



Addis Ababa University

Addis Ababa Institute of Technology (AAiT)

School of Electrical and Computer Engineering

**Addis Ababa Light Rail Transit Signaling
System Design Analysis**

By

Tebebu Terefe

A thesis submitted to the School of Graduate Studies of Addis Ababa University in
partial fulfillment of the requirement for the Degree of Master of Science in
Electrical Engineering (Railway)

Advisor

Dr. Yalemzewd Negash

August 2014

Addis Ababa, Ethiopia

Addis Ababa University
Addis Ababa Institute of Technology (AAIT)
School of Electrical and Computer Engineering

Addis Ababa Light Rail Transit Signaling System Design Analysis

By

Tebebu Terefe

Electrical and Computer Engineering Department

Approval by Board Examiners

_____	_____	_____
Chairman, Department Graduate Committee	Signature	Date
<u>Dr. Yalemzewd Negash</u>	_____	_____
Advisor	Signature	Date
_____	_____	_____
Internal Examiner	Signature	Date
_____	_____	_____
External Examiner	Signature	Date

Table of Contents

List of figures.....	iii
List of tables	iv
Acronyms.....	iv
Abstract.....	vi
Chapter One.....	1
1 Introduction	1
1.1 Motivation and Background	1
1.2 Literature review	3
1.3 Problem statement.....	4
1.4 Objective	8
1.4.1 General Objective	8
1.4.2 Specific Objective.....	8
1.5 Organization of the Thesis	9
1.6 Methodology used in this thesis.....	10
Chapter Two	11
2 New design of AA LRT signaling system	11
2.1 Design parameters	11
2.2 Level 0 CTCS	12
2.3 LRT System Requirements	12
2.3.1 System Design	12
2.3.2 System Safety Principles	13
2.3.3 Braking Distance	14
2.3.4 Speed Restrictions	16
2.3.5 Automatic Fixed Block Signaling	17
2.3.6 Fixed block throughput for three aspect signaling system	19
2.3.7 Station Headway.....	26
2.4 Equipment Requirements.....	29
2.4.1 Numbering Schemes.....	29
2.4.2 Wayside Signals	29
2.4.3 Track Circuits	30
2.4.4 Axle Counters	33

2.4.5	Central Traffic Control System	33
2.5	Provision of equipment	40
Chapter Three		42
3	Comparison of Existing and new signaling system	42
3.1	Safety	42
3.2	Operational efficiency.....	43
3.3	Cost	43
3.4	Energy consumption	44
3.5	Customers satisfaction	44
Chapter Four		45
4.	Results and discussions	45
4.1	Braking distance of EW and NS line to the stations.....	45
4.2	Speed Restrictions.....	47
4.3	Headway calculation.....	49
4.4	Speed Profile and Average operating Speed.....	50
Chapter Five		53
5.	Conclusions and Recommendation	53
5.1	Conclusions.....	53
5.2	Recommendation	54
Bibliography		55
Appendix A: Braking Distance Calculations.....		57
Appendix B: provisions of equipment.....		63
Appendix C: Speed profile of EW line.....		67

List of figures

Figure 1.1: NS and EW line of Addis Ababa LRT system.....	5
Figure1.2 Vertical curve between EW4 and EW5	7
Figure 2.1 A 3-Aspect Fixed Block layout.....	18
Figure2.2 Distance-time plot of two consecutive trains (acceleration and braking curves omitted for clarity).....	23
Figure 2.3 Speed profile and wayside signals	40
Figure 2.4 Wayside equipment between stations EW3 and EW2	41
Figure 4.1 Speed profile of the track section between EW22 and EW21	50

List of tables

Table 1.1 Track lengths of the line constructed on overhead, underground and on the ground.	5
Table 1.2 Horizontal curves existing on main line constructed on the ground	6
Table 3.1 Comparison between the existing and new system	42
Table 4.1 Breaking distance to the stations of EW line	46
Table 4.2 Breaking distance to the stations of NS line	47
Table 4.3 Speed limits on curves of EW line	48
Table 4.4 Speed limits on curves of NS line	49
Table 4.5 Headway time for different speed operations	50
Table 4.6 The time taken for the train from Station EW22 to EW21	51
Table 4.7 Time taken for the train to travel between stations	51

Acronyms

AFBS: Automatic Fixed Blocking System

AFO:	Audio Frequency Overlay
AIM:	Advanced Information Management
ATP:	Automatic Train Protection
ATS:	Automatic Train Stop
CBI:	Communication Based Interlocking
CTCS:	China Train Control System
CTC:	Central Traffic Control
EMI:	Electro Magnetic Interference
ERTMS:	European Rail Traffic Management System
ETCS:	European Train Control System
ETS:	Edmonton Transit System
EW:	East–West line
FCU:	Field Code Unit
ID:	Identification
LAN:	Local Area Network
LRT:	Light Rail Transit
NS:	North–South line
RAMS:	Reliability, Availability, Maintainability and Safety
SIL:	Safety Integrity Level
SOP:	Safe Operating Procedure
STM:	Specific Transmission Module
TCP:	Transmission Control Protocol
UPS:	Uninterruptable power supply
VLC:	Vital Logic Controller
VMS:	Voice Management System
WSC:	Wayside Cabinets

Abstract

The Signal System, which includes the functions of signal protection, grade crossing protection, and traffic signal coordination, shall be designed to allow light rail transit vehicles to meet the required line capacity, while providing a safe and operationally flexible system. Light rail shall operate in dedicated right-of-way or share the street with existing traffic. The dedicated portions of right-of-way shall use conventional fixed color light signals for train separation and safe braking distance.

In view of that, in this thesis work the existing Addis Ababa LRT signaling system is analyzed. Strong sides and limitation of the existing design are discussed. And it is found that the signaling design on the line constructed ground has limitations according to safety, operational efficiency and other factors which are discussed well. Afterwards different design approaches will be presented and CTC level 0 is chosen according to parameters stated. Therefore, on this section the design will be made to implement Automatic Block Signaling, wayside signals and cab signaling systems.

Then braking distance of each stations are calculated so as the wayside signals are placed on safe locations. In order to calculate the operational efficiency the headway time between trains calculated. The speed limit of all necessary curves, switches and turnout are calculated and the average speed of the system is obtained.

Finally the new design versus the existing design is compared based on safety, operational efficiency, cost, energy consumption and passenger satisfaction issues. And it is found that the new design improve headway time by 63.84% and improves the average speed by 63.97% that leads the system with new design is more efficient than the existing design.

Keywords: CTC, AFBS, Breaking distances, Headway time

CHAPTER ONE

1 Introduction

1.1 Motivation and Background

Any rail transportation infrastructure, whether metros or mainline railways, represents a tremendous capital investment in terms of the right-of-way and stations, with significant on-going life-cycle costs to maintain the infrastructure in a state-of good repair. The actual safe movement of passengers and freight on this infrastructure is however only possible through the implementation of signaling and train control systems. Indeed, it is the signaling or train control systems that enable the return on the infrastructure investment to be realized. While signaling or train control systems are the enabler of rail/transit operations, they can also impose a constraint on operations for example by constraining the achievable line capacity or by limiting the flexibility of train movements while, in addition, incurring substantial ongoing maintenance costs. The goal of future signaling or train control systems therefore can be stated as to maximize (optimize) the utilization of the rail transportation infrastructure and to remove the signaling system as a constraint on rail system operations, while still providing for the high level of safety of train movements expected by the passengers. This would be achieved by:

- ✓ maximizing line capacity (limited only by the infrastructure and rolling stock performance),
- ✓ providing for high system availability (with degraded modes of operation in the event of equipment failure), and
- ✓ Permitting flexible train movements i.e. any train movement that is supported by the infrastructure should be safely permitted by the signaling or train control systems - all with a system design that minimizes life cycle costs.

Many rail transportation authorities have demonstrated the business case for re-signaling with a modern signaling system on the basis that the only other alternative would be to construct additional rail lines to accommodate the required capacity, which would be orders-of magnitude more expensive.

So, looking to the future, we can expect the priority for signal and train control engineers to be increasingly focused on optimizing the movement of passengers and freight, by maximizing the utilization of the available rail infrastructure and by enhancing rail/transit operations, in addition to ensuring the safety of train movements.

The key elements of any signaling and train control system will continue to be:

- a) A method to safely and reliably locate the position of every train operating within the network within an accuracy and precision to meet both the safety and operational requirements.
- b) A method to safely and reliably communicate status and command information between central, wayside and train-borne equipment where the data communications infrastructure has sufficient bandwidth and exhibits sufficiently low latency to support both the safety and operational requirements with a protocol structure that supports timely and secure delivery of train control messages.
- c) A method to establish limits of movement authority for every train operating in the network and a method to enforce compliance with these authorities.
- d) A method to manage and regulate train movements utilizing optimization algorithms and decision support systems to ensure stability of network operations even in cases of operations at the capacity limit.
- e) An ability to integrate seamlessly with other operating elements of a metro or railway system to include traction power systems, tunnel and station ventilation systems, passenger information systems, etc. in a manner that exploits the operation and safety capabilities of the signaling and train control system, such as:
 - Real-time availability of precise location, speed, and operational status of each train.
 - Ability to communicate train health status and other system alarms to a central control location.
 - Real-time ability to restrict train movements in response to detected hazardous or other conditions.
 - Inherent bidirectional capability and ability to reroute and reverse train movements either automatically or in response to user inputs.
 - Ability to predict train arrival times at downstream stations for schedule regulation and other purposes.
 - Ability to coordinate multiple train movements for junction management and/or energy optimization purposes [5].

1.2 Literature review

The preliminary design of LRT signaling system [1] is designed by Chinese Corporate, China Railway Group Limited. This document is prepared to determine the main design principle, design scheme, function, composition, and other issues of the signaling system so as to allow the detailed design to proceed and complete the technical document and engineering document in the subsequent stages.

This thesis work analyzes the strong and weak side of this document, and will give the solutions for limitations.

ETCS (European Train Control System) [15] is a subsystem of ERTMS (the European Rail Traffic Management System). Sometimes, it is described as ERTMS/ETCS. ERTMS includes ETCS (Euro-cab), GSM-R (Euro-radio), Euro-balise, Euro-interlocking and so on.

The background of ETCS is the requirements of the European railway network development. With development of European high speed, railway network, apart from the different languages, there exist the strong barrier to cross-European borders since there are at least 15 different ATP systems in operation in Europe. Moreover, the ATP systems are incompatible and produced by their own suppliers. In order to make the systems be compatible and break the monopolies, the idea of ETCS was put forward. Supported by the European Union, the European researchers and the six main European railway-signaling suppliers called as UNISIG began to work for ETCS ten years ago.

The applications of ETCS are divided into several levels. They are Level 0, level STM, level 1, level 2 and level 3. European Train Control System is the document in which Chinese Train Control System is ultimately developed [12]. Through this thesis work for the sake of comparison between different signaling levels it is widely used.

Like Europe, Chinese Railway is facing to remove the incompatible obstacle of the different signaling systems on the network. The European Railway needs ETCS, and the Chinese Railway needs CTCS [12]. It is needed that signaling systems for high speed lines and conventional lines, passenger lines and freight lines are unified as standardization, i.e. CTCS.

The purpose of CTCS is to define the signaling systems for Chinese Railways. CTCS will become the standard of the signaling systems in Chinese Railways. The existing signaling systems will be interoperable with the new signaling systems. In the future, all signaling

systems, imported systems or home-made systems, wayside systems or onboard systems must be in line with the CTCS standardization. Apart from interoperability, the interface standard between the signaling systems, migration from existing signaling to CTCS, data transmission format between the subsystems, safety and reliability, capacity increase, easy maintenance, lower investment and open market etc. are considered during CTCS working.

Based on the present situation of signaling system on Chinese Railway Network, CTCS will be divided into the several levels, referring to ETCS. CTCS is planned to be divided into the following five levels. Since, the contractor and designer of AA LRT system is Chinese companies, they have used their own Train Control System. So that, for the reason of compatibility with the existing system this thesis work prefer to use Chinese Train Control System and it is shortly explained as follows [12].

Edmonton LRT signaling design guidelines [3] provides the guidelines and general requirements that are needed by the signals consultant for the design of the extensions to Edmonton's LRT signal system and its related components. These guidelines are supplemented by the engineering standards contained in the ETS Engineering Standards Manual for LRT Signals. This thesis work is mainly adopted from this document because of parameteric similarities between Edmonton LRT system and AA LRT system.

Edmonton LRT signal system provides all the necessary failsafe protection measures to ensure safe train operation as described in the following subsections. It consists of one double tracked line approximately 13.1km in length. The next phase to be implemented is a 2.3 km south extension.

1.3 Problem statement

Railway signaling techniques shall be applied at various LRT locations to enhance safety in the movement of trains and to improve the overall efficiency of train operations. These functions include the protection and control of track switches; the protection for following trains operating with the normal current of traffic; and highway grade crossing warning. The need for signaling, and the type of signalization provided, shall be determined by the specific requirements of each line segment. Designer shall review past signal systems designs in order to understand and use past design principles in order to maintain commonality in designs.

Addis Ababa light rail signaling Preliminary Design Chapter XIV - Signaling System, which is designed by CHINA RAILWAY GROUP LIMITED, states the signaling for the line section constructed on the ground as “For the line section constructed on the ground, manual driving by viewing shall be adopted. The driver shall drive the train manually through control of the running speed and the safety headway with the front train. The driver shall ensure the operation safety of the train through this driving mode [1]”

The length and the stations covered by the line section constructed on the ground are summarized as follows:



Figure 1.1: NS and EW line of Addis Ababa LRT system

	Overhead (2.662km common line)				Underground				On the ground				Total
	N-S	E-W	Total	Percent	N-S	E-W	Total	Percent	N-S	E-W	Total	Percent	
Construction length(km)	5.363	3.804	9.167	27.21%	2.390	-----	2.390	7.09%	8.936	13.194	22.13	69.98%	31.621
Number of stations	8	1	9	23.08%	1	2	3	7.69%	13	14	27	69.23%	39

Table 1.1 Track lengths of the line constructed on overhead, underground and on the ground [1].

The above table shows that, most of the track line constructed on ground, which 22.13km out of the total 31.621km length. That covers 69.98% of the total construction. In addition to that out of the total 39 stations, 27 of them are found on the part of the track line constructed on ground. Even though most of the track line constructed on the ground, it will operated manually without signaling system except the turnout and level crossing areas.

Is it safe and efficient to drive the train manually in Addis Ababa?

1. As a technology provides new and efficient signaling approaches, now a days most of the railway services uses modern signaling system, since those systems are mainly improves safety and operational efficiency.
2. The topology of Addis Ababa is not suitable for manual driving by viewing because of many vertical and horizontal curves exist which can cover the line of sight of the driver from the status of the ahead track beyond the curves. This condition will be worst during night time, rainy and fogy environment.

EW curve locations (between stations)	Degree of curvature	EW curve locations (between stations)	Degree of curvature
EW5 – EW6	24 ⁰ 30'	NS6 – NS7	79 ⁰ 11'; 69 ⁰ 41'
EW6 – EW7	32 ⁰ 52'	NS7 – NS8	30 ⁰ 00'
EW8 – EW9	20 ⁰ 09'	NS9 – NS10	13 ⁰ 57'
EW13 – EW14	28 ⁰ 23'	NS11 – NS12	57 ⁰ 13'
EW21 – EW22	63 ⁰ 10'	NS12 – NS13	27 ⁰ 57'; 31 ⁰ 21'
		NS13 – NS14	28 ⁰ 02'
		NS25 – NS26	23 ⁰ 41'

Table 1.2 Horizontal curves existing on main line constructed on the ground [1].



