	-46	615
NS21-NS20	-48.866	107
NS20-NS19	-55	280
NS19-NS18	46	165
NS17-NS16	-46	155
NS16-NS15	-47	160
NS15-NS14	-43	72
NS14-NS13	-55	142

Interval	Grade (‰)	Length of grade section (m)
NS12-NS11	50	185
NS12-NS11	45	185
NS12-NS11	42	155
NS12-NS11	-40	130
NS12-NS11	-50	110
NS10-NS9	-47	103
NS10-NS9	-44	258
NS9-NS8	-50	130
NS8-NS7	-40	115

Table 4.23 Intervals with a grade of 30‰ or above on the main track of the EW line[43].

Interval	Grade (‰)	Length of grade section (m)
EW22-EW21	-55	142
EW21-EW20	55	435
EW20-EW19	-55	280
EW19-EW18	46	165
EW17-EW16	-46	155
EW15-EW14	-49	356

EW13-EW12	44.5	195
EW12-EW11	-53.5	315
EW9-EW8	43.5	205
EW7-EW6	53.5	220
EW4-EW3	40	145
EW2-EW1	-50	225
EW2-EW1	50	90

For braking distance calculation we need the speed when the brake applies to the train. The range of the speed varies is from 20km/h to 70km/h (80km/hr)

Here, the formula 4.3 is used to calculate the braking distance for some selected stations. But, this may not indicate for the whole section, instead, it is for some part of the given section (block). In this case, blocks are selected according to their length which have a major effect on the calculation of headway time as well as train synchronization.

The calculation of the braking distance at each station will be carried out below, taking into account the speed and gradient curve.

Now lets take for some sample stations and their speed

Table 4.34 Sample stations their speed and grades [43].

Stations	Speed	Grade
EW15 - EW14	60	-49
EW22-EW21	50	-55
EW18 - EW17	45	20.73
EW13-EW12	35	44.5
EW2-EW1	70	50
NS22-NS21	35	-46
NS14-NS13	60	-55
NS12-NS11	55	42
NS15-NS14	20	-49
NS10-NS9	45	-47

Detailed calculations of the braking distances in NS, EW line and common line can be referred in appendix

East West Line

East West Line

✚ For EW15-EW14 here $u = 60\text{km/h} = 16.6667\text{m/s}$, $\alpha = -49/1000 = -0.049$,

$$S = \frac{(-U^2)}{2(a - g * \tan\alpha)} = - \frac{(16.6667)^2}{2((-1 - 9.8 \tan(-0.049)))} \\ = 140.63\text{m}$$

✚ For EW22-EW21 such that $u=50\text{km/hr} = 13.8889\text{m/s}$, $\alpha=-46/1000=-0.046$

$$S = \frac{(-U^2)}{2(a - g * \tan\alpha)} \\ = - \frac{(13.8889)^2}{2((-1 - 9.8 \tan(-0.055)))} = 97.37\text{m}$$

✚ For EW18-EW17, values are $U=45\text{km/hr} = 12.5\text{m/s}$, $\alpha=45/1000=0.045$

$$S = \frac{(-U^2)}{2(a - g * \tan\alpha)} = S = \frac{(12.5)^2}{2(1 - 9.8 * \tan 0.045)} = 78.73\text{m}$$

✚ For EW13-EW12, values are $u=35\text{km/hr}=9.72222\text{m/s}$, $\alpha=35/1000=0.035$

$$S = \frac{(-U^2)}{2(a - g * \tan\alpha)} = S = \frac{(9.72222)^2}{2(1 - 9.8 * \tan 0.0445)} \\ = 47.62\text{m}$$

✚ For station EW2-EW1 values are $u=70\text{km/hr}=19.4444\text{m/s}$, $\alpha=-50/1000=-0.05$

$$S = \frac{(-U^2)}{2(a - g * \tan\alpha)} = S = \frac{(19.4444)^2}{2(1 - 9.8 * \tan(-0.05))} \\ = 187.43\text{m}$$

North South Line

Table 4.46 Calculated braking distance between the stations of NS line

Stations	Braking distance(m)
NS15-NS14	15.56
NS22-NS21	47.71
For NS14-NS13	137.59
NS10-NS9	77.5
NS12-NS11	115.87

For the common line

Table 4.57 Calculated braking distance between the stations in the common line

Stations	Braking distance(m)
NS17 - NS16	117.63
NS18 - NS17	77.761
NS19 - NS18	77.515
NS20- NS19	39.533

4.2.3 Overlaps

Overlaps are used to provide a small safety margin against possible overrun of a signal. They are also used to guarantee a space interval between two trains. This means that it is not possible to clear the signal in rear until the tail of a train has cleared a point some distance beyond the next signal.

4.2.4 Train Length

The last factor in the headway of a given line is maximum length of trains using the line. Train length normally does not have significant effect on the headway unless long trains are in use, but nevertheless it must take into consideration.

4.2 Braking Time (Bt)

The time taken by the train to cover the braking distance after the driver applies the brake when approaching the station. It can be expressed as:-

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

Detailed calculates is done on appendix

NS line

Table 4.68 Barking times of NS line

Speed(kh/hr)	Braking time(sec)
20	2.8
35	4.91
45	6.2
55	7.58
60	8.26
70	9.03

EW line

Table 4.79 Braking times of EW line

Speed(km/hr)	Braking time(sec)
35	4.89
45	6.29
50	7.012
60	8.44
70	9.64

Common line

Table 4.810 Braking times of common line

Speed(km/hr)	Braking time(sec)
31.86	4.47
45	6.22
45	6.20
55	7.69

4.3 Operating Margin Time (OMT)

This time is the constant amount of time a train spends on its reaction periods to issue commands, such as applying brakes. The infrastructure managers have the responsibility to determine a regular time, and this is mostly approximately 5 to 10 seconds.

4.4 Release Time (R_t)

Release time is required for a train's entire length to cross the signal at one of the stations, or complete its departure and entry into another station. Its also can be expressed as:-

R_t = Length of train /Speed, such that the length of the trains operating in AALRT typically 59m long.

Table 4.911 Release time

Speed (km/h)	Release time(sec)
20	10.62
35	6.07
45	4.68
55	3.86
60	3.54
70	3.03

4.5 Time Lock Switches

On the mainline, time lock switches are manually operated switches found in the t-rail. They are padlocked for security, just like all other mainline t-rail switches. These, however, have an extra lock built in that prevents the switch from being thrown until a timer has finished counting down, thus the name. On the switch machine, there will be a sight glass that shows the lock's status. Under The switch will provide a path for two successive trains coming from the same direction (which is either from NS or EW direction) after 840 seconds, however it takes 420 seconds for trains coming from two directions (EW and NS).Normal functioning conditions, it will say padlocked when the lock is locked and display locked when the lock is unlocked but before the timer expires[43].

