Addis Ababa Institute of Technology
School of Civil and Environmental Engineering

Analytical Methods to Estimate Railway Capacity
A Case study to apply on the Addis Ababa Light Rail Transit Project
(AA -LRT)

A Thesis Submitted to the school of civil and Environmental Engineering of Addis Ababa Institute of Technology, Presented in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Railway Engineering

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Addis Ababa, Ethiopia

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Addis Ababa Institute of Technology

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DECLARATION

I hereby declare that the thesis entitled "**Analytical Methods to Estimate Railway Capacity-A Case study to apply on the Addis Ababa Light Rail Transit Project**" has been carried out by me under the supervision of Dr. Alemayehu Ambo, Institute of Technology, Addis Ababa University, Addis Ababa during the year 2015-2016 for the partial fulfillment of the requirements for the Degree of Master of Science in Civil Railway Engineering. I further declare that this work has not been submitted to any other University or Institution for the award of any degree or diploma.

Amanuel Abreham

Addis Ababa

December, 2015

C E R T I F I C A T E

This is to certify that the thesis entitled "**Analytical Methods to Estimate Railway Capacity-A Case study to apply on the Addis Ababa Light Rail Transit Project**" is an authentic work carried out by Amaneul Abreham under my guidance and supervision. This is the actual work done by Amaneul Abreham for the partial fulfillment of the requirements for the Degree of Master of Science in Civil Railway Engineering from Addis Ababa University, Addis Ababa.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACCRONYMS

LRT:	Light Rail Transit
AALRT:	Addis Ababa Light Rail Transit
CREC:	China Railway Engineering Corporation
ERC:	Ethiopian Railway Corporation
GTP	Growth and Transformation Plan
UIC:	Union internationale Des Chemines (International Union of Railways)
TCRP:	Transit Cooperative Research Program
TCQSM:	Transit Capacity and Quality of Service Manual
TNTR:	Total number of Trains
TRB:	Transport Research Board

ABSTRACT

Public mass transportation systems have become an important part of major economic activities in developing cities. The initial high construction cost of urban rail transportation calls for the efficient utilization of the existing infrastructure and estimation of its maximum capacity. A reliable estimation of railway capacity is a basic condition for allocation of railway resources and has a vital importance in evaluation of existing railway infrastructure. Therefore, it is necessary to develop procedures that reliably estimate the railway capacity using data typically available to planners. This thesis studies method that can be applicable in both planning and detailed design stage in Ethiopian condition depending on the available data .An overview concept of railway capacity and the main parameters affecting railway capacity are presented. A simulation method is a widely used technique in railway planning and operation to generate realistic estimates. Analytical methods of estimation railway capacity provide firsthand information about the capacity at early planning stage when most of the factors shaping up the railway capacity are not known and has also provide a reliable result in detailed design stage when it is applied to a simple rail network system like AALRT. In the detailed design report of AALRT, the procedure used in determination of the capacity is not described and only the output results are provided. Therefore, developed methodologies to analyze, improve and control railway capacity utilization are needed for Ethiopian condition. This thesis presents how to determine the number of trains required for a given passenger volume and headway using analytical method and mainly focuses on methods to calculate the main parameters affecting the capacity of Light rail transit system. Methodologies that describe the procedures to follow in estimation and analysis of railway capacity are developed. Two approaches of estimating railway capacity are presented. The first approach is an economical way of estimating railway capacity based on peak hour passenger volume and the second approach is the estimation of achievable capacity using the maximum throughput of the railway line. The combinations of the two approaches enable planners or designers to estimate the capacity of railway at different values of headway and train controlling systems. Using these two approaches, the proposed capacity of AALRT is evaluated and its maximum achievable capacity is estimated. The computational results at the end shows that the proposed headway of AALRT can be improved by reducing total round trip time of the trains and the proposed excess number of trains can be used to reduce the headway of the operation.