Figure1.2 Vertical curve between EW4 and EW5

3. The only possible way to drive through these curves safely is decreasing the speed of the train. As a result of this the allowable line and curve speeds will not be achieved. Therefore, the operational efficiency of the system will decrease to a significant amount.
4. Additionally, the experience of our drivers is questionable to judge the braking distance and most of hazardous conditions by themselves as the system is new for our country. Therefore, the drivers should have supervised and intervene on their decisions using signaling systems.
5. Headway time designed for the present Addis Ababa Light Rail Signaling system is 6min [1]. That means 6min will be taken for the next train to follow the leading one. In the peak hour if there are 20 [1] trains on operation, 120min takes to complete one cycle of operation, which covers around 32km, by a single train. So the average speed of a train will be:

$$V_{av} = \frac{S_{tot}}{t_{tot}} \quad (1.1)$$

$$V_{av} = \frac{32km}{120min} = 16km/hr$$

Where: V_{av} = average speed of the train

S_{tot} = total distance to cover one cycle of East-West or North-South line

t_{tot} = total time to cover one cycle of East-West or North-South line

The average speed (16km/hr) is so small which can be improved by using different approaches of light rail transit signaling systems.

6. Future traffic:

If additional trains are added and the demand of this transport service increases, it is difficult to manage the future traffic using existing signaling system.

1.4 Objective

1.4.1 General Objective

The signal system must be designed on the basis that a single failure by either a system or by human error does not result in loss of life and or property damage. The design objective is to provide safeguards in the signal system to prevent such a possibility, while still facilitating an efficient LRT operating system.

1.4.2 Specific Objective

➤ Safety Critical:

A fully automatic safety critical and failsafe system must be employed to prevent hazardous conditions from occurring during normal system operations. Safety Critical systems must be designed to activate in the event of system or human error and the system must not hamper the normal safe conditions in train traffic operation. All systems (safety critical or not) must be designed fail safe to prevent an unsafe condition from occurring. No latent failure must result in an unsafe condition when combined with any other failure. The system must ensure that safe operating procedures and methods are maintained.

➤ Installation of automatic systems is needed to;

- Provide the level of safety required to prevent train on train and other types of collision with fixed objects and conflicting vehicular or pedestrian traffic.
- Provide service efficiency through automation in performing routine and repetitive tasks and functions.
- Enforce operating safety rules and equipment restrictions.

➤ For a safety critical design the required level of safety must prevent the following incidents from happening:

- Head to tail collisions between trailing and leading trains.
- Head to head collisions with opposing trains.
- Head to side collisions with other trains.

- Derailments caused by excessive speed, or improper equipment operation.
 - Collisions with vehicular and pedestrian traffic.
- All conceivable modes must be employed to protect against possible conflict and collision between trains, fixed objects and other traffic under normal operations. To meet this goal automatic systems must be installed on the wayside and on the train that will prevent the selection of conflicting routings, maintain adequate train separation and will bring about the enforced and non-recoverable stopping of an encroaching train.

The system is divided into blocks and permission to enter the block will not be given unless free and unrestricted travel at posted speed, free of conflicts, can be made to the end of the block.

- Wayside Equipment:

The signal wayside system must be a centralized design to minimize the number of wayside boxes distributed across the system. This is done to allow ease of maintenance and troubleshooting given the climatic conditions in Addis Ababa.

1.5 Organization of the Thesis

The thesis is organized into six chapters including this introduction. The rest of the thesis is organized as follows:

Chapter 2 presents a review of different LRT system requirements such as calculation of safe breaking distance, speed restrictions of available curves and switches, automatic fixed blocking system in order to find some parameters for the design.

Chapter 3 focuses on the comparison of the existing and the newly proposed design in this thesis.

In Chapter 4, all results of speed profiles and obtained parameters are discussed.

Finally, Chapter 5 draws the conclusions from the work done in this thesis and recommends further research possible in the future.

1.6 Methodology used in this thesis

This research is based on the design of the existed AA LRT signaling system and observations of constructions held on North-South and East-West line. Data gathered from field and existing preliminary design controlled and synthesized based on variables such as safety, operational efficiency, cost, energy efficient system and soon in order to come up with different and more suitable signaling design for AA LRT system.

Based on the existing data the hypothesis is made which is Chinese or European signaling level 0 should implemented on main line constructed on the ground. And I tried to prove my hypothesis through getting enough facts about the headway time and the consequences by improving the average speed of the operation such as operational efficiency and energy consumption. Safety issues are also the main parameter that has to be improved on my new design.

Chapter Two

2 New design of AA LRT signaling system

2.1 Design parameters

The following parameters are taken from AA LRT signaling design [1].

Type of track construction

Independent or isolated from rail vehicles except for level crossings

Composed of East-West line and North-South line

East–West line,

Full length of East-West line of phase one is about 16.998km

A total of 22 stations

North-South line,

Full length is around 16.689km

A total of 22 stations

Common track length is around 2.662km

Type of rail = Welded

Minimum Curve Radius: 50 meters in general,

The greatest vertical gradient of Mainline Interval is 5%

Type of train = Tramcar whose length is 28.400m

Rated Passengers: 6 persons/m², 286 persons in one tram car in total.

Maximum speed = 70km/hr

Average Acceleration for Start-Up: 1m/s²

Average Deceleration for Braking:

- 1) The Average Deceleration of Normal Braking with Rated Load (including control response time) : $\geq 1.0\text{m/s}^2$
- 2) The Average Deceleration of Emergent Braking with Rated Load (including control response time) : $\geq 1.5\text{m/s}^2$

2.2 Level 0 CTCS

Based on the following conditions the appropriate selection is made.

- Maximum operation speed is 70km/hr.
- Already Chinese system is under construction.
- Cost of installation should be considered. Higher levels are safer and efficient but needs high installation cost.

Therefore, Chinese Train Control System level 0 is an appropriate choice because of compatibility issue with the existing system and speed criteria.

CTCS is classified by Level 0 and Level 1 while only ETCS Level 0 simplifies into line which is not installed with ETCS facilities. In contrary to Europe, the train is operated with most various on-board signal system, in the case of china, ground signal system and on-board signal system are coexisted with traffic light according to the line and it is operated by them. The ground signal system is classified with ETCS Level 0(the lowest level) on-board signal system is classified with ETCS Level 1 in order to sort of both system [2].

CTCS level 0 consists of the existing track circuits, universal cab signaling (the digital, microprocessors-based cab signaling that be compatible with the six kinds of track circuits) and train operation supervision system. With level 0, wayside signals are the main signals and cab signals are the auxiliary signals. It is the most basic mode for CTCS. It is no necessary to upgrade the wayside systems for CTCS level 0. The only way to realize the level 0 is to equip with the on-board system. CTCS level 0 is only for the trains with the speed less than 120km/h[12].

- Track circuit or axel counters (Train detection)
- Train signal (or wayside signal)
- Cab signaling

2.3 LRT System Requirements

2.3.1 System Design

The design and operation of the Addis Ababa LRT signal system must allow for a worst case hazardous situation. The system operation must be designed to achieve the safest operation possible consistent with the required operational efficiency. Fully automatic safety critical

failsafe systems must be employed to prevent the occurrence of a hazardous condition during normal system operations.

For any future LRT extensions, the new LRT vital logic control system must allow train movements in both directions on one track, i.e. each track is fully bi-directional. It must also allow trains to automatically turn back at a station should that station be chosen to act like the end-of-line station due to special circumstances [3].

2.3.2 System Safety Principles

As safety is of primary importance, the signals design must be based on safety critical. Automatic Fixed Block System (AFBS) engineering design principles described later in this chapter that is failsafe.

Automatic systems must be installed both on the wayside and the LRT train that will prevent the selection of conflicting routings, maintain adequate train separation and will bring about the enforced and non-recoverable stopping of an encroaching train.

The signal system for each LRT line is to be divided into fixed blocks. Permission for the train entering the block must not be given unless free and unrestricted travel at posted speed, free of conflicts can be made to the end of the block. A red block signal will not turn green unless all the following conditions have been satisfied:

- Tracks within the block and overlap block are not occupied,
- The train is traveling in the correct direction,
- The next block signal is operating properly, which means no signal lamp element is burnt out,
- No conflicting route into the block territory (including the overlap block),
- Track switches are properly lined and locked (electrically and mechanically).

The design and layout of the signal system must consider:

- Static and dynamic clearance envelopes
- Safe braking standards for trains
- Worst case stopping distance
- Approach to signal blocks or grade crossings [3]

2.3.3 Braking Distance

Ref. [6] have discussed braking distance of train on “*Calculating Train Braking Distance,*” study and this thesis work used it as follows.

Braking distance depends on:

- the speed of the train when the brakes are applied;
- the deceleration rate available with a full-service brake application, which varies according to the coefficient of friction between wheel and rail;
- the delay from when the brakes are commanded by the train driver to when they are actually become effective (brake delay time);
- the state of the wear of the brake pads and the air pressure available in the brake cylinders;
- the geography of the track, in particular the track gradient the train travels over from when the brakes are commanded to where the front of the train stops;
- the mass distribution of the train.

Stopping a train requires work. This work equals the change in the train’s kinetic energy plus the change in its potential energy (change in height due to the gradient of the track). The ‘work’ is the energy in decelerating the train over the stopping distance, i.e. the product of the train’s mass (m), the train’s acceleration rate (a) (deceleration is negative acceleration) and the stopping distance (S).

The change in ‘kinetic’ energy relates to the change in the train’s speed i.e. the difference of the speed at which deceleration began (U) and the ‘at stop’ speed (0 km/hr). 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:

$$maS + \frac{1}{2}mU^2 + mg(h_2 - h_1) = 0 \quad (2.1)$$

where ‘ g ’ is the acceleration due to gravity and $h_2 \geq h_1$

Mass is common in all the terms in the equation, and therefore can be cancelled out. This suggests that mass has no direct effect on the stopping distance. However, mass has an effect on the stopping distance as the location of the train’s center of mass varies with the mass distribution. Mass also affects the deceleration rate of a particular item of rolling stock. For

freight wagons, where the mass can vary from no load to full load, there are two levels of brake force used i.e. “empty” and “loaded”. The design of the brake system is such that as the load increases, there is a point where the force changes from “empty” to “loaded”. For braking distance calculations the lowest deceleration rate is used to calculate the deceleration rate for the complete train.

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 slope. For small α , which is the case for railways (mountain rack railways aside), $\tan \alpha$ equals $\sin \alpha$. $\sin \alpha$ is the change in height ($h_2 - h_1$) over the stopping distance(S):

$$h_2 - h_1 = S(\sin \alpha) = S(\tan \alpha) \quad (2.2)$$

Substituting (2) into (1) and rearranging:

$$S = \frac{(-U^2)}{2(a - g \tan \alpha)} ; \text{ for } a < 0 \quad (2.3)$$

The term “ $-g \tan \alpha$ ” is the gravitational acceleration. For uphill track gradients ($h_2 \geq h_1$), gravity assists deceleration.

It is impossible to calculate the precise stopping distance as this distance can vary significantly due to the condition of the train and the environmental conditions at the time. To take the conservative approach, allow for the worst case conditions would grossly impact on track asset utilization. The industry approach is to assume that the train’s brake system is healthy and that the specified adhesion for that class of train is available when the brakes are required to be applied.

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 Equation 2.3. However to compensate for these simplifications and the variable factors, an allowance of 15-20% is usually added. This distance is the minimum distance that needs to be provided [6].

Brake delay time

Allowing 15-20% does not compensate for ignoring the brake delay time. For example, consider a train that has a brake deceleration rate of 1ms^{-2} , and a brake delay time of 5s. Assuming an initial speed of 100km/h and level track, the required braking distance is 524m. Ignoring the brake delay time, the braking distance would be 385m. Adding 20%, increases this to 462m, i.e. some 62m short. This is much worse for long trains where the brake delay time is much longer [6].

For “short” brake delay times the error is not that significant as there are other factors which compensate:

- the train driver would normally initiate a brake application on sighting the first warning to the Limit of Authority ahead, which is well before the calculated full-service braking distance location (a full-service brake is a fairly severe brake application and train driver’s drive more conservatively);
- there is also retardation due to track curvature and viscous drag which is ignored in the calculations.

If it can be demonstrated that each of the new train’s parameters are on the “safer” side when compared to any other train for which the signaling was designed then the new train can be introduced. “Safer” in this case means:

- the maximum train speed is equal to or less;
- the full-service deceleration rate is equal to or greater;
- the brake delay time is equal to or shorter; and
- train length is equal. If any of the parameters are not “safer” e.g. the maximum speed is higher or the brake delay time is longer, then a re-calculation of all braking distances is required. Depending on the intended operating routes, this could involve thousands of calculations.

2.3.4 Speed Restrictions

The maximum allowable operating speed of the train on main line is based on a variety of safety factors. It is therefore necessary to have speed enforcement devices installed to minimize the potential for errors or operating procedure violations.

A speed check enforcement device must be installed along the main line to ensure that a posted speed is not exceeded if it is determined that excessive speed at this location may pose a threat to public or passenger safety. The speed check must trigger the trains automatic braking system once the train exceeds the posted speed limit.

Note: The maximum allowable operating posted speed is 70 km/hr.

Maximum Speed The maximum train run speed is limited to approximately 70km/hr.

Speed restrictions may be due to curves, special work, or speed controls approaching a terminal station. If the speed limits are not known they can be approximated from the following equation [17].

$$v_{sl} = (87R(e + f))^{\frac{1}{2}} \quad (2.4)$$

Where; v_{sl} = speed limit in *km/h*

R = radius of curvature in *meters*

e = super elevation ratio (height the outer rail is raised divided by track gauge) usually not greater than 0.10

f = comfort factor (ratio of radial force to gravitational force—0.13 is the maximum used in rail transit with some systems using as low as 0.05)

2.3.5 Automatic Fixed Block Signaling

Automatic Fixed Block Signal system (AFBS) shall be installed at certain locations along the LRT right-of-way to permit higher operating speeds than would be possible by relying on line-of-sight operation without signals. The AFBS system shall provide information to train operators concerning the condition and occupancy of the track ahead, and provide sufficient stopping distance, when required. Where operationally and technically feasible, Automatic Train Stop (ATS) shall be provided if a train passes a stop signal. All signals will follow a standard “Green-Yellow-Red” configuration.

In all circumstances, except as detailed below, each signal shall be located at least Safe Braking Distance in advance of the previous signal. Permitted train speed shall be a determining factor when calculating Safe Brake Speed for a specific section of track. Occasionally, the physical location of station platforms, power switches, line of sight limitations, etc. will make it impossible to locate the signals at a Safe Braking Distance apart. Overlap circuits greater than the ATS distance shall be used in advance of the AFBS signal. The Overlap circuit may be a mainline track circuit or an Audio Frequency Overlay (AFO) circuit [9].

Wherever an overlap is provided, a signal will not clear from Red to Yellow until the leading train is clear of the next signal and the overlap track circuit in advance of that signal. Functionally, this means that if a train overruns a Red signal, the signal system’s Automatic Train Stop (ATS) will be activated and the train will be brought to a stop. A leading train in the area will be at least the length of the overlap beyond the Red signal just overrun. This overlap, while not the calculated “worst case” braking distance, will provide a measure of safety to ensure that there is no leading train immediately beyond a Red signal [9].

Fixed block signaling is the most widely used form of signaling, both for urban and inter-city railway operations. Consider a 3-aspect arrangement as shown in Figure 2.1

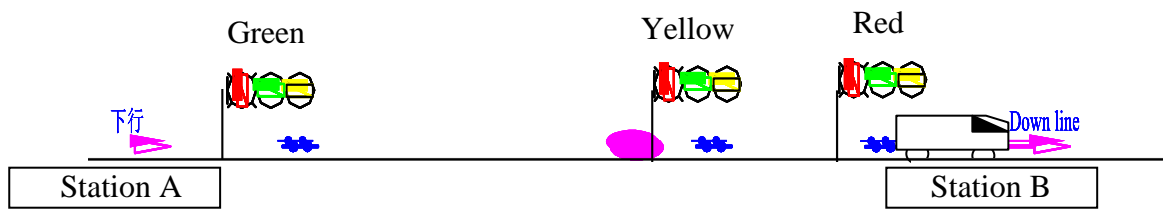


Figure 2.1 A 3-Aspect Fixed Block layout

Each track is divided into discrete sections called blocks. Each block is equipped with failsafe track circuit devices that sense and indicate the presence of a train within the block. A train is not permitted to enter a block until a signal indicates that the train may proceed, a dispatcher or signalman instructs the driver accordingly, or the driver takes possession of the appropriate token. In most cases, a train cannot enter the block until not only the block itself is clear of trains, but there is also an empty section beyond the end of the block for at least the distance required to stop the train [3].