4.6 Travel Time

The duration needed to complete one section, or the distance between one station and the next. The length of time required to finish a stretch or the distance between stations. The distance between stations for the NS-line are reported as 1972, 738, and 445m for longest, average, and shortest distances, respectively, while for the EW-line are given as 1260, 762, and 445m, respectively, since AA-LRT operating speeds range from 20-70km/h. For the common line the distance is 445, 560, 688, 735 meters in NS16, NS17, NS18, NS19, NS20 respectively

NS line

Table 4.1012 Travel time for the average distance between the stations of NS line

Speed(km/hr)	Travel time(min)
20	2.214
35	1.26
45	0.984
50	0.899
60	0.738
70	0.633

EW line

Table 4.1113 Travel time for the average distance between the stations of EW line

Speed(km/hr)	Travel time(min)
20	2.29
35	1.3

45	1.016
50	0.914
60	0.762
70	0.653

Common line

Table 4.12+4 Travel time for the average distance between the stations of EW line

Speed(km/hr)	Travel time(min)
20	1.82min
35	1.04 min
45	0.809min
60	0.606 min
70	0.52min

4.7 Dwell time

The train's dwell time is the period when a train will stop at the station. Therefore, it is a sum of running time and all stations' durations that constitutes the overall travel time. Longer standing times induce headway variability and reduce the overall rail system performance by generating delays. The dwell time of AA the LRT currently ranges from 25 to 40 seconds. The reduction of the dwell time can often lead to reduced progress. The duration of time spent in the apartment shall be determined by several different factors, such as the size of the door on the train and the number of travellers waiting for a ride or step height from the platform to the floor of the car.

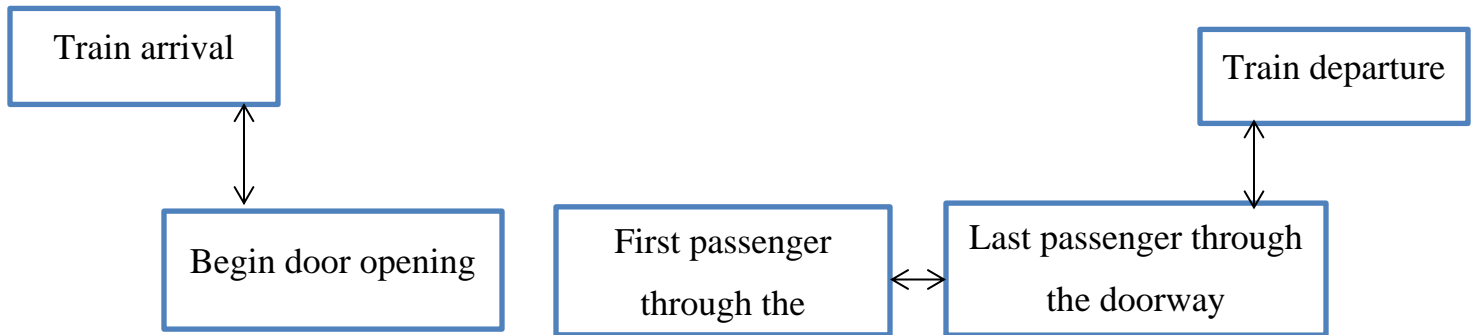


Table 4.3 Sub-processes of train dwell time[48].

Now that the primary components of the headway have been calculated in the aforementioned subtopics, we must determine the needed headway at various sampled stations and at various sampled speeds. Headways can be determined both in terms of distance and time.

Headway time= Travel time + Braking time + Release time+ Dwell time + Operating margin time (all values are in converted into minutes)

North South line

Headway₂₀= Travel time₂₀ + Braking time₂₀ + release time₂₀+ Dwell time₂₀+ Operating margin time₂₀

Table 4.1315 Headway of NS line at different speeds

Speed(km/hr)	Headway(min)
20	3
35	2.0621
45	1.785
50	1.713
60	1.55
70	1.463

East west line

Table 4.1416 Headway of EW line at different speeds

Speed(km/hr)	Headway(min)
20	3.1492
35	2.1026
45	1.8188
50	1.715
60	1.582
70	1.4845

Common line

Table 4.1517 Headway of common line at different speeds

Speed(km/hr)	Headway(min)
35	1.8367
45	1.6107
45	1.6107
55	1.5175

Three categories are used to group the aforementioned headway values. That is progress on the common line, progress on the other sections of the NS-line, and progress on the other sections of the EW line. Due to the following two factors, a common headway must be used on both the East-West and North-South lines. The first justification is that as both lines share a single line, trains from various lines should arrive at the same frequency in order to share this common line fairly. Trains traveling from various lines toward the common line must have a common headway in order to arrive at a constant frequency, but they also need to be appropriately timed.

4.8 Capacity

Capacity is a measure of the ability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific service plan.

Capacity is a matter of two things:

(i) Train capacity: The maximum number of passengers on the train.

(ii) Line capacity: The greatest number of trains that can be run across a line during peak hours, in a single direction, on a single track, is referred to as line capacity. In this thesis mainly focusing on line capacity

Line capacity(L_c) = $60/\text{Headway time} = 60/4 = 12$ trains per hour

Calculated line capacity: 12 trains/hour

Railway capacity is mainly affected by three factors

- Minimum technical headway: it is defined by the characteristics of the railway infrastructure and rolling stock in the early stages of design;
- Operational strategy: it depends on the service frequencies, station locations, demands and other practical issues;
- Standards and regulations: these differences between companies and countries[49]

Knowing the infrastructure and the schedule is required to assess the capacity consumption. Building up the infrastructure and producing the schedule are thus the initial steps in assessing the railway capacity. The railway network must be separated into line sections in order to assess the railway capacity using the UIC 406 approach. The timetable must be shortened for each line segment in order to obtain the shortest headway distance between trains. Utilizing an analytical approach, the UIC 406 capacity method can be used to calculate the capacity consumption as the total of the operation time, buffer time, maintenance time, and single track time supplements.