Keywords: Capacity; Dwell time; Simulation, headway

1. INTRODUCTION

1.1. Background

Transportation is a large and an important part of the economy which is a dynamic sector that increases continuously. There are many modes of transport that include: road, air, rail, water, pipeline, cable, etc. Air, road and water are the most dominant modes with rail as the most pioneer in the economic progress of developed countries. Rail transportation has remained as an important segment and source of economic development of many countries of the world. This is because of the railway transport has obvious advantage over other means of transportation in the movement of goods and passengers in large volume/number.

In Ethiopia, the railway transportation started in early 20th century between Addis Ababa, the capital city and the Port of Djibouti located 781 km away at the coast of the Red Sea. The railway was busy at the beginning but declined through time until it finally stopped in early 21st century. However, it slowly revived and is now operating between Diredawa and Djibouti. The Ethiopian Government has formulated an ambitious railway development program (5,000 km) under the GTP. In this regard, it has planned to invest a huge capital on the construction. Currently, the construction of the Addis Ababa Light Rail Transit is progressing and in the verge of completion. In view of the above, the ongoing construction of the railway system calls for a better understanding of its utilization and traffic properties.

Railway is a complex traffic system and efficient utilization of the infrastructure is critical as building line is extremely costly. The efficient utilization requires the service to be fast, frequent, comfortable and reliable. In order to do that, the comprehensive overview of railway capacity needs to be systematically explored and studied. The goal of capacity analysis is to determine the maximum number of trains that would be able to operate on a given railway infrastructure, during a specific time interval, given the operational conditions. The determination and evaluation of a reliable capacity of railway infrastructure is an essential part of railway operations and have vital importance in operation planning. Rail capacity calculation methods and procedures have been proposed in different manuals and by research organizations and are utilized by rail operators and in capacity addition feasibility studies.

The method of calculating railway capacity depends on the stage of the project. For example, at a planning or feasibility stage, information on rail configuration and system should be designed with demand level and economic criteria. Factors shaping up rail capacity, like stations, signaling type, are not decided at planning stage of the project. Those factors are usually decided at a later stage of the project, such as at a preliminary design or detailed design stage. Many studies in railway operation around the world show that estimated capacity at planning and design stage is found to be different.

At operation stage of railway project, the estimation of railway capacity mainly focuses on the efficient use of the infrastructure and requires extensive actual field data on the infrastructure, technical and operational aspects, such as, signaling, and control system. The infrastructure parameters like the types of block and signaling system, type of track structure and speed limit, time table and quality of service can highly affect the capacity of the railway system (Alex L.*et al*, 2006). The type of infrastructure, new or existing, and train mix can be categorized as traffic parameters which need to be considered in analyzing railway capacity. At operation stage, train-stop time which accounts for the time the trains spend stopping on the line and the planned and unplanned events of track interruption for maintenance, commercial stop and due to train failure are main parameters which affects the efficient utilization of railway capacity. (Abril *et al.*, 2008)

As part of various initiatives to develop sustainable transport system of the Addis Ababa city, comprehensive transportation studies done in past suggested development of multimodal transport system. Subsequently, studies were also done to determine suitable public mass transit system technology as per local needs (Lyon, 2012).Based on the recommendations of these studies, the LRT network was thus finalized and is currently under implementation.

The proposed route has a total length of 34.25 km (North-South line 16.9 km and East-West line 17.35 km) including a common-track section of 2.63km. The main section of the East-West Line is nearly 17.410 km long stretching from Ayat Village to Tor Hailoch; passing through Megenagna, Legehar and Mexico areas. Similarly, the main section of the North-South Line is 16.561km long and passes through Menelik Square, Merkato, Lideta, Legehar, Meskel Square, Gotera and terminating at Kaliti area. Figure 1.1 shows the Addis Ababa LRT network.