The condition of the block signal is a RED (stop) indication. The signal will not turn GREEN (go) unless it is safe to enter the block and the signal light is operating properly. Trains attempting to enter the block that has a red block signal will be stopped automatically by the train stop magnet associated with the block signal. Vital Software must be designed using the check-redundancy principles. These systems must be proved to be independently safe from external influences such as, but not limited to, EMI, interfaced system or sub-systems, and human operation from either the local control panel or central train control.

A two-aspect signaling system does not provide the capacity normally required on busy rail transit lines—those with trains an hour or better. Increased capacity can be obtained from multiple aspects where intermediate signals advise the driver of the condition of the signal ahead, so allowing a speed reduction before approaching a stop signal. Block lengths can be reduced relative to the lower speed, providing increased capacity.

The increased number of blocks, and their associated relay controls and color-light signals, is expensive. There is a diminishing capacity return from increasing the number of blocks and aspects.

In signaling-based systems with closely spaced signals, this overlap could be as far as the signal following the one at the end of the section, effectively enforcing a space between trains of two blocks.

When calculating the size of the blocks, and therefore the spacing between the signals, the following have to be taken into account:

- Line speed (the maximum permitted speed over the line-section)
- Train speed (the maximum speed of different types of traffic)
- Gradient (to compensate for longer or shorter braking distances)
- The braking characteristics of trains (different types of train, e.g. freight, High-Speed passenger, have different inertial figures)
- Sighting (how far ahead a driver can see a signal)
- Reaction time (of the driver) [3]

2.3.6 Fixed Block Throughput for three aspect signaling system

Ref. [17] Determining the throughput of any rail transit train control system relies on the repetitive nature of rail transit operation. In normal operation trains follow each other at regular intervals traveling at the same speed over the same section of track.

All modern trains have very comparable performance. All low-performance equipment is believed to have been retired. Should a line operate with equipment with different performance and/or trains of different length, then the maximum throughput rates developed in this section should be based on the longest train of the lowest performing rolling stock.

Trains operating on an open line with signaling protection but without station stops have a high throughput. This throughput is defined as line or way capacity. This capacity will be calculated later in this section although it has little relevance to achievable capacity except for systems with off-line stations. Only Automated Guide way Transit, or some very high capacity lines in Japan, can support off-line stations.

Stations are the principal limitation on the maximum train throughput—and hence maximum capacity—although limitations may also be due to turn-back and junction constraints. The project survey of operating agencies indicated that the station close-in plus dwell time was the capacity limitation in 79% of cases, turn back constraints in 15%, and junctions in 5% of cases. Further inquiry found that several turn back and junction constraints were self-imposed

due to operating practices and that stations were by far the dominant limitation on throughput [17].

In a well-designed and operated system, junction or turn back constrictions or bottlenecks should not occur. A flat junction can theoretically handle trains with a consolidated headway approaching 2 min. However, delays may occur and systems designed for such close headways will invariably incorporate grade-separated (flying) junctions. Moving-block signaling systems provide even greater throughput at flat junctions.

A two-track terminal station with either a forward or rear scissors cross-over can also support headways below 2 min unless the cross-overs are long, spaced away from the terminal platform, or heavy passenger movements or operating practices when the train crew changes ends (reverses the train) result in long dwells. The latter two problems can be resolved by multiple-platform terminal stations by establishing set-back procedures for train crews.

In this chapter the limitations on headway will be calculated for all three possible bottlenecks: station stops, junctions and turn backs.

All the reports deal with station stops as the principal limitations on capacity and use Newton's equations of motion to calculate the minimum train separation, adding a variety of nuances to accommodate safety distances, jerk limitations, braking system and drivers' reaction times plus any operating allowance or recovery margin.

Station Close-in time:

The time between a train pulling out of a station and the next train entering—referred to as close-in—is the main constraining factor on rail transit lines. This time is primarily a function of the train control system, train length, approach speed and vehicle performance. Close-in time, when added to the dwell time and an operating margin, determines the minimum possible headway achievable without regular schedule adherence impacts—referred to as the noninterference headway. When interference occurs, trains may be held at approaches to stations and interlocking. This requires the train to start from stop and so increases the close-in time, or time to traverse and clear an interlocking, reducing the throughput. With throughput decreased and headways becoming erratic, the number of passengers accumulated at a specific station will increase and so increase the dwell time. This is a classic example of the maxim that when things go wrong they get worse.

The minimum headway is composed of three components:

- the safe separation (close-in time),
- the dwell time in the station, and
- an operating margin.

The best method to determine the close-in time is from the specifications of the system being considered, from existing experience of operating at or close to capacity or from a simulation. The classical expression for the minimum headway of the typical rail transit three-aspect block-signal system is [17]

$$H(t) = \frac{\frac{2BL}{v_{ap}} + D_w + \sqrt{\frac{2L}{a}}}{1 - M} \quad (2.5)$$

The block length must be greater than or equal to the service stopping distance.

$$BL \geq SD = \frac{V_{ap}^2}{2d} \quad (2.6)$$

Where; $H(t)$ = headway in seconds

BL = block length approaching station (m)

D_w = station dwell time in seconds

SD = service stopping distance for level track (m)

L = length of the longest train (m)

v_{ap} = maximum approach speed (m/s)

a = average acceleration rate through the station platform clear-out (m/s^2)

d = braking rate (m/s^2)

M = headway adjustment combining operational tolerance and dwell time variance
(constant)

Although the headway adjustment factor, M , can encompass a variety of items, it is difficult to encompass all the variables that can affect headway. These include

- any distance between the front of the train and the start of the station exit block, particularly if the train is not berthed at the end of the platform;
- control system reaction time;
- on manually driven trains, the train operator sighting and reaction time;
- the brake system reaction time;

- an allowance for jerk limitation;
- speed restrictions on station approaches and exits whether due to speed control for special work or curves; and
- grades approaching and leaving a station.

In addition, the length of the approach block and the approach speed are not readily obtainable quantities. Consequently this traditional method is not recommended and an alternate approach will be developed. This uses more readily available data accommodating many of the above variables. This approach encompasses both manually and automatically driven trains, multiple command cab controls, and, by decreasing block length, a moving-block system. Even so, it should be borne in mind that not all variables can be included, and assumptions and approximations are still needed. This approach, while more comprehensive than many in the literature, is not as good as using information from signaling engineers, based on actual block positions, or from a comprehensive and well-calibrated simulation.

Calculating Line Headway

On a level, tangent (straight) section of track with no disturbances the line headway $H(l)$ is given by [17]:

$$H(l) = \frac{L + S_{min}}{v_l} \quad (2.7)$$

where $H(l)$ = line headway in seconds

S_{min} = minimum train separation in meters

L = length of the longest train in meters

v_l = line speed in m/s

The minimum train separation corresponds to the sum of the operating margin and safe separation distance shown in Figure 3.2. It can therefore be further subdivided: (all in meters)

$$S_{min} = S_{sbd} + S_{td} + S_{om} \quad (2.8)$$

Where; S_{min} = minimum train separation distance

S_{sbd} = safe braking distance

S_{td} = train detection uncertainty distance

S_{om} = operating margin distance

The safe braking distance is based on the rail transit assumption of brick-wall stops using a degraded service braking rate. The train detection uncertainty reflects either the block length

or the distance covered in the polling time increments of a moving block signaling system. The operating margin distance is the distance covered in this time allowance. This will be omitted from further consideration in this section.

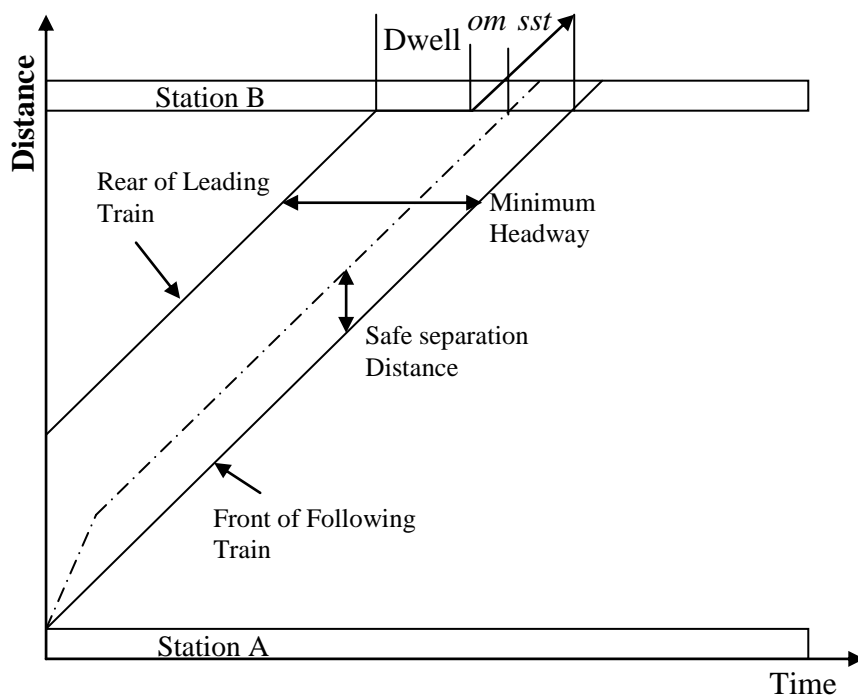


Figure 2.2 Distance-time plot of two consecutive trains (acceleration and braking curves omitted for clarity) [17]

Substituting for S_{min} and removing S_{om} produces

$$H(l) = \frac{L + S_{td} + S_{sbd}}{v_l} \quad (2.9)$$

There are several components in the safe braking time. The largest is the time to brake to a stop, using the service brake. A constant K is added to assume less than full braking efficiency or reduced adhesion—75% of the normal braking is an appropriate factor. There is also the distance covered during driver sighting and reaction time on manually driven trains, and on automatically driven trains brake equipment reaction time and a safety allowance for control failure. This over speed allowance assumes a worst case situation whereby the failure occurs as the braking command is issued with the train in full acceleration mode. This is often termed runaway propulsion. The train continues to accelerate for a period of time t_{os} until a speed governor detects the over speed and applies the brakes [17].

$$S_{sbd} = \frac{100}{K} S_{bd} + S_{br} + S_{os} \quad (2.10)$$

Where; S_{sbd} = safe braking distance in meters

S_{bd} = service braking distance in meters

K = braking safety factor

S_{br} = train operator sighting and reaction distance and/or braking system reaction distance in meters

S_{os} = overspeed travel distance in meters

The distance to a full stop from speed V_l at the constant service braking, deceleration or retardation rate is given by:

$$S_{bd} = \frac{V_l^2}{2d_s} \quad (2.11)$$

Where; d_s = service deceleration rate in m/s^2

To be rigorous, the safe braking distance should also take into account grades, train load—passenger quantities and any snow and ice load and, in open line sections, any tail wind. These add complexities beyond the scope of this study and, except for downgrades, contribute a very minor increment to the result. Consequently they have been omitted. The effect of grades will be examined in the sensitivity analysis at the end of this section. Modern rail transit equipment uses a combination of friction and electrical braking, in combination with slip-slide controls, to maintain an even braking rate. An allowance can be added for the jerk limiting features that taper the braking rate at the beginning and end of the brake application.

The distance an automatically operated train moves until the over speed governor operates can be expressed as

$$S_{os} = v_l t_{os} + \frac{a_l t_{os}^2}{2} \quad (2.12)$$

Where; S_{os} = overspeed distance

t_{os} = time for overspeed governor to operate

a_l = line acceleration rate in m/s^2 at v_l

v_l = line speed

Substituting Equations 2.12, 2.11, and 2.10 in Equation 2.9 and adding a jerk limiting allowance produces

$$H(l) = \frac{L + S_{td}}{v_l} + \frac{100}{K} \left(\frac{v_l}{2d_s} \right) + \frac{a_l t_{os}^2}{2v_l} + t_{os} + t_{jl} + t_{br} \quad (2.13)$$

Where; t_{br} = train operator sighting and reaction time and/or braking system reaction time

t_{jl} = jerk limiting time allowance

Service acceleration is said to be following the motor curve as it reduces from the initial controlled rate to zero at the top, maximum, or balancing speed of the equipment. The acceleration rate at a specific speed may not be readily available and an approximation is appropriate for this item—a small component of the total line headway time. On equipment with a balancing speed of 70 km/h, the initial acceleration is maintained until speeds reach 10-20 km/h then tapers off, approximately linearly until speeds of 50-60 km/h, then approximately exponentially until it is zero. At line speeds appropriate to this analysis the line acceleration rate can be assumed to be approximate to the inverse of speed so that for intermediate speeds [17]

$$a_l \cong a_s \left(1 - \frac{v_l}{v_{max}} \right) \quad (2.14)$$

Where; v_l = line speed in m/s

v_{max} = maximum train speed in m/s

a_l = line acceleration rate in m/s^2

a_s = initial service acceleration rate in m/s^2

The train detection uncertainty distance is not readily available but can be approximated as either the block length(s)—again not easily obtained—or the braking distance plus some leeway as a surrogate for block lengths on a system designed for maximum throughput. This quantity is particularly useful as a simple method to adjust for the differences between the traditional three-aspect signaling system, cab controls with multiple aspects (command speeds) and moving-block signaling systems [17].

$$S_{td} \cong B \left(\frac{v_l^2}{2d_s} \right) \quad (2.15)$$

Where; B = a constant representing the increments or percentage of the braking distance—or number of blocks—that must separate trains according to the type of train control system.

A B -value of 1.2 is recommended for multiple command cab controls [17]. A value of 2.4 is appropriate for three-aspect signaling systems where there is always a minimum of two clear blocks between trains [17]. The value of B for moving-block signaling systems can be equal

to or less than unity and is developed in the next section. Accepting these approximations and substituting Equations 2.14 and 2.15 in Equation 2.13 produces

$$H(l) = \frac{L}{v_l} + \left(\frac{100}{K} + B \right) \left(\frac{v_l}{2d_s} \right) + \frac{a_l t_{os}^2}{2v_l} \left(1 - \frac{v_l}{v_{\max}} \right) + t_{os} + t_{jl} + t_{br} \quad (2.16)$$

Where; $H(l)$ = line headway in seconds

L = length of the longest train in meters

v_l = line speed in m/s

K = braking safety factor—worst case service braking is $K\%$ of specified normal rate—typically 75%

B = separation safety factor—equivalent to the number of braking distances (surrogate for blocks) that separate trains

t_{os} = overspeed governor operating time (s)

t_{jl} = time lost to braking jerk limitation (s)

t_{br} = operator & brake system reaction time (s)

a_l = line acceleration rate in m/s^2

d_s = service deceleration rate in m/s^2

2.3.7 Station Headway

Station headway, the time for one train to replace another at the maximum load point station, is by far the most common capacity limitation. Having derived an expression for line headway that uses readily available information with as few approximations as possible, it is possible to adapt this to station headway by

- changing line speed to approach speed and solving for this speed,
- adding a component for the time a train takes to clear the platform,
- adding the station dwell, and
- adding an operating margin.

The time for a train to clear the platform is [17]

$$t_c = \sqrt{\frac{2(L+D)}{a_s}} \quad (2.17)$$

Adding Equation 2.17 to 2.16 plus components for dwell and an operating margin produces the station headway

$$H(l) = \sqrt{\frac{2(L+D)}{a_s}} + \frac{L}{v_a} + \left(\frac{100}{K} + B\right) \left(\frac{v_a}{2d_s}\right) + \frac{a_s t_{os}^2}{2v_a} \left(1 - \frac{v_{la}}{v_{max}}\right) + t_{os} + t_{jl} + t_{br} + t_d + t_{om} \quad (2.18)$$

Where; $H(l)$ = station headway in *seconds*

L = length of the longest train in *meters*

D = distance from front of stopped train to start of station exit block in *meters*

v_a = station approach speed in *m/s*

v_{max} = maximum line speed in *m/s*

K = braking safety factor—worst case service braking is $K\%$ of specified normal rate—typically 75% [17].