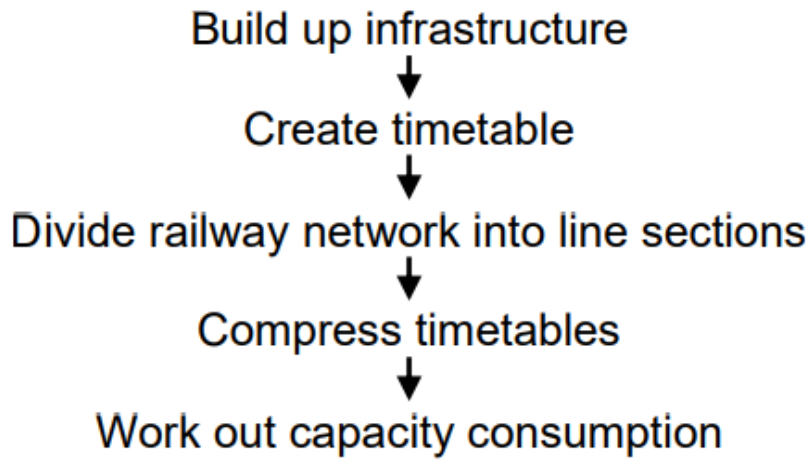


Table 4.4 General workflow of UIC406 method[50].

Need for capacity assessment of railway

- Increase in demand or number of passengers
- Increased demand for punctuality and safety

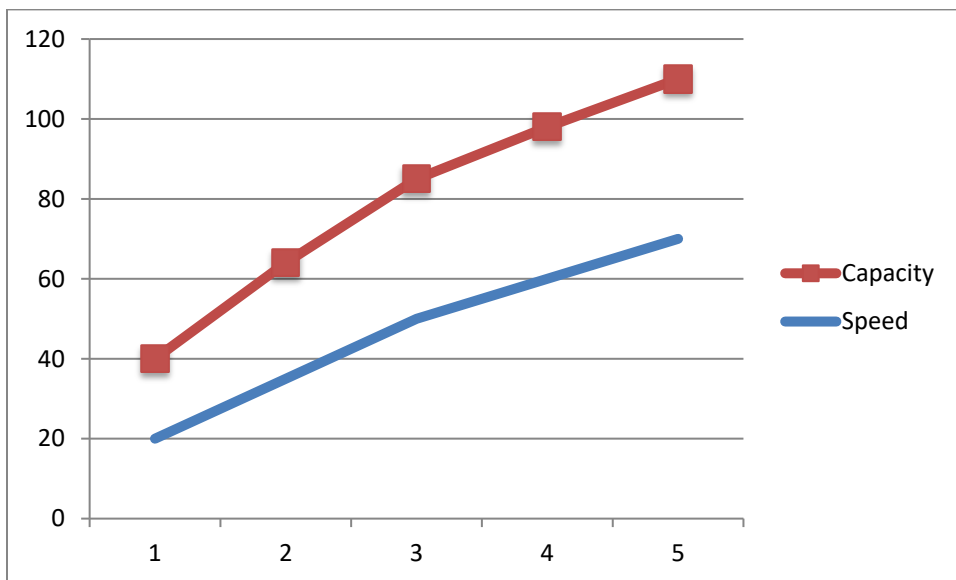


Figure 4.5 Relationships between Speed and Capacity

4.9 Synchronizing Train Departure/Arrival

In order to provide a more frequent service on the shared portion and to reduce any potential waiting times at the common line's entry, the departure timings of those trains from distinct track lines should be coordinated.

To compute the time table for the five trains we require the departure and arrival times of the trains at each station to the next.

Arrival time₁=departure time₁+ running time₁

Departure time₁=arrival time₁+ activity time (dwell time, passing time etc)

Assuming that the departure time of train A from station 1(menelik II square) is 0 then the departure times of train B, C, D and E will be the multiple of the headways before it as the headway of is 110 sec calculated in the north line

The times of each station's departure and arrival are calculated in the table below.

Table 4.1618 Arrival and departure times of trains in each station

Addis Ababa Light Rail North to South Line Timetable

	Train A		Train B		Train C		Train D		Train E	
	Arrival	Departure	Arrival	Departure	Arrival	Departure	Arrival	Departure	Arrival	Departure
Menelik II Square		0		110		220		330		440
Atikilt Tera	75.9	105.9	185.9	215.9	295.9	325.9	405.9	435.9	515.9	545.9
Gojam Berenda	181.8	211.8	291.8	321.8	401.8	431.8	511.8	541.8	621.8	651.8
Autobus Tera	287.7	327.7	397.7	427.7	507.7	537.7	617.7	647.7	727.7	757.7
Sebategna	403.6	443.6	503.6	533.6	613.6	643.6	723.6	753.6	833.6	863.6
Abnet	519.5	559.5	609.5	639.5	719.5	749.5	829.5	859.5	939.5	969.5
Darmar	635.4	816.68	715.4	745.4	825.4	855.4	935.4	965.4	1045.4	1075.4
St. Lideta	892.58	932.58	821.3	851.3	931.3	961.3	1041.3	1071.3	1151.3	1181.3
Tegbaret	1008.48	1048.48	927.2	957.2	1037.2	1067.2	1147.2	1177.2	1257.2	1287.2
Mexico	1124.38	1184.38	1033.1	1063.1	1143.1	1173.1	1253.1	1283.1	1363.1	1393.1
Leghar	1260.28	1300.28	1139	1169	1249	1279	1359	1389	1469	1499
Stadium	1376.18	1416.18	1244.9	1274.9	1354.9	1384.9	1464.9	1494.9	1574.9	1604.9
Meshwalekya	1492.08	1532.08	1350.8	1380.8	1460.8	1490.8	1570.8	1600.8	1680.8	1710.8
Riche	1607.98	1647.98	1456.7	1486.7	1566.7	1596.7	1676.7	1706.7	1786.7	1816.7
Temenja Yazh	1723.88	1763.88	1562.6	1592.6	1672.6	1702.6	1782.6	1812.6	1892.6	1922.6
Lancha	1839.78	1879.78	1668.5	1698.5	1778.5	1808.5	1888.5	1918.5	1998.5	2028.5
Nefas Silk 2	1955.68	1995.68	1774.4	1804.4	1884.4	1914.4	1994.4	2024.4	2104.4	2134.4
Nefas Silk 1	2071.58	2111.58	1880.3	1910.3	1990.3	2020.3	2100.3	2130.3	2210.3	2240.3
Adey Abeba	2187.48	2227.48	1986.2	2016.2	2096.2	2126.2	2206.2	2236.2	2316.2	2346.2
Saris	2303.38	2343.38	2092.1	2122.1	2202.1	2232.1	2312.1	2342.1	2422.1	2452.1
Abo Junction	2419.28	2459.28	2198	2228	2308	2338	2418	2448	2528	2558
Kality	2535.18	2575.18	2303.9	2333.9	2413.9	2443.9	2523.9	2553.9	2633.9	2663.9
Station 23	2651.08	2691.08	2409.8	2439.8	2519.8	2549.8	2629.8	2659.8	2739.8	2769.8

4.10 Comparison between the New Designed and Existing Headway

Currently, AALRT trains have an average speed of approximately 20 kmh with a stop time of 15 minutes in both E-W line and N-S line but according to the aforementioned information it is possible that this could fall to 4 minutes .This results indicate that, using a positive train railway control which has direct capacity implications, progress can be made.