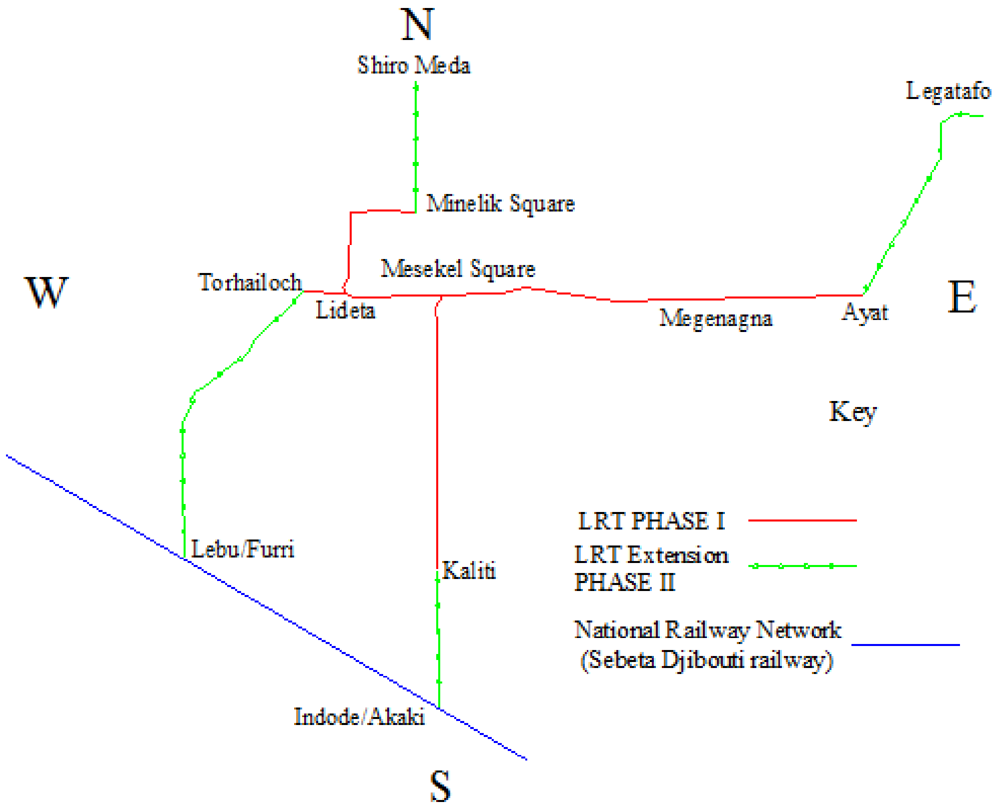

Figure 1.1 Addis Ababa Light Rail Network, Source: ERC Website. (WWW.ERC.gov.et)

At the early planning stage, the railway capacity was estimated to be 80,000 passengers per hour. (ERC, 2011).After the completion of the detailed design, the recent studies show that the capacity is about 60,000 passengers per hour (CREC, 2012)

Railway capacity is not static. It is extremely dependent on how it is used (Abril *et al*, 2008).It varies with changes in infrastructure and operating conditions. In order to maximize the efficiency of the AA LRT line, more reliable capacity calculation analysis and methods should be carried out.

The use of analytic methods and optimization modeling, to inform train planning and project development, has increased in popularity over the last 20 years. It has attained particular prominence over the last decade following the introduction of several integrated simulation packages capable of undertaking timetable development, simulation and analysis of rail operations (SKM, 2012).

The detail study of factors affecting capacity, like infrastructure, traffic and operation, human factors and even external factors such as weather conditions, are necessary to provide a suitable foundation for defining, analyzing and improving railway capacity.(Abril *et al*, 2008)

This study will focus on methods used for estimation of railway capacity in planning and detail design and the result will be used for evaluation of the capacity of the Addis Ababa Light Rail Transit project (AA LRT).

1.2. Objectives and Scope of the Study

1.2.1. General Objective

The main aim of this research is to conduct a comprehensive study on the railway capacity analysis and to develop a methodology of estimating railway capacity for efficient utilization.