B = separation safety factor—equivalent to number of braking distances plus a margin, (surrogate for blocks) that separate trains

t_{os} = time for overspeed governor to operate

t_{jl} = time lost to braking jerk limitation— (*seconds*) typically 0.5 seconds

t_{br} = operator and brake system reaction time

t_d = dwell time (*seconds*)

t_{om} = operating margin (*seconds*)

a_s = initial service acceleration rate in m/s^2

d_s = service deceleration rate in m/s^2

Typical values will be used and this equation solved for the approach speed under two circumstances:

1. three-aspect signaling system ($B = 2.4$)
2. multiple command speed cab controls ($B = 1.2$) [17].

A 45-sec dwell time is used—typical of the busiest stations on rail transit lines operating at capacity—together with an operating margin time of 20 sec [17]. The brake system reaction time will use a moderate level of 1.5 sec—this should be higher for old air brake equipment, lower for modern electronic control, particularly with hydraulically actuated disk brakes. Other factors remain at the levels used in the line headway analysis.

Two factors have not been taken into account in the determination of minimum headways in the preceding section— grades and fluctuations in traction voltage.

Grades

The principal effect of grades is where downgrades into stations increase the braking distance and the distance associated with the runaway propulsion factor. A simple method to compensate for grades is to adjust the service braking and acceleration rates in Equation 2.18 while holding the component of the equation that relates to the time for a train to exit a platform constant. The acceleration due to gravity is 9.807 m/s^2 . Thus each 1% in downgrade reduces the braking rate by 0.098 m/s^2 . Note that most rail transit systems have design standards that limit grades to 3 or 4%, a few extend to 6% and the occasional light rail grade can extend to 10%. The impact of grades is greater into a station. The greatest impact is a downgrade into a station which increases the braking and so the safe separation distance. Block lengths must be longer to compensate for the longer braking distances.

Line Voltage

Rail transit in Addis Ababa is supplied by direct current power at a potential of 750 volts. As more power is drawn through the substations, feeders or overhead catenary, the voltage drops. Voltage is higher in the vicinity of substation feeders and drops off with distance. Voltage is said to be regulated within a system specification that is typically +20% to -30%. The lowest voltage occurs at locations most remote from sub-stations in the peak hour when the maximum number of trains are in service. The lower voltage reduces train performance—at a time when the heavy passenger load is doing likewise. Both acceleration and balancing speed are reduced; braking is not affected.

The acceleration of a train is approximately proportional to the power applied to the motors, which in turn is proportional to the square of the supply voltage. This is particularly true for older equipment with switched resistor controls, less so with modern electronically controlled equipment. Consequently, for older equipment without on-board motor voltage feedback and control, the common 10% reduction in voltage will reduce acceleration to 81% of normal; the very rare 30% drop will reduce acceleration to 49% of normal.

Reduced acceleration affects the platform clear out component of the headway calculation. The resultant headway sensitivity to voltage is shown below. At a typical 15% drop in voltage headway increases by 3.2 seconds, a 2.7% change. It is not possible to calculate line voltage at any instance of time without a complete train performance and traction supply system simulation. This will automatically occur if a simulation is used to determine the minimum headway. Otherwise it is uncertain whether a manual adjustment should be made

based on the above chart—with certain designs of modern rolling stock the effect of voltage drop can be less than shown.

2.4 Equipment Requirements

Due to the harsh weather conditions all new outdoor wayside equipment must be rated for temperatures that exceed the summer and winter conditions normally expected in Addis Ababa.

In addition all outdoor equipment of AA LRT must meet the following requirements [3]:

- Must be highly reliable i.e. the equipment has been used and is proven by other Transit properties operating in an environment similar to the Addis Ababa LRT System.
- Must be rustproof

From an equipment maintenance perspective it is desirable to keep the number of different equipment suppliers to minimum for the following reasons:

- To eliminate interfacing requirements (the black conversion box)
- To minimize spatial requirements
- To minimize the amount of additional staff training (required for new systems)
- To maintain consistency in operational functionality
- To consolidate spares inventory and control

2.4.1 Numbering Schemes

All equipment, relay, contacts and terminals for all LRT extensions must be identified, located and numbered with a numbering scheme. It is through the numbering system that a signal maintenance technician is able to identify where a specific point or piece of equipment is located within the system.

Most equipment on the main line of the existing LRT system is identified by the chainage location of the equipment in reference to the Control Center. Signals (Block and call-on) and speed checks have a unique identifier, indicating the track and the distance [3].

2.4.2 Wayside Signals

Based on failsafe signal design principles, all signal lights must be monitored by the current flowing through the signal lamp element. A RED light or an AMBER light must have double element incandescent lamp, the principal and the secondary element. A “signal disturbed” alarm must be issued as soon as the principal element has burnt out.

For LED signal aspects, light-out detection must be provided with status information sent to the CTC system. LED light-out alarm must be failsafe. LED light-out must be equivalent to a red signal.

All signal lights must be lit and complete with proper lenses and filters. The power supply for the LRT signal lights must come directly from the relay room controlling that particular signal. The outgoing power must not be grounded (isolated power). Shields on signal lights must be provided so that glare from the sun will not interfere with the Motorman's vision.

Label all new block signal and grade crossing protection call-on signal lights with white letters and numbers on black background to match existing. Provide clear labeling for all new track switches and speed checks so that it is easily identified by the Motorman.

Location of all wayside equipment must be clear from the dynamic movement of the trains [3].

2.4.3 Track Circuits

The track circuit is an electrical circuit which includes a length of running rails (or special rails) and permits detection of the presence of a train. It may also be used to communicate commands, instructions, or indications between the wayside and a train. They provide information on the location of the trains, and this information is used to command train speeds so that the trains operate safely. For instance, if a train attempts to approach too close to the rear of another train, information on the locations of the two trains, provided by the track circuits, is used to command slowdown or stop of the following train before there is danger of a rear-end collision [18].

A. D.C. Track Circuits

In all track circuits an electrical signal of some kind is impressed between the running rails, and the presence of a train is detected by the electrical connection that the wheels and axles of the train make between the two running rails. In D.C. track circuits, the electrical signal is direct current, usually supplied by batteries. The detector for the electrical signal is a relay.

The track circuit consists of a block or length of track which is defined at each end by insulated joints in the running rails. The insulated joints provide electrical insulation between a given track circuit and the adjoining tracks which comprise other track circuits. The signal source, in this case a battery, is connected to the rails at one end of the track circuit while the receiver (a relay) is connected to the other end, When no train is present, the track circuit is said to be unoccupied, and the direct current supplied by the battery is transmitted by the

running rails to the relay and energizes it or “picks it up”. When the relay is energized, the upper set of relay contacts is connected causing the green signal light to be turned on. When a train enters the track circuit its wheels and axles connect the two running rails together, shorting the battery and thereby reducing the current through the relay. This causes the relay to “drop”. This action connects the bottom set of relay contacts, turning off the green signal light and turning on the red light to indicate that the block is occupied by a train. The resistor in series with the battery protects the battery by limiting the current the battery must provide when a train is present.

The relay would have several sets of contacts connected in combination with the contacts from other relays in nearby track circuits to form logic circuits for the control of the signaling devices (the red and green lights).

The breaking of any conductor or the loss of power in the circuit will cause either a red signal or no signal at all to be displayed. A red or “dark” signal is always to be interpreted as a command to stop. To put it another way, all signaling systems are designed so that a green signal (meaning proceed) is presented only when the track circuits provide positive information that it is safe to do so.

The double-rail D.C. track circuit is susceptible to interference when the running rails are also used as the return for D.C. electric propulsion current. For this reason, D.C. circuits are not used in rail rapid transit. Single-rail D.C. track circuits could be used, but in fact all modern rail rapid transit systems use some form of A.C. track circuit.

B. Power-Frequency A.C. Track Circuits

The power-frequency A.C. track circuit is energized by an alternating electrical current with a frequency in the range of 50 to 150 hertz. Except for the type of current and apparatus used, the A.C. track circuit is similar in operation to the D.C. track circuit described above.

As with the D.C. circuit, the A.C. track circuit consists of a block or length of track which is defined at each end by insulated joints in one or both of the running rails.

The A.C. signal source (usually a transformer) is connected to the rails at one end of the track circuit while the receiver (a relay) is connected to the other end, In addition to the signal source and the receiver, the A.C. track circuit contains a pair of impedance bonds at each pair of insulated joints. An impedance bond is a center-tapped inductance which is connected

across the rails on both sides of the insulated joints. The purpose of the impedance bonds is to provide continuity between the track circuits for the D.C. propulsion power and to distribute the propulsion current between the two running rails. The impedance bonds do this while still maintaining relatively high impedance at the signaling frequencies between the two rails and between adjacent track circuits.

C. High-Frequency A.C. Track Circuits

Some A.C. track circuits use a current that alternates at a frequency in the range of hundreds or thousands of hertz. Because this frequency range corresponds roughly to the spectrum of audible sound, such circuits are sometimes called audio-frequency track circuits.

High-frequency A.C. track circuits eliminate the need for insulated joints in the running rails. Because insulated joints are expensive to install and to maintain, eliminating them leads to a significant cost reduction. Eliminating insulated joints also allows the track circuit to operate with the continuous welded rails being used in some newer installations. Since no insulated joints are used in the running rails, the ends of the block established by special transformers are connected to the rails.

The transformer winding attached to the rails is usually a single turn of heavy copper bar stock. The transformer core is often a toroid. The other transformer winding is tuned to resonate at the operating frequency by a capacitor. The transmitter is the A.C. signal source and provides electrical energy at the operating frequency in the audio-frequency range. The receiver in this case is not simply a relay, as with the A.C. and power-frequency A.C. track circuits, but an electronic circuit which responds to the electrical signal provided by the transmitter. The receiver may be used to actuate a relay which performs functions like those in the D.C. or power-frequency A.C. track circuits. Thus, when no train is present the high-frequency A.C. potential supplied by the transmitter is connected to the running rails by the transformer and transmitted along the running rails to the other transformer and its associated receiver. When the receiver detects the high-frequency A.C. signal, the relay is energized and the green signal light is turned on. When a train enters the block, the circuit behaves much as it would with the A.C. or power-frequency A.C. track circuits, That is, the train wheels and axles connect the two running rails together, and the current to the receiving transformer and its associated receiver causes the track circuit relay to drop, turning off the green light and turning on the red light.

In practice, it is necessary to accommodate the adjacent track circuits on either side, Rather than install two separate transformers for each track circuit, a second resonant winding can be included in each transformer or a heavy primary winding can be passed through more than one transformer core. Thus, a single transformer assembly is used at the boundary between adjacent track circuits and serves each. Although part of the same transformer assembly, the resonant windings are effectively isolated from each other because they are tuned to and operate on different frequency.

2.4.4 Axle Counters

An alternative method of determining the occupied status of a block is using devices located at its beginning and end that count the number of axles entering and leaving. If the same number of wheels leaves the block as enter it, the block is assumed to be clear. Although axle counters can provide similar functionality to track circuits, they also exhibit a few other characteristics. In a damp environment an axle counted section can be far longer than a track circuited one. The low ballast resistance of very long track circuits reduces their sensitivity.

Track circuits can automatically detect some types of track defect such as:

- ✓ A broken rail.
- ✓ In the event of power restoration after a power failure, an axle counted section is left in an undetermined state until a train has passed through the affected section. When a block section has been left in an undetermined state, it may be worked under pilot working. The first train to pass through the section would typically do so at a speed no greater than 20 mph (32 km/h) or walking pace in areas of high transition, reverse curvature and may have someone who has a good local knowledge of the area acting as the pilot man. A track circuited section will detect the presence of a train in section immediately.
- ✓ If part of the train is left in the section, that part will continue to be detected by the track circuit [3].

2.4.5 Central Traffic Control System

Addis Ababa LRT CTC system carries out data acquisition, processing, monitoring, presentation, and archiving function for train system data received from field code units (FCU's). It must include complete centralized traffic control, train routing, train tracking functions, and processing of train and crew data. Functions also exist for information storage

and retrieval, playback of rail operations, and simulation of rail operations. The CTC system must include report generation functions, extensive user interface displays of the LRT network, interfaces to train control status boards, and a repository of online documentation [3].

System Software

The CTC software must be built on the ARINC Advanced Information Management (AIM) or

- ETS approved platform. The CTC application software components must include the following functions: Communication Processing (the extension of data acquisition and control functions)
- System Processing (data processing and calculations, control processing, centralized traffic control, train tracking, train routing, train scheduling, event and alarm processing, data recording archival playback)
- Display Processing (console management)
- Maintenance Processing (graphic editor, dialog editor, database and display linking, database management, simulation, configuration tools)
- Management Processing (forms and reports)
- User processing (graphical user interface)

Network Infrastructure

The CTC system must be distributed over several LRT facilities consisting of the following:

- A real time redundant computer server system. Maintenance Facility server room operating in a hot standby mode.
- An Emergency Backup computer server facility serving in cold standby mode.
- The equipment directly available to the LRT Control Centre personnel consists of two (2) consoles, each with multiple monitor workstations.
- Four (4) FCUs, one in each in relay rooms. This FCU is a Modicom 984 mini-PLC system that receives status indications from the territorial wayside equipment and conveys commands from the ETS Control Centre to the territorial vital logic control system.
- Four (4) Protocol Converters, one in each relay. The Protocol Converter is a Moxa programmable network gateway device (Modbus TCP to Genysis protocols) that provides a nonvital interface to the Signal System by receiving status indications from and conveying commands from the ETS Control Centre to the territorial Vital Logic Controller (VLC). Only the VLC interfaces with territorial wayside LRT

signaling equipment

- A dual channel Ethernet fiber optic communication network. System servers, and user workstations are connected in redundant fashion via the dual channel Ethernet LAN.
- UPS power for centralized servers, emergency backup server, communication networks, station and Control Centre LAN's, FCUs, Protocol Converters, and the LRT control stations.
- Network Connections between facilities are via redundant Ethernet tributary interfaces within SONET OC-3 ADMs in Station Communications Rooms and LRT Signal Rooms. Tributaries must have a minimum of 6 X VT1.5 for bandwidth.

CTC Workstation Specifications

The workstations used for operation of the CTC system must be from the latest generation of PC based equipment and software. The current generation of workstation equipment must have the following minimum specifications [3]:

- Intel Core 2 Duo Processor based workstation
- 3 GB RAM
- High performance video board
- 200 GB Ultra SCSI hard drive
- SCSI controller
- Dual Network Interface Controllers
- Windows XP Professional or the latest version compatible with the CTC client software

CTC Server Specifications

The servers used for operation of the CTC system must be from the latest generation of PC based equipment and software. The current generation of server equipment must have the following minimum specifications [3]:

- Intel Core 2 Duo Processor based workstation
- 8 GB RAM
- 1 TB SCSI hard drive
- SCSI controller
- Dual Network Interface Controllers
- Windows Server 2008 or latest version compatible with the CTC server software

Field Code Units

The Field Code Units (FCU's) in the LRT CTC system are the Modicon 984-A 120 compact PLC system. Redundant communications is established via the Optical Fiber Node Multiplexers (SONET OC-3 ADMs) to the FCU using Moxa ModBus Serial to ModBus TCP network conversion devices. For details on this equipment, refer to the ARINC user manual for the PLC system. As the LRT system is expanded the Vital relay logic and FCU interface will be phased out with the use of VLCs and gateway Protocol Converters or other compatible systems approved by ETS.

Protocol Converters

The Protocol Converters currently utilized in the existing LRT CTC system to interface to VLCs are the Moxa ModBus gateway M-Gate devices. These devices are configured in a redundant pair for each VLC to CTC Interface. For details on this equipment, refer to the Signal System Operations and Maintenance Manual for the CTC Interface. Gateway devices must support real-time transmission of all required CTC indications and controls as well as health status.