The line capacity for a single line and direction is 4 trains per hour based on the current timetable's headway duration of 15 minutes. The line's capacity can be expanded to 12 trains per hour for a single direction while maintaining the same speed, reducing the headway to 4 minutes.

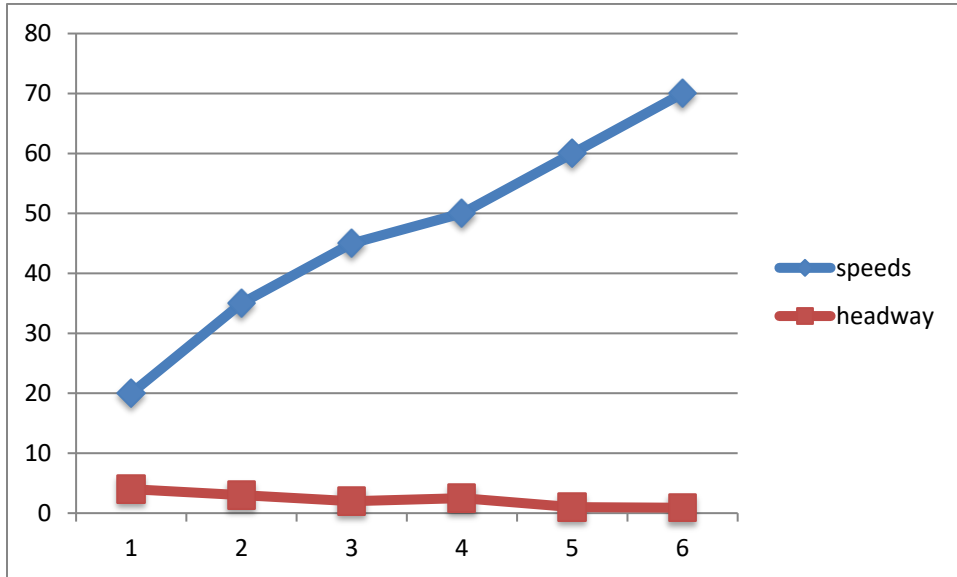


Figure 4.6 Relation between headway and approaching speeds

The values of the primary parameters are calculated, and then the calculated and existing parameters are compared. As a result, the results show that the primary parameters for designing the timetable depend on speed and that different speed can lead to different values for the parameters. Because of this, the majority of the computations in the previous sections were performed at a few predetermined rates. As a result, a choice can be made by contrasting two speeds (and their computed characteristics) on either side of the decision.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS

We can run with better headways without increasing the operational speed; for example, the Addis Ababa LRT currently uses 15 minutes of headway when the speed is averaging 20-70 km/h. The calculated results show that this significant headway can be reduced by up to 4 minutes without slowing down operation. As more trains with 4 minute headway are in operation, the ALRT's capacity will increase. To determine the best combination of those parameters to strike a balance between construction cost and minimal headway in order to maximize the economic and social benefits of the railway. Different combinations of those parameters will result in different construction costs and corresponding minimal headways.

In general, factors including headway dwell time, journey duration, speed, signaling system, braking distance, synchronization of trains, and other resources should be taken into account while designing the headway.

The mainline railway signaling systems may be modified in the future, however there are several obstacles to its development. Dynamic headway control faces two major technical challenges: communication channels and positioning systems.

Fortunately, there is no need for railway capacity beyond the capability of PTC right now. So, my research into modern communication systems should stay at the conceptual stage.

At the operational stage, given the existing infrastructure and rolling stock, trains at the optimum point may achieve maximum capacity, but the technical factors are difficult to change and become irrelevant. Instead, the key factor which has prevented railway lines from achieving their optimal use is an operating strategy. To meet demand for railway capacity, new signaling systems should be studied and implemented. By employing advanced radio transmission methods and PTC systems, an Optimal Headway system is proposed.

The conceptual design of signaling systems should not be limited to the options present in the field of railways in order to fulfill the future requirements in terms of railway capacity and dependability. In some cases, processes in the operation, such as lengthy departure procedures, or external variables, like the weather and rolling stock issues, can lower the capacity of a railway. This is because the capacity of a railway is not "only" dependent on the rolling stock, the infrastructure, and the timetable. Processes include things like staff schedules, departure processes, and the volume of passengers at the stations.

REFERENCES

- [1]. Y. Zhao and P. Ioannou, [1] T. Albrecht, K. Luddecke, and J. Zimmermann, "A precise and reliable train positioning system and its use for automation of train operation," in *2013 IEEE International Conference on Intelligent Rail Transportation Proceedings*, Beijing, China: IEEE, Aug. 2013, pp. 134–139. doi: 10.1109/ICIRT.2013.6696282

- [2]. W. H. K. Lam, C. Y. Cheung, and 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, Nov. 1998, Accessed: Jul. 15, 2023. [Online]. Available: <https://trid.trb.org/view/542081>
- [3]. D. Barney, D. Haley, and G. Nikandros, “Calculating Train Braking Distance”
- [4]. “Calculation and Optimization of Train Headway in CBTC System | Semantic Scholar.” (accessed Jul. 15, 2023)
- [5]. Y. Zhang, “Calculation Methods of Minimal Headway for High-Speed Railways,” Sep. 2015, pp. 203–213. doi: 10.1061/9780784479384.026
- [6]. V. Singh, “Communication-Based Train Control System”
- [7]. V. Singh, “Communication-Based Train Control System”
- [8]. “Communications-Based Train Control (CBTC)” | <https://railsystem.net/communications-based-train-control-cbtc/> (accessed Jul. 13, 2023)
- [9]. J. Xun, J. Yin, R. Liu, F. Liu, Y. Zhou, and T. Tang, “Cooperative control of high-speed trains for headway regulation: A self-triggered model predictive control based approach,” *Transportation Research Part C: Emerging Technologies*, vol. 102, pp. 106–120, May 2019, doi: 10.1016/j.trc.2019.02.023
- [10]. B. Ning, T. Tang, K. Qiu, C. Gao, and Q. Wang, “CTCS–Chinese Train Control System,” in *WIT Transactions on State of the Art in Science and Engineering*, B. Ning, Ed., 1st ed. WIT Press, 2010, pp. 1–7. doi: 10.2495/978-1-84564-494-9/01
- [11]. Syammirredzuan, *English: The system was equipped with Zone Controllers (ZC), track mounted tags and uses radio communication between trackside equipment on the train.* 2020. Accessed: Jul. 16, 2023. [Online]. Available: https://commons.wikimedia.org/wiki/File:CBTC_System_Architecture.png
- [12]. “ERTMS in brief,” *ERTMS*. <https://www.ertms.net/about-ertms/ertms-in-brief/> (accessed Jul. 13, 2023)