1.2.2. Specific Objectives

The specific objectives of this study are to:

- Develop a computational model for transit planners and designers to analyze the capacity and performance of rail transit system in Ethiopia;
- Analyze the capacity of Addis Ababa Light Rail Transit system (AA LRT) using analytical method in planning and detailed design stage; and
- Provide different options to improve the capacity of the Addis Ababa Light rail transit (AA LRT)

1.2.3. Scope

This study is limited to double track railways with passenger stations for light rail transit systems. Different methods of estimating railway capacity are reviewed and those which are applicable within the Ethiopian condition, depending on the available data, are used to estimate and evaluate the capacity of the Addis Ababa Light Rail Transit system. The use of simulation tools which are capable of estimating and evaluating railway capacity is beyond the scope and budget of this research.

This research enables the practitioners to analyze the existing systems and services and plan for new ones using important infrastructural and operational variants. The study focuses on methods used to estimate railway capacity at planning and detail design stages since the operation of AA-LRT has not yet started during the time of this research. However, the developed method can be applicable to analyze the capacity of the existing system when the operation starts.

1.3. Problem Formulation

An efficient utilization of the existing railway infrastructure is an essential component of a high-quality transportation system and has become a central task for management of railway infrastructure.

The expensive initial cost of the ongoing new railway project, Ethiopia is envisaged to focus on an effective way of utilization of the capacity. Capital expansion is a very costly means of increasing capacity. More cost-effective solutions to successfully manage the existing capacity can be done through different analytical and computer-based decision support systems.

Therefore, it is necessary to perform the required capacity studies to develop methods and procedures to reliably estimate railway capacity of a given rail line using data typically available at planning, detailed design and operation stages. This helps to work out what part of extra traffic can be absorbed by the existing infrastructure and how much investment will be required for new infrastructure.

This study will develop railway line capacity calculation procedure within the Ethiopian condition by reviewing different methods of estimating railway capacity at planning stage, which can be utilized by planners, engineers and pertinent professionals at detailed design stage, depending on data availability and resource accessibility. The developed methods and procedures will be used to evaluate the proposed capacity of AALRT project.

In addition, a trial will be made to present different scenarios for increasing the line capacity.

2.0. LITERATURE REVIEW

2.1. Definition of Railway Capacity

The first step in studying and analyzing the efficient utilization of railway infrastructure is to define the term capacity. Although capacity seems to be a self-explanatory term in common language, its scientific use may lead to substantial difficulties when it is associated to objectives and quantifiable measures. It is a complex term that has numerous meanings and for which numerous definitions have been given (Abril *et al*, 2007)

Given the complexity underlying railway capacity, there is no one common and unique definition. Burdett & Kozan (2006) define capacity as "the maximum number of trains that can traverse the entire railway or a certain critical section in a given duration of time". Similarly, Abril et al. (2007) has a similar view and defines capacity as the "maximum number of trains that would be able to operate on a given railway infrastructure, during a specific time interval, given the operational conditions". Furthermore, as Subhro (2013) quoted, Krueger (1999) defines capacity as a measure of the ability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific plan.

The International Union of Railways (UIC, 2004) develops a little further and clarifies that "railway infrastructure capacity depends on the way it is utilized" and the main "basic parameters underpinning capacity are the infrastructure characteristics themselves and these includes the signaling system, the transport schedule and the imposed punctuality level". It finally concludes that "the capacity of any railway infrastructure is the total number of possible paths in a defined time window, considering the actual path mix or known developments respectively and the Infrastructure Manager own assumptions".

Landex (2008) quoted, Barter (2008) states that capacity should be measured according to the punctualities and performance targets. In fact, quality of operations is an important aspect of the capacity definition, since higher number of trains result in higher risk of delays.