User Interface

The CTC User Interface must allow Controllers at the LRT Control Centre to:

- Monitor all train movements on the system
- Monitor train schedule adherence
- Receive alarms from the LRT signal system
- Observe wayside signal statuses
- Observe track switch position, correspondence, and locking statuses
- Observe grade crossing warning system statuses
- Switch system control between the CTC system and the local control panels in the relay rooms
- Activate and de-activate automatic routing functions
- Line or cancel routes
- Throw track switches
- Block and de-block track sections
- Block and de-block wayside signals
- Reset false occupancies on track circuits

Control Functions

The CTC control console will enable a control operator or technician located at the LRT Control Centre to issue all operational commands accepted by the signal system, including:

- Turn CTC on for a signaling territory
- Turn CTC off for a signaling territory
- Put the system in Automatic routing mode for a signaling territory
- Put the system in Manual mode for a signaling territory
- Line any available routes via entrance/exit selection
- Cancel a route
- Throw a switch to reverse
- Throw a switch to normal
- Clear a trailed switch (if available in that signaling territory)
- Reset false occupancies on track circuits (if available in that signaling territory)
- Block a track
- De-block a track
- Block a signal
- De-block a signal
- Acknowledge/reset an alarm

Monitoring Functions

The CTC control console must enable a control operator or technician located at the LRT Control Centre to monitor field conditions of the signal system, including:

- Communication status between CTC server and Signal Room control system (rotating world for each Signal Room)
- Occupancy on all track circuits
- Route entrance selected
- Route exit lined
- Track switch normal position/correspondence for all track switches
- Track switch reverse position/correspondence for all track switches
- Track switch locking status for all track switches
- Red aspect status for all block signals
- Green aspect status for all block signals
- Amber aspect status for all call-on signals
- Green aspect status for all call-on signals
- Blocked status for all block signals

- Blocked status for all call-on signals
- Blocked status for all track sections
- CTC status (On or Off)
- Routing status (Auto On or Off)
- Alarm statuses (Loss of line power, Ground faults, Trailed switches. Burnt signal filaments, Fiber network status)
- Grade crossing warning system status for all grade crossings
- Pedestrian crossing warning system status for all pedestrian crossings

Train Tracking

Train tracking functionality must be included in the CTC system to permit identification and tracking of trains operating over the LRT including unscheduled trains, test cars, training cars, work trains and maintenance equipment. The train tracking function includes the following features:

- Assigns, verifies, and modifies train ID's (6 digit alphanumeric characters)
- Continually monitors the location and train ID of all trains and maintains correlation of each track occupancy with the proper train ID and schedule
- Reports train locations and train ID'S to the PA/VMS system which predicts the train location to support the announcement of an imminent train arrival at a station
- Displays the location of all trains, including train ID's, on control consoles and the status board.
- Updates the tracking database as new data is received.
- Provides the Controller with the capability to correct problems in the locations and identities of trains including assigning train ID's, changing train ID'S, moving train ID's from one occupancy to another, deleting train ID'S, swapping train ID'S and entering and changing train consists.
- Provides a convenient initialization procedure to allow the Controller to establish the train ID'S of all trains when the CTC system is initialized.

Schedule Adherence and Monitoring Functions

Schedule Adherence and Monitoring functionality must be included in the CTC system to work with and interface to the PA/VMS system to permit schedule performance monitoring of trains operating over the LRT as well as drive related automated visual and audible messaging at the station platforms. The schedule adherence and monitoring function includes the

following features:

- Report track occupancies and interlocking switch states in real-time required by the PA/VMS system for the proper triggering of next train and estimated time of arrival audible and visual train destination messages at passenger station platforms.
- Report train ID sequences and changes there of required by the PA/VMS system for the proper triggering of next train and estimated time of arrival audible and visual train destination messages at passenger station platforms.
- Receive PA/VMS health status messages and annunciate all alarm states.

Display Conventions

Alarms are sub-divided into categories that are defined by the priority and urgency. Alarm categories must define what level of audible and visual indications are to be presented to the system Controller. Alarms that are reported by the system are:

- Red signal overruns
- Non-commanded or unexpected changes of a train control system devices
- Loss of an FCU
- Application program errors
- Data source communication errors
- CTC system hardware or software errors
- Detection of a Controllers attempt to log off before releasing control of the territory
- Loss of normal power to a CTC system UIS power unit
- Field red signal filament open
- Track switch failed
- Track circuit reset fault
- Ground fault on signal control circuit
- Main control power off

Event Recorders

The CTC servers record the status of all wayside signal equipment and all control activities on the CTC system. Administrators of the CTC system can retrieve all recorded data or play back the event recorded in the system. Any proposed LRT extensions must be able to provide the same information to the existing CTC system.

A data-logger must be installed in each relay room to prevent the loss of data between the relay rooms to the CTC servers in the event of a communication line breakdown.

The data-logger must record all changes on the status of all wayside signal equipment within the territory covered by the relay room signal control system. It must also record the commands being executed within its territory in response to the command issued via the CTC System from the LRT Control Centre or the Local Control Panel in the signal room.

The data-logger in each signal room must have the capacity to store a minimum of 60 days of data collected from the signal room. It should be capable of storing data in a First-In-First-Out (FIFO) methodology within the 60 day frame period. All events recorded in the Signal Room data-logger must be date and time stamped. It must be on UPS power that is capable of supplying 6 hours of power after normal power supply failure.

The data logger can be included in the VLC or it may be contained in a separate processing unit that monitors the CTC interface and stores a history of controls and indications for future recall.

2.5 Provision of equipment

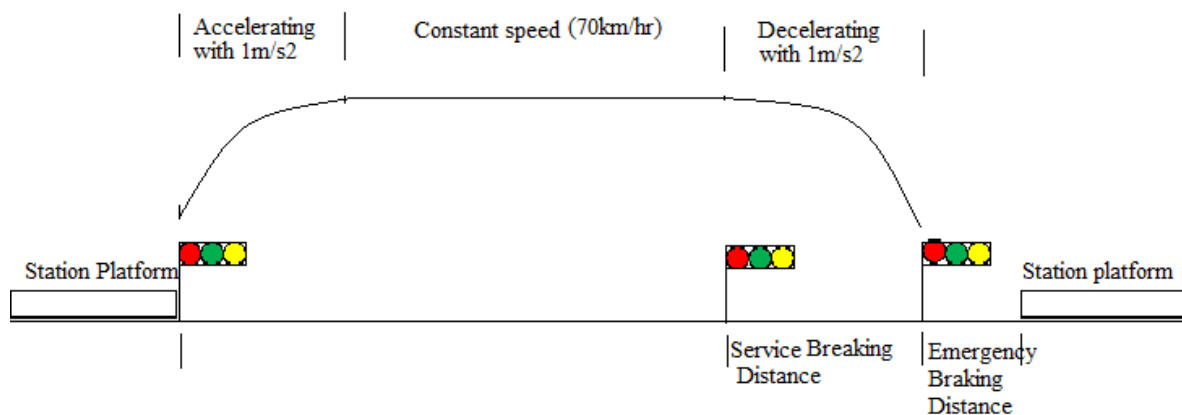


Figure 2.3 Speed profile and wayside signals

The provision of the equipment between two station is done as follows.

The first 3-aspect signal placed as exit signal at the end of the station. The signal will be set up at the emergency braking distance before the next track circuit. And the emergency braking distance is calculated as

$$S_{eb} = \frac{u^2 - v^2}{2d} \quad 2.19$$

Where, u^2 = Final speed (0km/hr)

v^2 = Approaching speed (70km/hr = 20m/s²)

d = Emergency deceleration (-1.5m/s²)

$$S_{eb} = \frac{0^2 - 20^2}{2 \times (-1.5)} = 133m$$

The second 3-aspect signal will be placed at any suitable point greater than service braking distance before the third 3-aspect signal. All service braking distance to the station calculations are shown in Appendix A and the result is available on Table 4.1 and Table 4.2.

The third 3-aspect signal is the home signal. It is placed at the distance of emergency braking distance before the starting of the station.

All track circuits start emergency braking distance ahead of their through signals. If the train will fail to stop at the Red (stop) signal, the emergency braking will prevent it from getting in to the next track circuit.

Equipment provision between station EW2 and EW3 is shown below as example. The rest between station equipment are shown in Appendix B.

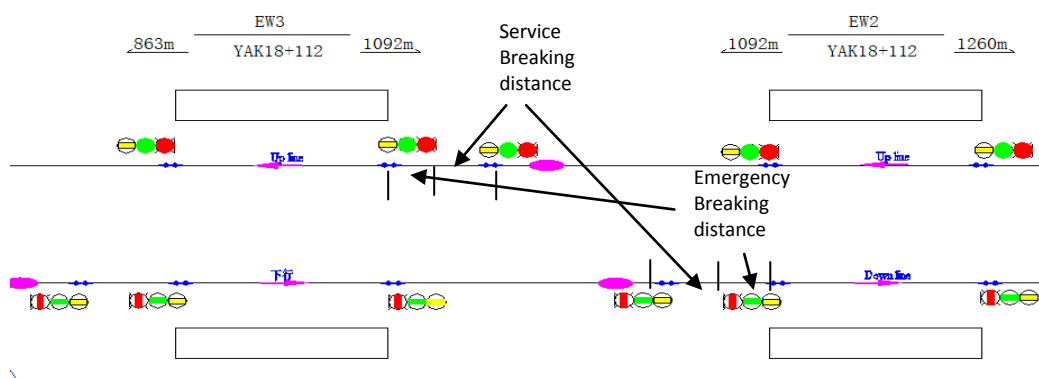


Figure 2.4 Wayside equipment between stations EW3 and EW2

Chapter Three

3 Comparison of Existing and new signaling system

From the result obtained in Chapter 4, the comparison between two systems summarized as follows.

	Existing System	New System	
Station Dwell time	13sec	25sec	45sec
Average Speed	18km/hr	34.4km/hr	27.85km/hr
Operational headway between two trains	6min	2.962min	3.662min
The minimum line headway capacity	45.1sec	-	35.74sec
Time taken to cover the total EW line distance	60min	29.62min	36.62min

Table 3.1 Comparison between the existing and new system

In addition, from other studies the difference between using signaling systems and operate the system without signaling systems based on the following parameters presented bellow.

3.1 Safety

All over the world Railway, transportation is increasingly used, because this mode of transport is more energy efficient and environmentally friendly than road transportation. Trains move on steel rail tracks and wheels of the railway vehicle are also flanged Steel wheels. Hence, least friction occurs at the point of contact between the track & wheels.

Therefore, trains carry more loads resulting in higher traffic capacity since trains move on specific tracks called rails, their path is to be fully guided and there is no arrangement of steering. Clear of obstruction as available with road transportation, so there is a need to provide control on the movement of trains in the form of Railway signals that indicate to the drivers to stop or move and the speed at which they can pass a signal.

Since the load carried by the trains and the speed which the trains can attain are high, they need more braking distance before coming to the stop from full speed. Without signal to be

available on the route to constantly guide the driver, accidents will take place due to collisions.

Signaling systems have a direct impact on safety and quality of service. Any alteration or evolution that is not carefully carried out has immediate consequences on the schedule for the least, as well as on the passengers' integrity for the worst.

There are two purposes achieved by using railway signaling.

1. To safety receive and dispatch trains at a station.
2. To control the movements of trains from one station to another after ensuring that the track on which this train will move to reach the next station is free from movement of another train either in the same or opposite direction. This Control is called block working [18].

3.2 Operational efficiency

Railway signaling plays an important role in determining the capacity of a section [19]. The capacity decides the number of trains that can run on a single day. From result 4.4 it can be seen that by using 3-aspect signaling system the average speed increased from the previous value 18km/hr [1] to 34.4km/hr. Increasing the speed of the train means increasing the line capacity of the system. Thus, by using proper signaling, the capacity of AA LRT can be increased to a considerable extent without resorting to overpriced alternatives [19].

The simulation figures indicate that the line capacity can be increased by from 10% to 30% after ETCS application in comparison with the existing line without ETCS [15]. Accordingly, using any of the CTCS levels, such as CTCS level 0, can improve the line capacity and the operational efficiency as well.

3.3 Cost

As far as reducing the cost of signaling systems and installations is being addressed, this may lead to the statement that they are too expensive. It seems useful to understand why this opinion is so largely widespread. First of all, signaling systems and installations must not be considered only as a spending. Signaling Systems and Installations contribute significantly to the reduction of the maintenance and operating costs [8].

The modern signaling systems or installations are without any doubt more expensive than in the past. They are more complex. Their validation process is far more complicated and

formal. Their lifetime is shorter. But their performance in terms of functionalities RAMS and flexibility is far ahead and has nothing to do with existing ones.

Nobody knew and perhaps up to now knows the exact development cost of existing signaling systems and the exact construction cost of existing installations. The comparison with the past is therefore quite subjective. Furthermore, there are unfortunately many examples of projects, which did not respect their initial budget and this is well known and more or less accepted. This point has a very negative effect on the perception of signaling field by top management or financial decision-makers [8].

3.4 Energy consumption

The analysis of energy costs in relation to income has a weakness, given that the unit income generated by each traffic unit (passenger-km) varies significantly according to each type of traffic. In urban services (20 km/h) the energy consumption is approximately 30% more than on intercity routes with average speeds of around 70 km/h [7]. Even though, the energy consumption of the train increases, income per traffic unit rises sharply when the average speed increases [7]. Even though this inducer (income per passenger-km) offers an example of the passengers' willingness to pay for an increase in the average speed of the trains (even if they had to pay more for an increase in energy consumption), it is true that from the technical point of view, the amount of energy consumed per passenger-km seems more important than energy costs as a percentage of total income.

3.5 Customers satisfaction

In the existing system the headway between two consecutive trains is 6min [1], which means passengers should have wait for 6min in order to take the next train. But if the system uses 3-aspects signaling system the headway will decrease to 3.66min as calculated in result 4.4 and the time in which the passengers will wait to take the next train decreased by 39%.

Not only that, but also the duration of time which takes to travel from one place to the other decreased with significant amount. For example, to cover the total length of EW line, which has 16.998km length, needs 1hr in existing system [1]. But with 3-aspects signaling system it will reduce to 36.6min as calculated in result 4.4. Thus, the passengers can travel faster than the existing system.

Chapter Four

4. Results and Discussions

4.1 Braking distance of EW and NS line to the stations

Calculations:

Train's parameters

Average deceleration for braking: from 70km/h to stop [1];

- 1) The average deceleration of normal braking with rated load (including control response time): $=1.0\text{m/s}^2$
- 2) The average deceleration of emergent braking with rated load (including control response time): $=1.5\text{m/s}^2$

Braking delay time = included in deceleration

Maximum speed = 70km/hr

Other parameters

Acceleration due to gravity = 9.8ms^{-2}

Gradient = variable

Calculation Assumptions:

The method of calculation assumes the following:-

- Gravitational acceleration is 9.8ms^{-2} for the entire AA LRT network.
- The mass of the train is uniformly distributed throughout the length of the train i.e. the center of mass is longitudinally in the center of the train.
- The braking coefficient is not a function of speed and is a constant for a specific train type.
- For the period of the brake delay, there is no "acceleration" force from either gravity or the train's brake acting on the train, and after this time has elapsed there is full train braking force applied.
- Retardation due to track curvature and viscous drag can be ignored.

By using Equation 2.3 and line gradient profile information from Addis Ababa LRT design the following result is obtained to each station of EW and NS line. Each braking distance includes compensation allowance of 20% [6] for the driver reaction time and others variable factors.