- [13]. “Fixed block vs moving block. | Download Scientific Diagram.” (accessed Jul. 13, 2023)
- [14]. “Grade (slope),” *Wikipedia*. May 25, 2023. Accessed: Jul. 15, 2023. [Online]. Available:
[https://en.wikipedia.org/w/index.php?title=Grade_\(slope\)&oldid=1156860902](https://en.wikipedia.org/w/index.php?title=Grade_(slope)&oldid=1156860902)
- [15]. “History of ERTMS.” https://transport.ec.europa.eu/transport-modes/rail/ertms/history-ertms_en (accessed Jul. 13, 2023)
- [16]. A. Diaz de Rivera, C. T. Dick, and L. E. Evans, “Improving Railway Operational Efficiency with Moving Blocks, Train Fleeting, and Alternative Single-Track Configurations,” *Transportation Research Record*, vol. 2674, no. 2, pp. 146–157, Feb. 2020, doi: 10.1177/0361198120905842
- [17]. Y. Ding and S. I. Chien, “Improving Transit Service Quality and Headway Regularity with Real-Time Control,” *Transportation Research Record*, vol. 1760, no. 1, pp. 161–170, Jan. 2001, doi: 10.3141/1760-21
- [18]. Y. Nie, J. Geng, and J. Ma, “Influence of Phase Separation upon Headway of Trains of Passenger-Dedicated Line,” pp. 1257–1262, Apr. 2012, doi: 10.1061/41184(419)208
- [19]. L. Zhao, “Optimization of headway, stops, and time points considering stochastic bus arrivals”
- [20]. “Optimization of Train Headway in Automatic Train Control System | Request PDF.” https://www.researchgate.net/publication/331416722_Optimization_of_Train_Headway_in_Automatic_Train_Control_System (accessed Jul. 15, 2023)
- [21]. “Optimization of Train Headway in Automatic Train Control System | Request PDF.”
https://www.researchgate.net/publication/331416722_Optimization_of_Train_Headway_in_Automatic_Train_Control_System (accessed Jul. 15, 2023)

[22]. W. Hao, L. Meng, and Y. Tan, “Optimizing Minimum Headway Time and Its Corresponding Train Timetable for a Line on a Sparse Railway Network,” *Symmetry*, vol.12, no. 8, Art. no. 8, Aug. 2020, doi:10.3390/sym12081223.

[23]. W. Hao, L. Meng, and Y. Tan, “Optimizing Minimum Headway Time and Its Corresponding Train Timetable for a Line on a Sparse Railway Network,” *Symmetry*, vol. 12, no. 8, Art. no. 8, Aug. 2020, doi: 10.3390/sym12081223

[24]. E. Goddard, “Overview of signaling and train control systems,” in *The 9th Institution of Engineering and Technology Professional Development Course on Electric Traction Systems*, Nov. 2006, pp. 336–350

[25]. “Positive Train Control,” *Southern California Association of Governments*, Oct. 28, 2020. <https://scag.ca.gov/post/positive-train-control> (accessed Jul. 13, 2023)

[26]. “Positive Train Control,” *Southern California Association of Governments*, Oct. 28, 2020. <https://scag.ca.gov/post/positive-train-control> (accessed Jul. 13, 2023)

[27]. “Positive Train Control (PTC) | FRA.” <https://railroads.dot.gov/research-development/program-areas/train-control/ptc/positive-train-control-ptc> (accessed Jul. 14, 2023)

[28]. Z. Zhang, X. Liu, and K. Holt, “Positive Train Control (PTC) for railway safety in the United States: Policy developments and critical issues,” *Utilities Policy*, vol. 51, pp. 33–40, Apr. 2018, doi: 10.1016/j.jup.2018.03.002

[29]. Y. Zhao and P. Ioannou, “Positive Train Control With Dynamic Headway Based on an Active Communication System,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 16, pp. 1–9, Dec. 2015, doi: 10.1109/TITS.2015.2435515

[30]. “Positive Train Control With Dynamic Headway Based on an Active Communication System | Request PDF.”

https://www.researchgate.net/publication/279278069_Positive_Train_Control_With_

Dynamic_Headway_Based_on_an_Active_Communication_System (accessed Jul. 13, 2023)

[31]. “PTC System Information | FRA.” <https://railroads.dot.gov/train-control/ptc/ptc-system-information> (accessed Jul. 14, 2023)

[32]. P. Wang, Y. Zhou, J. Chen, Y. Wang, and P. Wu, “Real-Time Train Scheduling and Control Based on Model Predictive Control,” in *2010 Second WRI Global Congress on Intelligent Systems*, Dec. 2010, pp. 47–50. doi: 10.1109/GCIS.2010.186

[33]. P. Sels, T. Dewilde, D. Cattrysse, and P. Vansteenwegen, “Reducing the passenger travel time in practice by the automated construction of a robust railway timetable,” *Transportation Research Part B: Methodological*, vol. 84, pp. 124–156, Feb. 2016, doi: 10.1016/j.trb.2015.12.007

[34]. Birhanu Reesom Bisrat, Danson Byegon, Kudzai Vushe, “REVIEW PAPER ON POSITIVE TRAIN CONTROL TECHNOLOGY,” vol. 8, pp. 2394–3696, Jun. 2021

[35]. “Robust Train Timetabling Problem: Mathematical Model and Branch and Bound Algorithm | IEEE Journals & Magazine | IEEE Xplore.”