Landex (2008) argues that railway capacity depends on the railway infrastructure, on the operating plan (timetable and rolling stock scheduling) and on the operation quality goal.
For the purpose of this study, the capacity definition given by Transit Cooperative Research Program (TCRP) is considered in analyzing and evaluating the capacity of the Addis Ababa Light Rail Transit (AALRT) which stated that:

“Rail capacity can be defined as the maximum number of passenger passes at a single point in an hour, in one direction on a single track” (TCRP**,** 1996**).**

2.2. Types of railway capacity

UIC (2004) defines four types of railway capacities:

- Used /consumed Capacity;
- Unused capacity (the difference between capacity consumption and chosen time window);
- Usable capacity (Unused capacity that can be used for accommodating new train paths); and
- Lost capacity (Unused capacity that cannot be used for accommodating new train paths).

Krueger (1999) categorizes railway capacity into different types and the most important ones are: Theoretical Capacity, Practical Capacity, Used Capacity and Available Capacity.

Theoretical Capacity is the upper limit for line capacity which mathematically determines the maximum number of trains that could run over a route, with the trains running permanently and ideally at minimum headway. Frequently, it assumes that traffic is homogeneous, that all trains are identical, and that trains are evenly spaced throughout the day with no disruptions. It ignores the effects of variations in traffic and operations that occur in reality. Theoretical Capacity is calculated using an empirical formula. This number is relatively easy to generate (it depends on the longest distance between crossing stations for single-track lines or the minimum headway for double-track lines). It is not possible to actually run the number of trains that can be worked out mathematically.

Practical Capacity is the practical limit of ‘‘representative’’ traffic volume that can be moved on a line at a reasonable level of reliability. The ‘‘representative’’ traffic reflects the actual train mix, priorities, traffic bunching, etc. If the Theoretical Capacity represents the upper theoretical bound, the Practical Capacity represents a more realistic measure. Thus, practical capacity is calculated under more realistic assumptions, which are related to the level of expected operating quality and system reliability. It is the capacity that can permanently be provided under normal operating conditions. It is usually around 60–75% of the Theoretical Capacity, which has already been concluded by Kraft (1982).Practical

Capacity is the most significant measure of track capacity since it relates the ability of a specific combination of infrastructure, traffic, and operations to move the most volume within an expected service level.

Used Capacity is the actual traffic volume that runs on a railway line or section and usually lowers the practical capacity. It reflects actual traffic and operations that occur on the line. It is usually lower than the practical capacity.

Available Capacity is the difference between Used Capacity and Practical Capacity. It is an indication of additional traffic volume that could be handled in route. If it allows, new trains will be added; otherwise, it is lost capacity (Abril.M. *et al.* 2008).

The Transit Cooperative Research Program (TCRP) Manual uses two definitions of capacity; design capacity and achievable capacity. Design capacity is defined as, "The maximum number of passenger spaces past a single point in an hour, in one direction on a single track" (TCRP, 1966). Design capacity is similar to, or the same as, maximum capacity, theoretical capacity or theoretical maximum capacity expressions used in other work. Design capacity would be fully used only if passengers uniformly filled the trains throughout the peak hour. This does not occur and a more practical definition sometimes referred to as practical capacity is required.

Achievable Capacity is defined as the maximum number of passengers that can be carried in an hour in one direction on a single track allowing for the diversity of demand. Achievable capacity is similar to the concept of practical capacity, and takes into account that demand fluctuates over the peak hour and that not all trains or all cars of a train are equally and uniformly full of passengers.

In this research, Theoretical (Basic or maximum) and Practical (Achievable) type of capacity are used since the Study focuses on the evaluation and capacity estimation of AALRT in planning and detail design stages.

At planning level, theoretical type of capacity is used since the major factors required to estimate railway capacity, like stations, signaling type, are not decided at this stage. Those factors shaping up railway capacity is decided at detailed design stage and practical or Achievable Capacity is estimated using these factors.

Both Used and Available capacity are measured using the available data collected at operation stage. During the preparation of this research, the operation of AALRT has not started yet. Therefore, the methods and procedures used to estimate Used and Available capacity are included in the study.