East to West line-1 Breaking distances to the stations in meters			West to East line-2 Breaking distances to the stations in meters		
To the station	With out compensation allowance	With compensation allowance	To the station	With out compensation allowance	With compensation allowance
EW1	Starting Station	0	EW22	Starting Station	0
EW2	175.66	210.792	EW21	189	226.8
EW3	190.3	228.36	EW20	210.3	252.36
EW4	159.38	191.256	EW19	182.05	218.46
EW5	181.73	218.076	EW18	192.8	231.36
EW6	224.22	269.064	EW17	221.2	265.44
EW7	221	265.2	EW16	229	274.8
EW8	209.6	251.52	EW15	227.52	273.024
EW9	221.73	266.076	EW14	283.54	340.248
EW10	173.01	207.612	EW13	175.13	210.156
EW11	258.65	310.38	EW12	157.42	188.904
EW12	223.53	268.236	EW11	162.5	195
EW13	218.58	262.296	EW10	200.24	240.288
EW14	189.33	227.196	EW9	181.05	217.26
EW15	180	216	EW8	206.32	247.584
EW16	192	230.4	EW7	253.78	304.536
EW17	156.3	187.56	EW6	166.18	199.416
EW18	195.33	234.396	EW5	218.5	262.2
EW19	234.31	281.172	EW4	264.4	317.28
EW20	151.67	182.004	EW3	213.83	256.596
EW21	220.63	264.756	EW2	177.3	212.76
EW22	187.34	224.808	EW1	184.54	221.448

Table 4.1 Breaking distance to the stations of EW line

South to North line-1 Breaking distances to the stations in meters			North to South line-2 Breaking distances to the stations in meters		
To the station	With out compensation allowance	With compensation allowance	To the station	With out compensation allowance	With compensation allowance
NS6	Starting Station	0	NS27	Starting Station	0
NS7	171	205.2	NS26	214.62	257.544
NS8	158.2	189.84	NS25	170.87	205.044
NS9	149.56	179.472	NS24	150.5	180.6
NS10	134.2	161.04	NS23	343.37	412.044
NS11	217.48	260.976	NS22	364.36	437.232
NS12	291.79	350.148	NS21	325.73	390.876
NS13	161.68	194.016	NS20	210.3	252.36
NS14	145.14	174.168	NS19	152.7	183.24
NS15	236.36	283.632	NS18	193	231.6
NS16	192.6	231.12	NS17	229.46	275.352
NS17	158	189.6	NS16	225.84	271.008
NS18	194.55	233.46	NS15	199.44	239.328
NS19	234	280.8	NS14	268.8	322.56
NS20	152.23	182.676	NS13	254	304.8
NS21	184	220.8	NS12	241.8	290.16
NS22	151	181.2	NS11	316.46	379.752
NS23	150	180	NS10	334.5	401.4
NS24	164.3	197.16	NS9	319.56	383.472
NS25	257.8	309.36	NS8	249.62	299.544
NS26	168.83	202.596	NS7	227	272.4
NS27	165.14	198.168	NS6	240	288

Table 4.2 Breaking distance to the stations of NS line

4.2 Speed Restrictions

The maximum curve radius for the maximum speed (70km/hr) is calculated using Equation 2.4 as follows assuming [17]

$e = 0$ (for the worst case of construction design) and

$f = 0.13$

$$R = \frac{V_{sl}^2}{87 \times 0.13} = 433m$$

Therefore, all curve speed restrictions below radius 433m is shown below on the following table.

East West Track locations, between stations	Curve radius (m)	Speed limit (km/hr)	Comment
EW22 – EW21	190	46.4	
	236	51.67	
EW19 – EW18	200	47.56	Above speed profile
EW18 – EW17	200	47.56	Above speed profile
EW17 – EW16	254	53.6	Above speed profile
EW15 – EW14	400	67.3	Above speed profile
EW14 – EW13	350	62.92	

Table 4.3 Speed limits on curves of EW line

North - South Track locations, between stations	Curve radius (m)	Speed limit (km/hr)	Comment
NS27 – NS26	300	58.25	
	65	27.1	
	300	58.25	
	404	67.6	
NS26 – NS25	354	63.3	
NS25 – NS24	300	58.25	
NS24 – NS23	50	23.78	
NS22 – NS21	100	33.63	
	100	33.63	
NS21 – NS20	50	23.78	
NS19 – NS18	200	47.56	
NS18 – NS17	204	48.03	
NS17 – NS16	254	53.6	
NS16 – NS15	300	58.25	

	50	23.78	
NS14 – NS13	286	56.87	
	350	62.92	
NS13 – NS12	294	57.66	
	236	51.66	
NS12 – NS11	200	47.56	
	350	62.92	
	350	62.92	
	300	28.25	
NS11 – NS10	352	63.1	
NS10 – NS9	375	65.12	
NS8 – NS7	232	51.22	
NS7 – NS6	146	40.64	
	146	40.64	

Table 4.4 Speed limits on curves of NS line

4.3 Headway calculation

The following considerations are taken to calculate headway between two trains:

- ✓ Train load effect on braking distance is ignored
- ✓ Weather condition that affects the coefficient of friction between train wheel and track is neglected.
- ✓ In an open line sections wind effect is not considered.
- ✓ On braking distance calculations deceleration from maximum speed to zero is taken as constant but it changed as the initial acceleration, approximately linearly, then approximately exponentially until it is zero.
- ✓ Voltage fluctuations as the acceleration of a train is approximately proportional to the power applied to the motors

By using Equation 2.18 and considering the above conditions the result of line headway with different speed of the train is given below.

Speed(km/hr)	Time to travel length (sec)	Time to brake (sec)	Over-speed acceleration Time (sec)	Over speed time (sec)	Jerk allowance (sec)	Line headway
10	72.00	2.7	0.4	3	0.5	78.61
20	36.00	5.41	0.2	3	0.5	45.10
30	24.00	8.11	0.13	3	0.5	35.74
40	18.00	10.81	0.09	3	0.5	32.40
50	14.40	13.51	0.07	3	0.5	31.49
60	12.00	16.22	0.06	3	0.5	31.78
70	10.29	18.92	0.05	3	0.5	32.75
80	9.00	21.62	0.04	3	0.5	34.16
90	8.00	24.33	0.03	3	0.5	35.86
100	7.2	27.03	0.03	3	0.5	37.76

Table 4.5 Headway time for different speed operations

The results of solving Equation 2.18 for minimum headway in Table 4.5 show a distinct optimum approach speed for fixed-block systems. The above calculations do not take into account any speed restriction in the station approach. Reference to the result of line headway shows a rapid fall off in throughput as the approach speed decreases and at 50km/hr maximum line headway time achieved.

4.4 Speed Profile and Average operating Speed

Speed profile of LRT train between EW22 and EW21 is given below as an illustration, and the rest is listed on Appendix C.

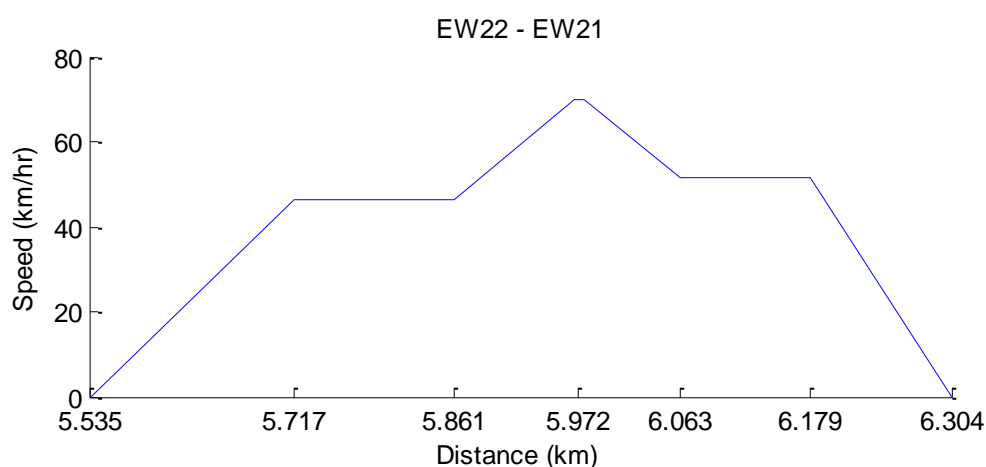


Figure 4.1 Speed profile of the track section between EW22 and EW21

The time taken between two positions considering track profile and speed limits is calculated as follows.

Distance (km)	Time(sec)
5.535 – 5.717	28.24
5.717 – 5.861	11.17
5.861 – 5.967	4.62
5.967 – 5.977	0.5
5.977 – 6.063	7.35
6.063 – 6.179	5.8
6.179 – 6.304	13.62
Station to Station	71.3
Dwell time	45
Total	116.3

Table 4.6 The time taken for the train from Station EW22 to EW21

Likewise all station to station time is calculated and the result is given below as follows

Station to Station distance	Profile time duration + dwell time
EW21 – EW20	$60.22 + 45 = 105.22$
EW20 – EW19	$54.094 + 45 = 99.094$
EW19 – EW18	$55.4 + 45 = 100.4$
EW18 – EW17	$49.12 + 45 = 94.12$
EW17 – EW16	$40.97 + 45 = 85.97$
EW16 – EW15	$38.36 + 45 = 83.36$
EW15 – EW14	$40.75 + 45 = 85.75$
EW14 – EW13	$58.74 + 45 = 103.74$
EW13 – EW12	$67.09 + 45 = 112.09$
EW12 – EW11	$59.08 + 45 = 104.08$
EW11 – EW10	$58.92 + 45 = 103.92$
EW10 – EW9	$58.3 + 45 = 103.3$
EW9 – EW8	$66.57 + 45 = 111.57$
EW8 – EW7	$74.36 + 45 = 119.36$
EW7 – EW6	$62.2 + 45 = 107.2$
EW6 – EW5	$55.41 + 45 = 100.41$
EW5 – EW4	$64.09 + 45 = 109.09$
EW4 – EW3	$60.33 + 45 = 105.33$
EW3 – EW2	$73.54 + 45 = 118.54$
EW2 – EW1	$83.19 + 45 = 128.19$

Table 4.7 Time taken for the train to travel between stations

Thus the total time taken by the train from station EW22 to station EW1 is 2197.04 seconds. That is equal to 36.62 minutes.

Therefore, the average speed on this line can be stated as:

$$V_{av} = \frac{S_{tot}}{t_{tot}} ;$$

Where, V_{av} = Average speed of the line

S_{tot} = Total distance of the line

T_{tot} = Total time to travel the total distance

EW line has a total length of 16.998km and the total time taken to cover this distance is found as 2197.04 sec.

Thus, the average speed of the line is

$$V_{av} = \frac{16998m}{2197.04sec} = 7.77m/s = 27.85 \text{ km/hr}$$

For 25min dwell time, this result increased to

$$V_{av} = \frac{16998m}{1777.04sec} = 9.57m/s = 34.4km/hr$$

The peak hour operational headway between two consecutive trains will be calculated as

The number of trains on the line = 10 trains

The total time to cover the line distance = 36.62min (for 45sec dwell time)

= 29.62min (for 25sec dwell time)

Headway between trains = $36.62/10 = 3.662$ min (for 45sec dwell time)

= $29.62/10 = 2.962$ min (for 25sec dwell time)

Chapter Five

5. Conclusions and Recommendation

5.1 Conclusions

By implementing three aspects signaling system throughout Addis Ababa LRT system we can get the following merits compared with the existing design

- ✓ The minimum line headway capacity improved from 45.1 sec to 35.74 sec.
- ✓ The average speed improved from 18km/hr to 27km/hr.
- ✓ The peak hour headway between each 20 trains improved from 6min to 3.662min based on preliminary design documents.

Each train took $36.62\text{min} \times 2 = 73.24 \text{ min} = 1\text{hr and } 13.24\text{sec}$ to complete one cycle. If 20 trains share this duration, the time between two consecutive trains becomes $73.24/20 = 3.662\text{min}$. This result is much better than the existing design whose headway time between trains is 6min.

If the dwell time of the station is taken as 25min, then the headway time between the trains will be more improved to 2.97min.

- ✓ Passengers from a given station in an hour

$1\text{hr}/3.662\text{min} = 60\text{min}/3.662\text{min} = 16.38 = 16\text{trains}$ are available

Thus, in an hour $250 \times 16 = 4000\text{passengers}$ will be served which higher than the existing service given as $1\text{hr}/6\text{min} = 60\text{min}/6\text{min} = 10\text{trains}$ available and $250 \times 10 = 2500$ passengers will be served.

For 25min dwell time it is increased to 5000 passengers/hour

5.2 Recommendation

This thesis work is mainly considered speed profile of the operation and the other factors are not included to get results.

The following areas are not covered in this thesis.

- To calculate speed profile the only constraint was gradient of the line, the other factors such as wind drag force and other resistances are not considered.
- The impact of three aspects signaling system in central train control system and its equipment compared with the existing signaling design.
- Reliability calculations such as MTBF (Mean Time Between Failures) of wayside and onboard equipment.
- Cost analysis of the system due to installation, maintenance and operating costs are not included.

Bibliography

- [1] Z. Tao, D. Hong, L. Hongxu “*Addis Ababa E-W and N-S (Phase I) Light Rail Transit Project Preliminary Design*,” China Railway Group Limited, June 2013, Vol. 1, Chapter 15
- [2] Y.K. Kim, Y.S. Song, S. Oh “*Study on the Plan of the KRTCS technology development unrelated to Speed and Operational Environment*,” Korea Railroad Research Institute, pp. 218
- [3] AECOM, “*LRT Design Guidelines for ETS Edmonton Transit System*,” The City of Edmonton, July 2011, pp. 7.1 - 7.31
- [4] European Committee for Electro-technical Standardization, “*Railway application – Communication, signaling and processing systems – Safety related electronic systems for signaling (EN 50129)*,” European Standard, May 2010
- [5] Dr. Alan F. Rumsey, “*What can signaling do to enhance rail operations?*,” IRSE International Technical Committee, September 20, 2009, p.p. 1-4
- [6] David Barney, David Haley and George Nikandros; “*Calculating Train Braking Distance*,” Signal and Operational Systems Queensland Rail, Queensland, Australia
- [7] Alberto Garcia, “*High speed, energy consumption and emissions*,” International Union of Railways , 21 December 2010, p.p. 15-18
- [8] Christian Sevestre, “*Reduction in cost of signaling*,” International Technical Committee, p.p. 2-3
- [9] “*RTD Light Rail Design Criteria*,” Regional transportation District, March 2013, Chapter 8.
- [10] “*TRIMET Design Criteria Revision 10.0*,” Tri-County Metropolitan Transportation District of Oregon, Portland, Oregon, January 2010.
- [11] “*Utah Transit Authority Light Rail Design Criteria*,” Utah Transit Authority, Chapter 13, Signal System, November 2007
- [12] B. Ning, “*Advanced Train Control System*,” WIT press publishes leading books in Science and Technology, Southampton, 2010
- [13] “*ETCS System Description*,” Railway Group Guidance Note, Issue One, February 2010
- [14] Sajed K. Abed, “*European Rail Traffic Management System – An Overview*,” DeltaRail Group Limited, Iraq J. Electrical and Electronic Engineering, Vol. 6 No. 2, 2010

- [15] W. Allison, G. Yarrow, “*Engineering Standard Signals, Signaling Design Principles,*” NSW Transport Rail Corp. Version 1.32, Issued 7, June 2013
- [16] “*Railway Signal and Traffic Control Systems Standards,*” Railway Association of Canada, Revised June 4, 2007
- [17] AUER, J.H., “*Rail-Transit People-Mover Headway Comparison,*” IEEE Transactions on Vehicular Technology, Institute of Electrical and Electronics Engineers, 1974
- [18] “*Automatic Train Control Technology,*” Battele Columbus Laboratories in support of the OTA study.
- [19] T. Takashige, “*Signaling Systems for Safe Railway Transport,*” Railway Technology Today 8
- [20] “*Principles of Train Working and Need for Signaling,*” Handbook on basic concepts of railway signaling.