<https://ieeexplore.ieee.org/document/6061961> (accessed Jul. 15, 2023)

[36]. Hu Weiwu, Zeng Wei, “Rules Governing Operation Organization.” Aug. 30, 2015

[37]. “Section 15 - Line of Sight,” no. 1, 2006

[38]. Y. Ding, Y. Bai, F. Liu, and B. Mao, “Simulation Algorithm for Energy-Efficient Train Control under Moving Block System,” in *2009 WRI World Congress on Computer Science and Information Engineering*, Mar. 2009, pp. 498–502. doi: 10.1109/CSIE.2009.323

[39]. M. B. Khan and X. Zhou, “Stochastic Optimization Model and Solution Algorithm for Robust Double-Track Train-Timetabling Problem,” *IEEE Transactions on Intelligent Transportation Systems*, vol. 11, no. 1, pp. 81–89, Mar. 2010, doi: 10.1109/TITS.2009.2030588

- [40]. R. Takagi, “Synchronisation control of trains on the railway track controlled by the moving block signalling system,” *IET Electrical Systems in Transportation*, vol. 2, no. 3, Sep. 2012, Accessed: Jul. 15, 2023. [Online]. Available: <https://trid.trb.org/view/1328655>
- [41]. Q. Zhang, X. Zhu, and L. Wang, “Track allocation optimization in high-speed railway stations from infrastructure management and service perspectives,” *Measurement and Control*, vol. 51, no. 7–8, pp. 243–259, Sep. 2018, doi: 10.1177/0020294018785187
- [42]. 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
- [43]. East-West Line (Phase1) Project of Addis Ababa, Ethiopia “*Technical Specification of Vehicles*” China Railway Group Limited, July 2013, pp.1-14
- [44]. Wu, L., Gao, J. Q., Mu, J. C. (2007). “Tracing Headway Control Model and Calculation of Passenger Dedicated Railway.” *Computer Applications*,27(11), 2643-2645
- [45]. Su, S. H., Tian, C. H., Chen, Z. Y. (2008). “Calculation and Analysis on Throughput Capacity of Passenger Dedicated Railway.” *China Railway Science*, 29(5):119-124
- [46]. Li, L., Peng, Q. Y., Li, X. (2008). “Analysis on Influence Factors of Minimum Train Time Interval based on CTCS Level 2.” *Railway Transport and Economy*, 31(4):90-93
- [47]. P. Barger, W. Schön, and M. Bouali, “A study of railway ERTMS safety with Colored Petri Nets,” *Proc. Rel. Risk Safety Theory Appl.*, vol. 2, Sep. 2009, doi: 10.1201/9780203859759.ch179
- [48]. P. Mahesh, M. Ambekar, S. P. Pandey, K. Gangadhare, and S. Hatawte, “TRAIN TRACKING SYSTEM BASED on GPS & GSM,” *International Journal of*

Engineering Research & Technology, vol. 2, no. 4, Jul. 2018, doi:
10.17577/IJERTCONV2IS04070

[49]. H. Duan, “MCloser running - railway capacity analysis and timetable improvement”.

Appendix

Some significant details about the AA-LRT are provided in the appendix.

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+4 83.00	X-996862.2995 Y-469474.0755	52	5		

Positive Train Control with Headway Optimization on an Active Communication System

2	EW2 2	YDK5+5 35.00	X-996839.1058 Y-469520.6163	769	5.00	2357.930	Ground station
					(side)		
3	EW2 1	YDK6+3 04.00	X-996911.0019 Y-470225.6892	732	4.0	2344.895	Ground station
					(side)		
4	EW2 0	YDK7+0 36.00	X-996835.8709 Y-470953.7219	735	4.00	2368.193	Elevated common rail station
					(side)		
5	EW1 9	YDK7+7 71.00	X-996741.9782 Y-471682.7001	688	4.00	2354.928	Elevated common rail station
					(side)		
6	EW1 8	YDK8+4 59.00	X-996801.1117 Y-472358.4619	560	4.00	2366.198	Elevated common rail station
					(side)		
7	EW1 7	YDK9+0 19.00	X-996887.5591 Y-472906.9799	445	4.00	2359.776	Elevated common rail station
					(side)		
8	EW1 6	YDK9+4 64.00	X-996902.5663 Y-473348.1557	640	4.00	2350.067	Elevated common rail station
					(side)		
9	EW1 5	YDK10+ 104.00	X-996795.6393 Y-473978.9619	593	4.00	2350.033	Elevated station
					(side)		
1	EW1	YDK10+	X-996726.4625		4.00	2333.711	

Positive Train Control with Headway Optimization on an Active Communication System

0	4	697.00	Y-474567.5919	675	(side)		Ground station
1	EW1	YDK11+	X-996789.6514	963	8.45	2342.382	Semi-underground station
1	3	372.00	Y-475223.6982		(island)		
1	EW1	YDK12+	X-997201.6457	758	4.00	2362.002	Ground station
2	2	335.00	Y-476091.8807		(side)		
1	EW1	YDK13+	X-997371.7463	746	4.00	2351.348	Ground station
3	1	093.00	Y-476830.3757		(side)		
1	EW1	YDK13+	X-997557.3654	776	4.00	2365.876	Ground station
4	0	839.00	Y-477552.2791		(side)		
1	EW9	YDK14+	X-997745.0504	829	8.95	2371.893	Semi-underground station
5		615.00	Y-478303.7177		(island)		
1	EW8	YDK15+	X-997812.0607	1083.6	4.00	2378.329	Ground station
6		444.00	Y-479122.4389		(side)		
1	EW7	YDK16+	X-997685.5967	970	4.0	2371.315	Ground station
7		530.00	Y-480196.9975		(side)		
1	EW6	YDK17+	X-997879.8411	724.82	4.00	2380.134	Ground station
8		500.00	Y-481125.6722		(side)		
1	EW5	YDK18+	X-997975.1137	860	4.00	2387.226	Ground
9		225.00	Y-481831.3394				

Positive Train Control with Headway Optimization on an Active Communication System

					(side)		station
20	EW4	YDK19+085.00	X-997939.3444 Y-482690.5893	863	4.00	2381.913	Ground station
					(side)		
21	EW3	YDK19+948.00	X-997893.5336 Y-483552.3376	1092	4.00	2386.685	Ground station
					(side)		
22	EW2	YDK21+040.00	X-997849.2514 Y-484643.1008	1260	4.00	2401.463	Ground station
					(side)		
23	EW1	YDK22+300.00	X-997912.7097 Y-485901.1314	182	4.00	2403.268	Ground station
					(side)		
24	Terminal	YDK22+482.00	X-997923.4631 Y-486082.8134		4		

Interval	Track distinction	Grade (‰)	Length of grade section (m)
EW22~EW21	Right	-55	142
	Left	-55	142

Positive Train Control with Headway Optimization on an Active Communication System

Interval	Track distinction	Grade (%)	Length of grade section (m)
EW21~EW20	Right	55	435
	Left	54.981	435.149
EW20~EW19	Right	-55	280
	Left	-55	280
EW20~EW19	Right	46	165
	Left	46	165
EW17~EW16	Right	-46	155
	Left	-46	155
EW15~EW14	Right	-49	356
	Left	-49	356
EW13~EW12	Right	44.5	195
	Left	44.5	195
EW12~EW11		-53.5	315