2.3. Approaches to estimate railway capacity

It is relatively straightforward to determine capacity on roads: it is normally determined based on vehicles per hour. Capacity on railways is, however, more difficult to determine because the capacity depends on the infrastructure, the timetable and the rolling stock (Alex L. *et al*, 2008).In this study, past approaches and various existing methods to analyze capacity utilization are reviewed. The research trends of major works and existing software packages are also studied.

The North American Transit Research Board's, Transit Cooperative Research Program (TCRP), provides a framework for measuring transit capacity (TRCP, 2004).The Report contains quantitative techniques for calculating the capacity of train services and rail stations. The techniques presented are static and can be calculated using an Excel spreadsheet. In addition, TCRP (TCRP, 1996) has released literature collections produced based on North American rail transit capacity experiences and capacity analysis methodologies.

The TCRP Report No. 13 (1996) provides a comprehensive description of the factors that determine rail transit capacity along with easy-to-use procedures for estimating practically achievable rail transit capacity under a variety of conditions. An excel spreadsheet of rail transit capacity modeling prepared by Tom Parkinson (TCRP User's Guide, 1996: xix-xxii) provides a good first-order estimate of railway capacity for planning purposes. This model clearly shows the relationship between theoretical capacity and the other factors which can restrict capacity such as a signal system.

The most widely used analytical methods in Europe is a leaflet code UIC 406 (2004) prepared by the International Union of Railways (UIC). The method presented in this leaflet enables to calculate railway capacity following common criteria and methodologies from an international standpoint for lines or corridors based on different criteria such as traffic quality, timetable quality or effective and economical utilization of infrastructure.

Railway infrastructure capacity depends on the way it is utilized. On a given infrastructure, capacity is based on the interdependencies existing between the number of trains, the average speed, the stability and heterogeneity (UIC, 2004)

Capacity Utilization Index (CUI), which is used in Great Britain, is an indicative measure of how much of the planning capacity of a section of railway is being utilized by the current timetable (Melody K., 2012).

2.4. Methods to estimate railway capacity

Numerous approaches have been developed to evaluate railway capacity. The most relevant methods can be classified into four categories: Analytical Methods, Parametric Methods, Optimization Methods, and Simulation Methods.

Abril M. (2007) argues that Analytical Methods are mainly devoted to identify preliminary solutions and reference values by means of mathematical formulae and algebraic expressions. Capacity utilization index (CUI), which is widely used in the UK, and UIC 406 capacity method which was developed by the UIC (2004) has been adopted in many European counties and are the most utilized formula for capacity (Melody K., 2012). In addition, the Transport Research Board has developed a spreadsheet for calculation of number of passengers that travel within an hour.

Parametric Models use some parameters of railway infrastructure and operation to describe and analyze capacity utilization. In this regard, Prokopy and Rubin (1975) developed parametric model that calculates Used capacity by means of train delay and a function of physical, operational and control parameters (Subhro M.,2012). Another parametric model was developed by Krueger (1999) for the Canadian National Railway.

Optimization Methods mainly aim at obtaining optimal saturated time-tables by using mathematical programming techniques and graph representations (Abril M. *et al*, 2007). Typical applications are used for solving scheduling problems under several constraints. Optimization Methods are extensively used for sub-problems of capacity utilization, especially train scheduling, rescheduling and routing as well as track and platform allocation (Melody K., 2012).

Simulation Method is the way of analyzing railway capacity utilization using tools or software package that has some direct or indirect features for improving timetable using simulating train scheduling and rescheduling. Several international companies are also working on computer-based simulation tools. One of them is the Open Track (Open Track Railway Technology).

In conclusion, analytical and parametric methods may be a good start for estimation of railway capacity but optimization and simulation methods need to be adapted to each application environment.

The four levels represent a general methodology for capacity management, where the first two levels represent a preliminary solution and the last two levels obtain a desired train schedule which is validated by means of simulation. An integrated approach also allows for the outputs from the high-level analysis and parametric, simulations to be used to optimize the inputs of detailed simulations.