Appendix A: Braking Distance Calculations

Braking distance calculations of EW line using equation 2.3

Between EW22 and EW21

-To station EW21

$$U_{189} = \sqrt{2 \times 189 \times \left(1 + 9.8 \times \frac{0.85}{100}\right)}$$

$$U_{189} = 20.23 \text{ m/s}$$

Therefore, BD = 189m

-To station EW22

$$U_{144.5} = \sqrt{2 \times 144.5 \times \left(1 + 9.8 \times \frac{0.45}{100}\right)}$$

$$U_{144.5} = 17.37 \text{ m/s}$$

$$S = \frac{(17.37)^2 - 20^2}{-2\left(1 + 9.8 \times \frac{1.5}{100}\right)} = 42.8 \text{ m}$$

$$\text{BD} = 144.5 + 42.8 = 187.34 \text{ m}$$

Between EW21 and EW20

-To station EW20

$$S = \frac{0^2 - 20^2}{-2\left(1 - 9.8 \times \frac{0.5}{100}\right)} = 210.3 \text{ m}$$

$$\text{BD} = 210.3 \text{ m}$$

-To station EW21

$$U_{65} = \sqrt{2 \times 65 \times \left(1 - 9.8 \times \frac{0.85}{100}\right)} = 10.92 \text{ m/s}$$

$$S = \frac{(10.92)^2 - 20^2}{-2\left(1 - 9.8 \times \frac{5.5}{100}\right)} = 304.5 \text{ m}$$

$$\text{BD} = 304.5 + 65 = 369.5 \text{ m}$$

Between EW20 and EW19

-To station EW20

$$U_{68.5} = \sqrt{2 \times 68.5 \times \left(1 + 9.8 \times \frac{0.5}{100}\right)} = 12 \text{ m/s}$$

$$S = \frac{(12)^2 - 20^2}{-2\left(1 + 9.8 \times \frac{5.5}{100}\right)} = 83.17 \text{ m}$$

$$\text{BD} = 68.5 + 83.17 = 151.67 \text{ m}$$

-To station EW19

$$U_{55} = \sqrt{2 \times 55 \times \left(1 + 9.8 \times \frac{1}{100}\right)} = 11 \text{ m/s}$$

$$S = \frac{(11)^2 - 20^2}{-2\left(1 + 9.8 \times \frac{4.6}{100}\right)} = 97.15 \text{ m}$$

$$\text{BD} = 97.15 + 55 = 152.15 \text{ m}$$

Between stations EW19 and EW18

-To station EW19

$$U_{50} = \sqrt{2 \times 50 \times \left(1 - 9.8 \times \frac{1}{100}\right)} = 9.49 \text{ m/s}$$

$$S = \frac{(9.49)^2 - 20^2}{-2\left(1 - 9.8 \times \frac{1.61}{100}\right)} = 184.31 \text{ m}$$

$$\text{BD} = 50 + 184.31 = 234.31 \text{ m}$$

-To station EW18

$$U_{79.43} = \sqrt{2 \times 79.43 \times (1 - 9.8 \times \frac{0.2}{100})} = 12.47m/s$$

$$S = \frac{(12.47)^2 - 20^2}{-2(1 + 9.8 \times \frac{0.8}{100})} = 113.36m$$

$$BD = 79.43 + 113.36 = 192.8$$

Between EW18 and EW17

-To station EW18

$$U_{186.6} = \sqrt{2 \times 186.6 \times (1 + 9.8 \times \frac{0.2}{100})} = 19.49m/s$$

$$S = \frac{(19.49)^2 - 20^2}{-2(1 + 9.8 \times \frac{1.9}{100})} = 195.33m$$

$$BD = 186.6 + 8.729 = 195.33m$$

-To station EW17

$$U_{45} = \sqrt{2 \times 45 \times (1 - 9.8 \times \frac{0.4}{100})} = 9.3m/s$$

$$U_{87} = \sqrt{(9.3)^2 + 2 \times 87 \times (1 - 9.8 \times \frac{1.12}{100})} = 15.53m/s$$

$$S = \frac{(15.53)^2 - 20^2}{-2(1 - 9.8 \times \frac{1.9}{100})} = 97.58m$$

$$BD = 45 + 87 + 97.58 = 229.6m$$

Between EW17 – EW16

-To EW17

$$U_{65} = \sqrt{2 \times 65 \times (1 + 9.8 \times \frac{0.4}{100})} = 11.62m/s$$

$$S = \frac{(11.62)^2 - 20^2}{-2(1 + 9.8 \times \frac{4.6}{100})} = 91.3m$$

$$BD = 65 + 91.3 = 156.3m$$

-To EW16

$$U_{40} = \sqrt{2 \times 40 \times (1 - 9.8 \times \frac{0.2}{100})} = 8.86m/s$$

$$U_{171} = \sqrt{(8.86)^2 + 2 \times 171 \times (1 - 9.8 \times \frac{1.2}{100})}$$

$$= 19.5m/s$$

$$S = \frac{(19.5)^2 - 20^2}{-2(1 - 9.8 \times \frac{4.6}{100})} = 18m$$

$$BD = 40 + 171 + 18 = 229m$$

Between EW16 and EW15

-To EW16

$$U_{157} = \sqrt{2 \times 157 \times (1 + 9.8 \times \frac{0.2}{100})} = 17.9m/s$$

$$S = \frac{(17.9)^2 - 20^2}{-2(1 + 9.8 \times \frac{1.4}{100})} = 35m$$

$$BD = 157 + 35 = 192m$$

-To EW15

$$U_{64} = \sqrt{2 \times 64 \times (1 + 9.8 \times \frac{0}{100})} = 11.3m/s$$

$$S = \frac{(11.3)^2 - 20^2}{-2(1 + 9.8 \times \frac{1.8}{100})} = 115.7m$$

$$BD = 64 + 115.7 = 179.74m$$

Between EW15 and EW14

-To station EW15

$$U_{136} = \sqrt{2 \times 136 \times (1 + 9.8 \times \frac{0}{100})} = 16.5m/s$$

$$S = \frac{(16.5)^2 - 20^2}{-2(1 + 9.8 \times \frac{4.6}{100})} = 44.1m$$

$$BD = 136 + 44.11 = 180.11$$

-To station EW14

$$U_{91} = \sqrt{2 \times 91 \times (1 + 9.8 \times \frac{1}{100})} = 14.14m/s$$

$$S = \frac{(14.14)^2 - 20^2}{-2(1 - 9.8 \times \frac{4.9}{100})} = 192.54m$$

$$BD = 91 + 192.54 = 283.54m$$

Between EW14 and EW13

-To EW14

$$U_{55} = \sqrt{2 \times 55 \times (1 - 9.8 \times \frac{1}{100})} = 9.96m/s$$

$$S = \frac{(9.96)^2 - 20^2}{-2(1 + 9.8 \times \frac{1.22}{100})} = 134.33m$$

$$BD = 55 + 134.33 = 189.33m$$

-To EW13

$$U_{133.3} = \sqrt{2 \times 133.3 \times (1 + 9.8 \times \frac{0.9}{100})} = 17.03m/s$$

$$S = \frac{(17.03)^2 - 20^2}{-2(1 + 9.8 \times \frac{3.2}{100})} = 41.83m$$

$$BD = 133.3 + 41.83 = 175.13m$$

Between EW13 and EW12

-To EW13

$$U_{197.8} = \sqrt{2 \times 197.8 \times (1 - 9.8 \times \frac{0.9}{100})} = 18.95m/s$$

$$S = \frac{(18.95)^2 - 20^2}{-2(1 + 9.8 \times \frac{0.2}{100})} = 20.78m$$

$$BD = 197.8 + 20.78 = 218.58m$$

-To EW12

$$U_{42} = \sqrt{2 \times 42 \times (1 + 9.8 \times \frac{1}{100})} = 9.6m/s$$

$$S = \frac{(9.6)^2 - 20^2}{-2(1 + 9.8 \times \frac{3.4}{100})} = 115.42m$$

$$BD = 42 + 115.42 = 157.42m$$

Between EW12 and EW11

-To EW12

$$U_{58} = \sqrt{2 \times 58 \times (1 - 9.8 \times \frac{1}{100})} = 10.23m/s$$

$$S = \frac{(10.23)^2 - 20^2}{-2(1 - 9.8 \times \frac{1.1}{100})} = 165.5m$$

$$BD = 58 + 165.5 = 223.53m$$

-To EW11

$$U_{56.4} = \sqrt{2 \times 56.4 \times (1 + 9.8 \times \frac{0.2}{100})} = 10.88m/s$$

$$S = \frac{(10.88)^2 - 20^2}{-2(1 + 9.8 \times \frac{3.34}{100})} = 106.12m$$

$$BD = 56.4 + 106.12 = 162.52$$

Between EW11 and EW10

-To EW11

$$U_{56.25} = \sqrt{2 \times 56.25 \times (1 - 9.8 \times \frac{0.2}{100})} = 10.5m/s$$

$$S = \frac{(10.5)^2 - 20^2}{-2(1 - 9.8 \times \frac{2.9}{100})} = 202.39m$$

$$BD = 56.25 + 202.39 = 258.65m$$

-To EW10

$$U_{40} = \sqrt{2 \times 40 \times (1 - 9.8 \times \frac{0.7}{100})} = 8.6m/s$$

$$U_{205} = \sqrt{(9.78)^2 + 2 \times 205 \times (1 + 9.8 \times \frac{4.35}{100})} = 18.19m/s$$

$$U_{124} = \sqrt{(8.6)^2 + 2 \times 124 \times (1 - 9.8 \times \frac{0.4}{100})} = 17.67m/s$$

$$S = \frac{(18.19)^2 - 20^2}{-2(1 - 9.8 \times \frac{4.35}{100})} = 37.51m$$

$$S = \frac{(17.67)^2 - 20^2}{-2(1 + 9.8 \times \frac{2.15}{100})} = 36.24m$$

$$BD = 53 + 205 + 37.51 = 295.51m$$

-To station EW8

$$BD = 40 + 124 + 36.24 = 200.24m$$

Between EW10 and EW9

$$U_{59} = \sqrt{2 \times 59 \times (1 + 9.8 \times \frac{0.2}{100})} = 10.97m/s$$

-To EW10

$$U_{95.63} = \sqrt{(10.97)^2 + 2 \times 59 \times (1 + 9.8 \times \frac{0.2}{100})} = 17.34m/s$$

$$U_{55} = \sqrt{2 \times 55 \times (1 + 9.8 \times \frac{0.7}{100})} = 10.84m/s$$

$$S = \frac{(10.84)^2 - 20^2}{-2(1 + 9.8 \times \frac{2}{100})} = 118.1m$$

$$S = \frac{(17.34)^2 - 20^2}{-2(1 - 9.8 \times \frac{0.4}{100})} = 51.69m$$

$$BD = 55 + 118.1 = 173.01m$$

$$BD = 51.69 + 95.63 + 59 = 206.32m$$

-To EW9

Between EW8 and EW7

$$U_{66.3} = \sqrt{2 \times 66.3 \times (1 + 9.8 \times \frac{1}{100})} = 12.07m/s$$

-To EW8

$$U_{85} = \sqrt{(12.07)^2 + 2 \times 85 \times (1 + 9.8 \times \frac{1.6}{100})} = 18.5m/s$$

$$U_{151} = \sqrt{2 \times 151 \times (1 - 9.8 \times \frac{0.2}{100})} = 17.2m/s$$

$$S = \frac{(18.5)^2 - 20^2}{-2(1 - 9.8 \times \frac{0.3}{100})} = 29.75m$$

$$S = \frac{(17.2)^2 - 20^2}{-2(1 - 9.8 \times \frac{1.16}{100})} = 58.62m$$

$$BD = 66.3 + 85 + 29.75 = 181.05m$$

$$BD = 151 + 58.62 = 209.62$$

Between EW9 and EW8

-To EW9

-To EW7

$$U_{53} = \sqrt{2 \times 53 \times (1 - 9.8 \times \frac{1}{100})} = 9.78m/s$$

$$U_{55} = \sqrt{2 \times 55 \times (1 + 9.8 \times \frac{1}{100})} = 10.99m/s$$

$$U_{75.5} = \sqrt{(10.99)^2 + 2 \times 75.5 \times (1 - 9.8 \times \frac{3.18}{100})} = 14.99m/s$$

$$S = \frac{(14.99)^2 - 20^2}{-2(1 - 9.8 \times \frac{2.95}{100})} = 123.28m$$

$$BD = 55 + 75.5 + 123.28 = 253.78m$$

Between EW7 and EW6

-To EW7

$$U_{112} = \sqrt{2 \times 112 \times (1 - 9.8 \times \frac{1}{100})} = 14.2m/s$$

$$U_{90} = \sqrt{(14.2)^2 + 2 \times 90 \times (1 - 9.8 \times \frac{1.7}{100})}$$

$$= 18.7m/s$$

$$S = \frac{(18.7)^2 - 20^2}{-2(1 + 9.8 \times \frac{3.38}{100})} = 18.9m$$

$$BD = 112 + 90 + 18.9 = 220.9m$$

-To EW6

$$U_{110} = \sqrt{2 \times 110 \times (1 + 9.8 \times \frac{0.4}{100})} = 15.12m/s$$

$$S = \frac{(15.12)^2 - 20^2}{-2(1 + 9.8 \times \frac{5.36}{100})} = 56.18m$$

$$BD = 110 + 56.18 = 166.18m$$

Between EW6 and EW5

-To EW6

$$U_{50} = \sqrt{2 \times 50 \times (1 - 9.8 \times \frac{0.4}{100})} = 9.8m/s$$

$$U_{80.7} = \sqrt{(9.8)^2 + 2 \times 80.7 \times (1 - 9.8 \times \frac{3.28}{100})}$$

$$= 14.34m/s$$

$$S = \frac{(14.34)^2 - 20^2}{-2(1 + 9.8 \times \frac{0.4}{100})} = 93.52m$$

$$BD = 50 + 80.7 + 93.52 = 224.22m$$

-To EW5

$$U_{50} = \sqrt{2 \times 50 \times (1 - 9.8 \times \frac{1}{100})} = 9.5m/s$$

$$U_{75} = \sqrt{(9.5)^2 + 2 \times 75 \times (1 - 9.8 \times \frac{1}{100})}$$

$$= 14.34m/s$$

$$S = \frac{(14.34)^2 - 20^2}{-2(1 + 9.8 \times \frac{0.4}{100})} = 93.5m$$

$$BD = 50 + 75 + 93.5 = 218.5m$$

Between EW5 and EW4

-To EW5

$$U_{46} = \sqrt{2 \times 46 \times (1 + 9.8 \times \frac{1}{100})} = 10.05m/s$$

$$U_{60} = \sqrt{(10.05)^2 + 2 \times 60 \times (1 + 9.8 \times \frac{0.7}{100})}$$

$$= 15.14m/s$$

$$S = \frac{(15.14)^2 - 20^2}{-2(1 + 9.8 \times \frac{1.3}{100})} = 75.73m$$

$$BD = 46 + 60 + 75.73 = 181.73m$$

-To EW4

$$U_{40} = \sqrt{2 \times 40 \times (1 - 9.8 \times \frac{1}{100})} = 8.49m/s$$

$$S = \frac{(8.49)^2 - 20^2}{-2(1 - 9.8 \times \frac{2.75}{100})} = 224.4m$$

$$BD = 40 + 224.4 = 264.4m$$

Between EW4 and EW3

-To EW4

$$U_{48.5} = \sqrt{2 \times 48.5 \times (1 + 9.8 \times \frac{1}{100})} = 10.32m/s$$

$$S = \frac{(10.32)^2 - 20^2}{-2(1 + 9.8 \times \frac{3.3}{100})} = 110.88m$$

$$BD = 48.5 + 110.88 = 159.39m$$

-To EW3

$$U_{43} = \sqrt{2 \times 43 \times (1 - 9.8 \times \frac{0.6}{100})} = 9m/s$$

$$U_{65} = \sqrt{9^2 + 2 \times 65 \times (1 - 9.8 \times \frac{0.6}{100})} = 13.57m/s$$

$$S = \frac{(13.57)^2 - 20^2}{-2(1 + 9.8 \times \frac{0.2}{100})} = 105.83m$$

$$BD = 43 + 65 + 105.83 = 213.83m$$

Between Stations EW3 and EW2

-To EW3

$$U_{140} = \sqrt{2 \times 140 \times (1 + 9.8 \times \frac{0.6}{100})} = 17.2m/s$$

$$S = \frac{(17.2)^2 - 20^2}{-2(1 + 9.8 \times \frac{0.3}{100})} = 50.3m$$

$$BD = 140 + 50.3 = 190.3$$

-To EW2

$$U_{100} = \sqrt{2 \times 100 \times (1 + 9.8 \times \frac{1}{100})} = 14.82m/s$$

$$S = \frac{(14.82)^2 - 20^2}{-2(1 + 9.8 \times \frac{1.7}{100})} = 77.3m$$

$$BD = 100 + 77.3 = 177.3m$$

Between EW2 and EW1

-To EW2

$$U_{105} = \sqrt{2 \times 105 \times (1 - 9.8 \times \frac{1}{100})} = 13.76m/s$$