Positive Train Control with Headway Optimization on an Active Communication System

Interval	Track distinction	Grade (%)	Length of grade section (m)
	Right		
	Left	-53.5	315
EW9~EW8	Right	43.5	205
	Left	43.5	205
EW7~EW6	Right	53.5	220
	Left	53.595	219.608
EW4~EW3	Right	40	145
	Left	40	145
EW2~EW1	Right	-50	225
	Left	-50	225
EW2~EW1	Right	50	90
	Left	50	90

Using below formula can calculate the braking distances of the sampled stations

$$S = \frac{-U^2}{2(a - g * \tan\alpha)}, \text{ for } a < 0 \quad (3)$$

East West Line

✚ For EW15-EW14 here $u = 60\text{km/h} = 16.6667\text{m/s}$, $\alpha = -49/1000 = -0.049$,

$$S = (-U^2)/2(a - g * \tan\alpha) = - (16.6667)^2 / [2((-1 - 9.8 \tan(-0.049)))] \\ = 140.63\text{m}$$

✚ For EW22-EW21 such that $u=50\text{km/hr} = 13.8889\text{m/s}$, $\alpha=-46/1000=-0.046$

$$S = (-U^2)/2(a - g * \tan\alpha) \\ = - (13.8889)^2 / [2((-1 - 9.8 \tan(-0.055)))] = 97.37\text{m}$$

✚ For EW18-EW17, values are $U=45\text{km/hr} = 12.5\text{m/s}$, $\alpha=45/1000=0.045$

$$S = (-U^2)/2(a - g * \tan\alpha) = S = (12.5)^2 / 2(1 - 9.8 * \tan 0.045) = 78.73\text{m}$$

✚ For EW13-EW12, values are $u=35\text{km/hr}=9.72222\text{m/s}$, $\alpha=35/1000=0.035$

$$S = (-U^2)/2(a - g * \tan\alpha) = S = (9.72222)^2 / 2(1 - 9.8 * \tan 0.0445) \\ = 47.62\text{m}$$

✚ For station EW2-EW1 values are $u=70\text{km/hr}=19.4444\text{m/s}$, $\alpha=-50/1000=-0.05$

$$S = (-U^2)/2(a - g * \tan\alpha) = S = (19.4444)^2 / 2(1 - 9.8 * \tan(-0.05)) \\ = 187.43\text{m}$$

North South Line

✚ For NS15-NS14 here $u = 20\text{km/h} = 5.55556\text{m/s}$, $\alpha = -49/1000 = -0.049$,

$$S = (-U^2)/2(a - g * \tan\alpha) = - (5.55556)^2 / [2(-1 - 9.8 \tan(-0.049)))] \\ = 15.56\text{m}$$

✚ For NS22-NS21 such that $u=35\text{km/hr} = 9.72222\text{m/s}$, $\alpha=-46/1000=-0.048886$

$$S = (-U^2)/2(a - g * \tan\alpha) \\ = - (9.72222)^2 / [2(-1 - 9.8 \tan(-0.055)))] = 47.71\text{m}$$

✚ For NS14-NS13, values are $U=60\text{km/hr}=16.6667\text{m/s}$, $\alpha=-55/1000=-0.055$

$$S = (-U^2)/2(a - g * \tan\alpha) = S = (16.6667)^2/2(1 - 9.8 * \tan(-0.055)) \\ = 137.59\text{m}$$

✚ For NS10-NS9, values are $u=45\text{km/hr}=12.5\text{m/s}$, $\alpha=-47/1000=-0.047$

$$S = (-U^2)/2(a - g * \tan\alpha) = S = (12.5)^2/2(1 - 9.8 * \tan(-0.047)) \\ = 77.5\text{m}$$

✚ For station NS12-NS11 values are $u=55\text{km/hr}=15.2778\text{m/s}$, $\alpha=42/1000=0.042$

$$S = (-U^2)/2(a - g * \tan\alpha) = S = (15.2778)^2/2(1 - 9.8 * \tan(-0.042)) \\ = 115.87\text{m}$$

For the common line (NS17 - NS16, NS18 - NS17, NS19 - NS18, NS20- NS19)

For NS17- NS16 here $u = 55\text{km/h} = 15.278\text{m/s}$, $\alpha = -46/1000 = -0.046$

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

For NS18- NS17 here $u = 45\text{km/h} = 12.5\text{m/s}$, $\alpha = 20.73/1000 = 0.0273$

$$S = (-U^2) / (2 (a - g (\tan \alpha))) = - (12.5)^2 / [2(-1 - 9.8 \tan (0.0273))] \\ = 77.761\text{m}$$

For NS19- NS18 here $u = 45\text{km/h} = 12.5\text{m/s}$, $\alpha = 46/1000 = 0.046$

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

For NS20- NS19 here $u = 31.86 \text{ km/h} = 8.85\text{m/s}$, $\alpha = -55/1000 = -0.055$

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

Braking time calculations

$$B_{45} = S_b/V = 77.5\text{m}/12.5\text{ms} = 6.2\text{sec}$$

NS line

$$B_{55} =$$

$$B_{20} = S_b/V = 15.56\text{m}/5.5556\text{ms} = 2.8\text{sec}$$

$$S_b/V = 115.87\text{m}/15.2778\text{ms} = 7.58\text{sec}$$

$$B_{35} = S_b/V = 47.71\text{m}/9.7222\text{ms} = 4.91\text{sec}$$

Positive Train Control with Headway Optimization on an Active Communication System

$$B_{60} = R_{55} = 59 / 15.2778 = 3.86 \text{sec}$$

$$S_b/V = 137.59 \text{m} / 16.6667 \text{ms} = 8.26 \text{sec} \quad R_{60} = 59 / 16.6667 = 3.54 \text{sec}$$

$$B_{70} = S_b/V = 175.53 \text{m} / 19.444 \text{ms} = 9.03 \text{sec} \quad R_{70} = 59 / 19.444 = 3.03 \text{sec}$$