$$S = \frac{(13.76)^2 - 20^2}{-2(1 + 9.8 \times \frac{5}{100})} = 70.66m$$

$$BD = 105 + 70.66 = 175.66m$$

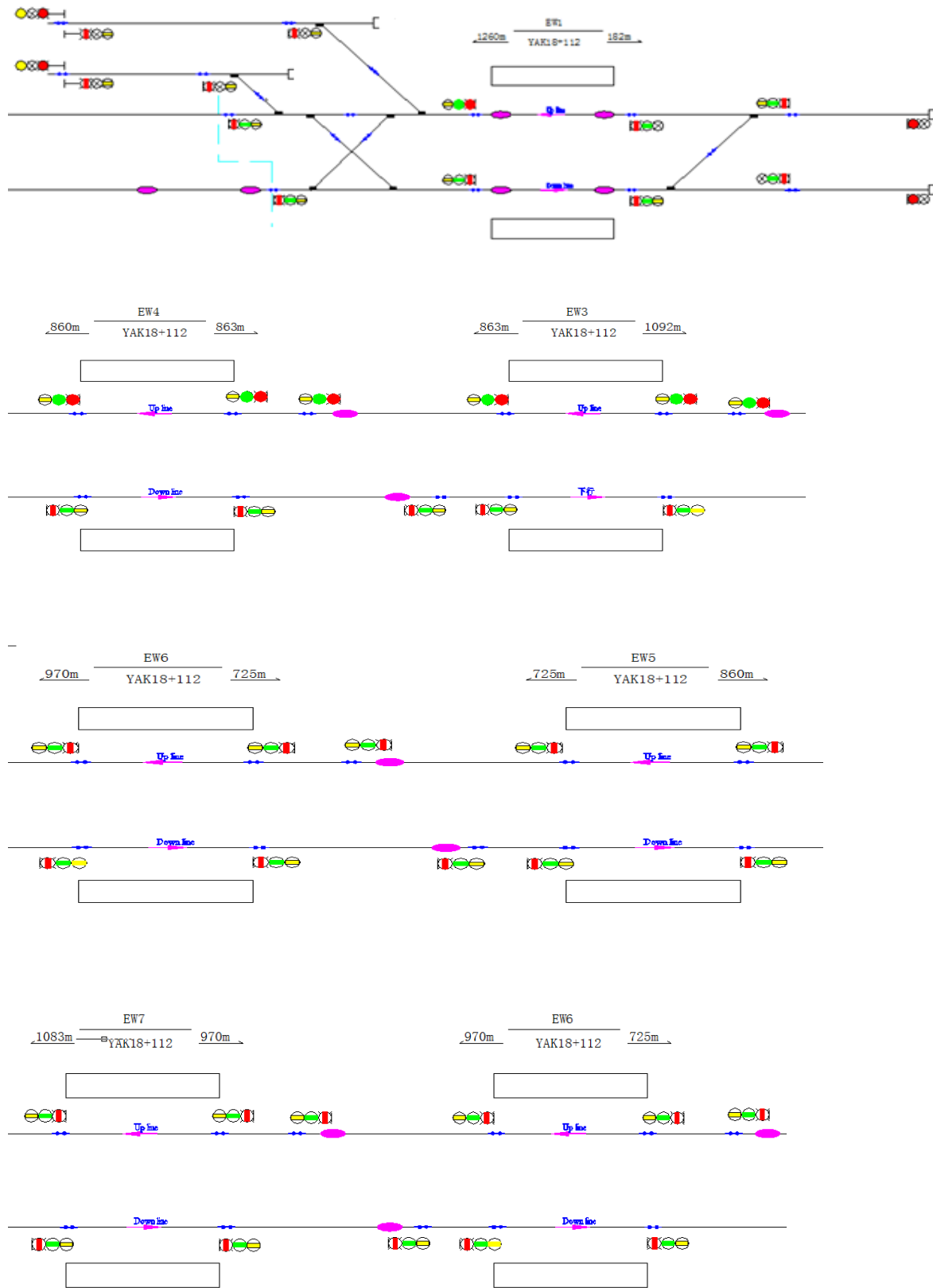
-To EW1

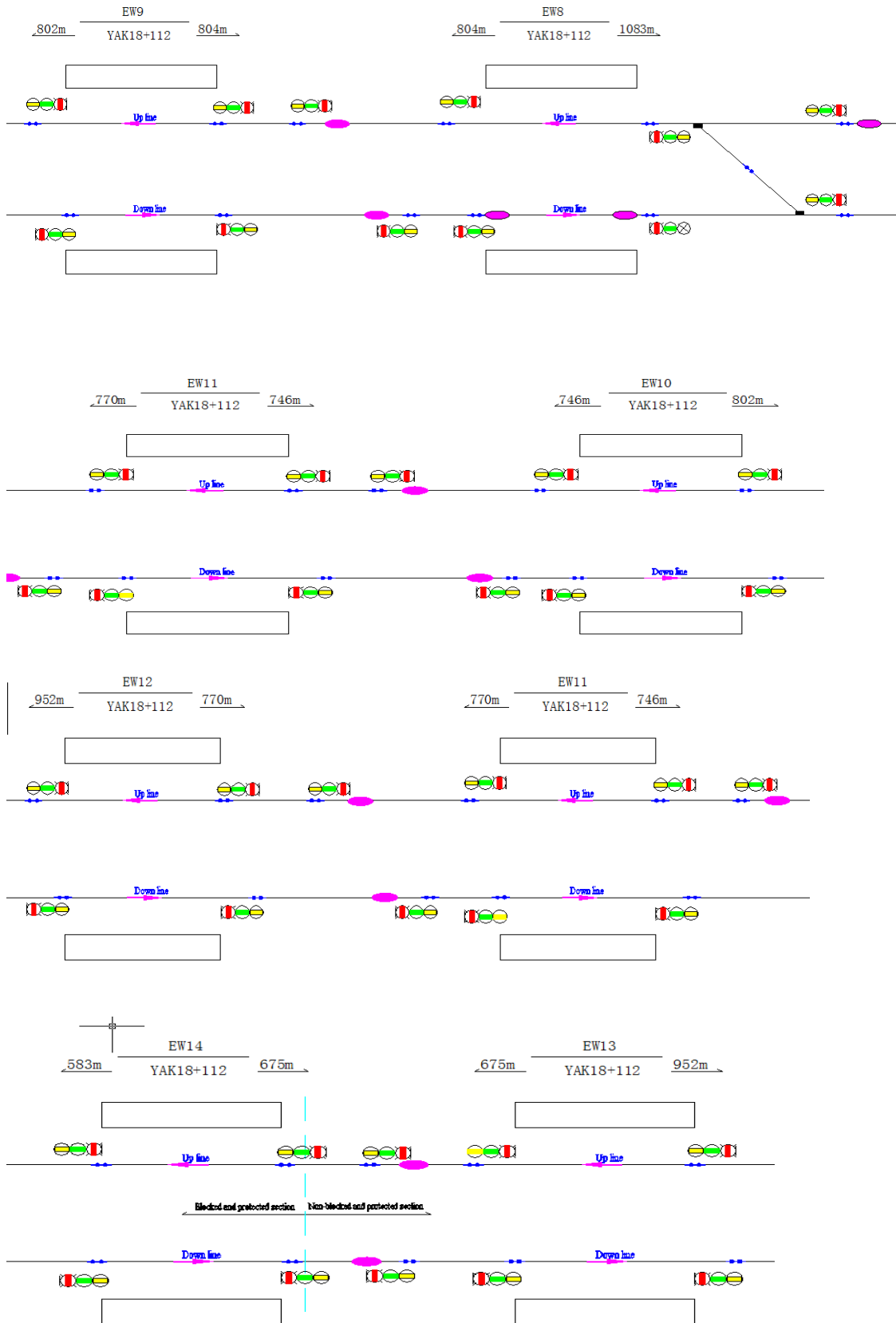
$$U_{170} = \sqrt{2 \times 170 \times (1 + 9.8 \times \frac{0.5}{100})} = 18.88m/s$$

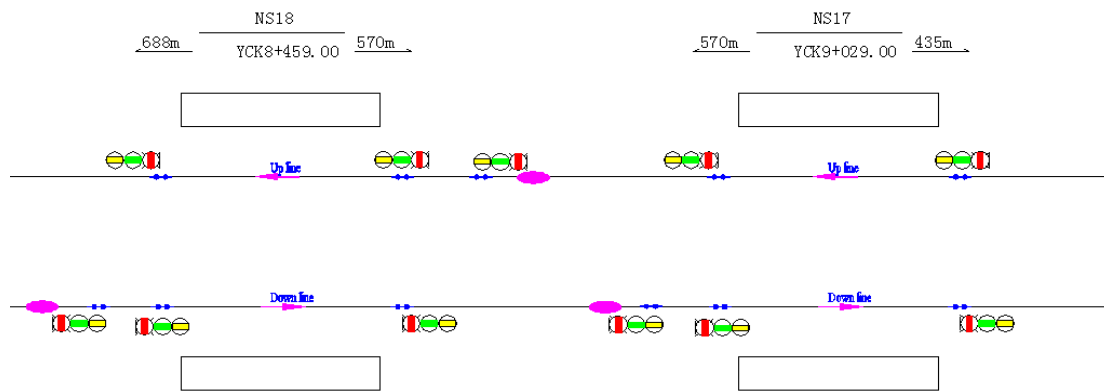
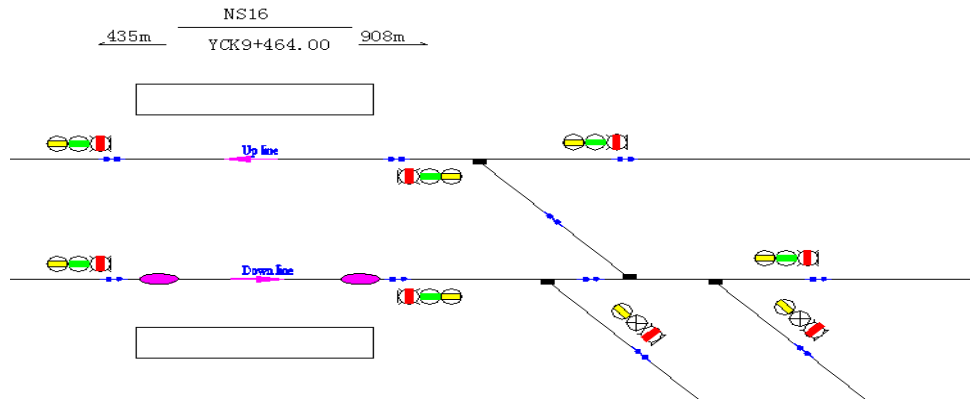
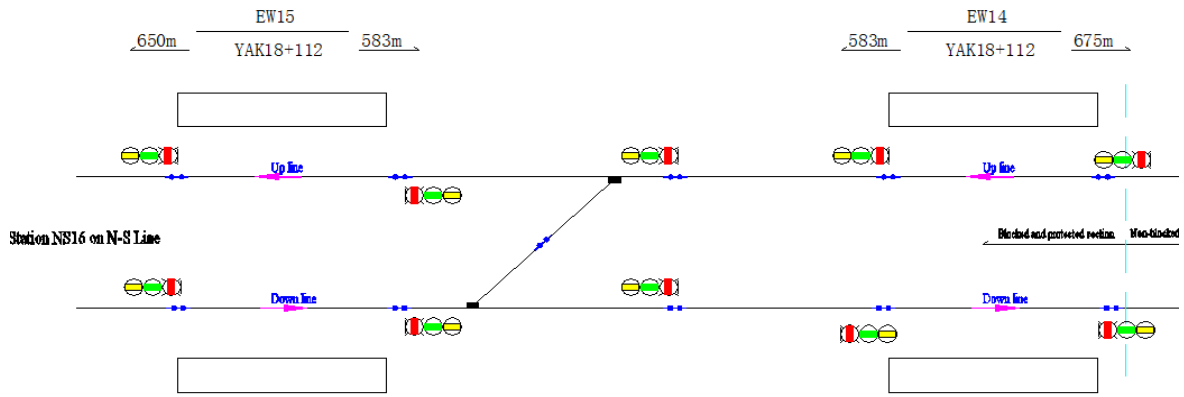
$$S = \frac{(18.88)^2 - 20^2}{-2(1 + 9.8 \times \frac{5}{100})} = 14.54m$$

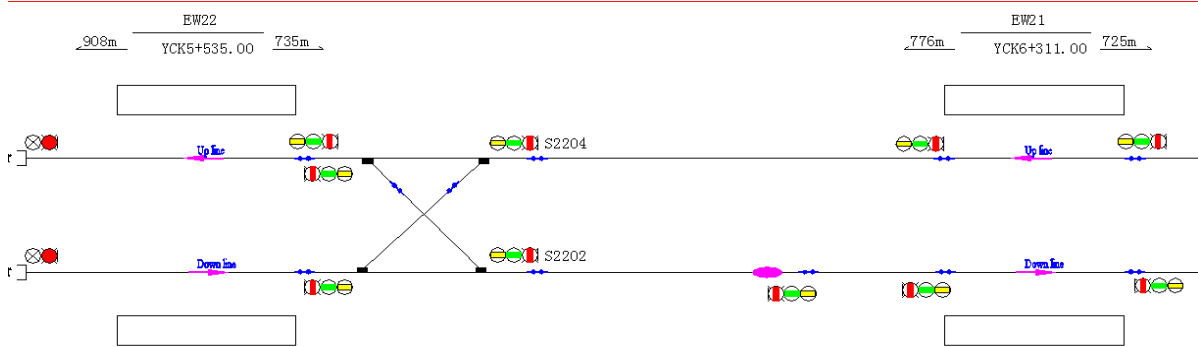
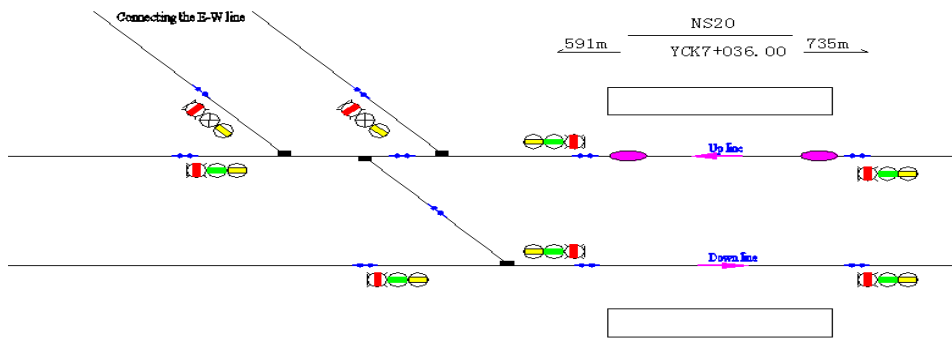
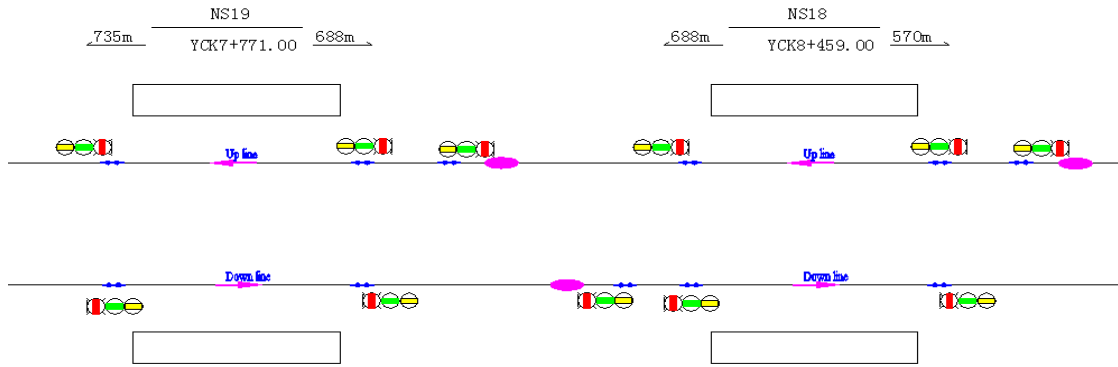
$$BD = 14.54 + 170 = 184.54m$$

Appendix B: provisions of equipment









Appendix C: Speed profile of EW line