EW line

$$B_{35} = S_b/V = 47.62 \text{m} / 9.7222 \text{ms} = 4.89 \text{sec}$$

$$B_{45} = S_b/V = 78.73 \text{m} / 12.5 \text{ms} = 6.29 \text{sec}$$

$$B_{50} =$$

$$S_b/V = 97.37 \text{m} / 13.8889 \text{ms} = 7.012 \text{sec}$$

$$B_{60} =$$

$$S_b/V = 140.63 \text{m} / 16.6667 \text{ms} = 8.44 \text{sec}$$

$$B_{70} = S_b/V = 187.43 \text{m} / 19.444 \text{ms} = 9.64 \text{sec}$$

Common line

$$B_{31.86} = S_b/V = 39.533 \text{m} / 8.85 \text{ms} = 4.47 \text{sec}$$

$$B_{45} = S_b/V = 77.761 \text{m} / 12.5 \text{ms} = 6.22 \text{sec}$$

$$B_{45} = S_b/V = 77.515 \text{m} / 12.5 \text{ms} = 6.20 \text{sec}$$

$$B_{55} =$$

$$S_b/V = 117.63 \text{m} / 15.2778 \text{ms} = 7.69 \text{sec}$$

Release time calculations

$$R_{20} = 59 / 5.5556 = 10.62 \text{sec}$$

$$R_{35} = 59 / 9.7222 = 6.07 \text{sec}$$

$$R_{45} = 59 / 12.6 = 4.68 \text{sec}$$

Travel time for the average distance between the stations:

$$T_{20} = S_{20} / V_{20} = 738 \text{m} / 20 \text{kmh} = 738 \text{m} / 5.5556 \text{ms} = 132.83 \text{sec} = 2.214 \text{min}$$

$$T_{35} = S_{35} / V_{35} = 738 \text{m} / 35 \text{kmh} = 738 \text{m} / 9.7222 \text{ms} = 75.9 \text{sec} = 1.26 \text{min}$$

$$T_{45} = S_{45} / V_{45} = 738 \text{m} / 45 \text{kmh} = 738 \text{m} / 12.5 \text{ms} = 59.04 \text{sec} = 0.984 \text{min}$$

$$T_{50} = S_{50} / V_{50} = 738 \text{m} / 50 \text{kmh} = 738 \text{m} / 13.89 \text{ms} = 53.13 \text{sec} = 0.899 \text{min}$$

$$T_{60} = S_{60} / V_{60} = 738 \text{m} / 60 \text{kmh} = 738 \text{m} / 16.667 \text{ms} = 44.3 \text{sec} = 0.738 \text{min}$$

$$T_{70}=S_{70}/V_{70}=738\text{m}/70\text{kmh}=738\text{m}/19.44$$

$$ms=37.963\text{sec}=0.633\text{min}$$

EW line

$$T_{20}=S_{20}/V_{20}=762\text{m}/20\text{kmh}=762\text{m}/5.555$$

$$6ms=137.158\text{sec}=2.29\text{min}$$

$$T_{35}=S_{35}/V_{35}=762\text{m}/35\text{kmh}=762\text{m}/9.722$$

$$2ms=78.377\text{sec}=1.3\text{min}$$

$$T_{45}=S_{45}/v_{45}=762\text{m}/45\text{kmh}=762\text{m}/12.5$$

$$ms=60.96\text{sec}=1.016\text{min}$$

$$T_{50}=S_{50}/V_{50}=762\text{m}/50\text{kmh}=762\text{m}/13.89$$

$$ms=54.859\text{sec}=0.914\text{min}$$

$$T_{60}=S_{60}/V_{60}=762\text{m}/60\text{kmh}=762\text{m}/16.66$$

$$7ms=45.719\text{sec}=0.762\text{min}$$

$$T_{70}=S_{70}/V_{70}=762\text{m}/70\text{kmh}=762\text{m}/19.44$$

$$ms=39.197\text{sec}=0.653\text{min}$$

North South line

Headway₂₀= Travel time₂₀ + Braking time₂₀ + release time₂₀+ Dwell time₂₀+
Operating margin time₂₀

$$\text{Headway}_{20}=2.214\text{min}+0.047+0.177+0.5+0.12=3\text{minutes}$$

$$\text{Headway}_{35}=1.26+0.081+0.1011+0.5+0.12=2.0621\text{minutes}$$

$$\text{Headway}_{45}=0.984+0.103+0.078+0.5+0.12=1.785\text{minutes}$$

$$\text{Headway}_{50}=0.899+0.13+0.064+0.5+0.12=1.713\text{minutes}$$

Common line

$$T_{20}=S_{20}/V_{20}=607\text{m}/20\text{kmh}=607\text{m}/5.555$$

$$6ms=109.259\text{sec}=1.82\text{min}$$

$$T_{35}=S_{35}/V_{35}=607\text{m}/35\text{kmh}=607\text{m}/9.722$$

$$2ms=62.4344\text{sec}=1.04\text{min}$$

$$T_{45}=S_{45}/v_{45}=607\text{m}/45\text{kmh}=607\text{m}/12.5$$

$$ms=48.56\text{sec}=0.809\text{min}$$

$$T_{60}=S_{60}/V_{60}=607\text{m}/60\text{kmh}=607\text{m}/16.66$$

$$7ms=36.419\text{sec}=0.606\text{min}$$

$$T_{70}=S_{70}/V_{70}=607\text{m}/70\text{kmh}=607\text{m}/19.44$$

$$ms=31.224\text{sec}=0.52\text{min}$$

$$\text{Headway}_{60}=0.738+0.14+0.059+0.5+0.12=1.55\text{minutes}$$

$$\text{Headway}_{70}=0.633+0.16+0.0505+0.5+0.12=1.463\text{ minutes}$$

East west line

$$\text{Headway}_{20}=2.29+0.0622+0.177+0.5+0.12=3.1492\text{minutes}$$

$$\text{Headway}_{35}=1.3+0.0185+0.1011+0.5+0.12=2.1026\text{minutes}$$

$$\text{Headway}_{45}=1.016+0.1048+0.078+0.5+0.12=1.8188\text{minutes}$$

$$\text{Headway}_{50}=0.914+0.117+0.064+0.5+0.12=1.715\text{minutes}$$

$$\text{Headway}_{60}=0.762+0.141+0.059+0.5+0.12=1.582\text{minutes}$$

$$\text{Headway}_{70}=0.653+0.161+0.0505+0.5+0.12=1.4845\text{minutes}$$

Common line

$$\text{Headway}_{35}=1.04+0.0754+0.1013+0.5+0.12=1.8367\text{minutes}$$

$$\text{Headway}_{45}=0.809+0.1037+0.078+0.5+0.12=1.6107\text{minutes}$$

$$\text{Headway}_{45}=0.809+0.1037+0.078+0.5+0.12=1.6107\text{ minutes}$$

$$\text{Headway}_{55}=0.705+0.1282+0.0643+0.5+0.12=1.5175\text{minutes}$$