2.5. Analytical Method

The analytical methods are the simplest methods for determining railway capacity. They usually obtain Theoretical Capacity through algebraic expressions, while Practical Capacity is obtained as a percentage of the Theoretical Capacity or by including regularity margins when they calculate the theoretical capacity. (João P., 2013).

The methods are aimed at determining the 'nominal capacity' of a rail line, given some (possibly restrictive) design assumptions. This represents a preliminary high level planning approach, which can also be used for comparison purposes. The output of this phase is not a detailed timetable but only some estimate or reference figure of its general characteristics about the utilization of the line, such as number of trains per unit time period or mix traffic shares among different train classes.

They usually obtain theoretical capacities and determine practical capacities either as a percentage of the theoretical capacity. Although the analytical methods are a good starting point to identify bottlenecks, the results are extremely dependent on the used method since different variables are taken into account (Abril M. *et al*, 2008).

More recently, Burdett and Kozan (2006) developed other approaches to evaluate theoretical capacity, which incorporate several factors, such as the mix of trains, the signal locations and dwell times. Some simple theoretical formula can estimate the maximum number of train for a line without timetable.

The most basic and earliest analytic railway capacity formula was developed by Poole (1962) for the ideal capacity where traffic is totally homogenous: The capacity in trains per day is computed by dividing 1,400 minutes by running time in minutes between two stations. It should be noted that this measure has very limited practicality as not all the minutes of a day can be used for running trains. However, it can provide some clues about theoretically maximum possible trains.

Lang and Soberman determines the capacity of a single track by number of trains that can pass a given point during 1 hour and the number of passengers carried in each train.

Subhro Mitra proposed the method in which the theoretical railroad capacity of track is measured by the maximum line throughput assuming all trains operated at the same speed, train movement is one direction only, and there is no significant grade which would result in variation of train speed (Subhro M., 2013)

The American Railway Engineering and Maintenance of Way Association (AREMA) (1998) present capacity equations for a single track in the Manual for Railway Engineering depending on the number of directions run on a single track and maximum gross headway in the direction of the run on a single track.

The most famous theoretical formula for capacity analysis is the UIC 406 capacity method developed by UIC (2004) which has been adopted in many European railways. The UIC 406 method provided a straight forward method of time table analysis and used capacity by compressing the time table so that the buffer time analysis and used capacity by compressing the timetable so that the buffer time is zero. (UIC, 2004)

The UIC 406 capacity method can be used in an analytical way determining the capacity consumption as the sum of the occupation time, buffer time, time supplements for single track operation and maintenance. This sum is then divided by the time window observed. In addition to the analytical way of determining capacity consumption, the capacity consumption can be measured by compressing the timetable graphs as much as possible in the line section and then using the compression ratio as a measurement of the capacity consumption.

The UIC 406 method enables the evaluation of capacity utilization for train path management but not infrastructure planning. However, the clues it provides for railway planners are limited.

In Transit Capacity and Quality of Service Manual (TCQSM) and Transit Cooperative Research Program (TCRP), prepared by the Transit Research Board (TRB), develops a framework to analyze and determine the capacity of rail transit modes in North America.

The TCRP Report uses two definitions of capacity; design capacity and achievable capacity. The basics of rail capacity are very simple; the product of how many trains can be operated in the peak hour and by the number of passengers that will fit on those trains. Trains usually have multiple cars, and number of cars per train is constrained by platform length.

Design capacity, in passengers per hour per direction (pphpd), is calculated using the following factors:

- number of seats per car,
- number of standees per car (= standing area x standing density),
- number of cars per train, and
- Train headway (minimum headway determined by a combination of the signaling system, station dwell, and terminus constraints).

The expression determines the number of trains per hour and is the inverse of the closest or minimum headway. It determines train throughput at the controlling station, usually the maximum load point station. The relevant minimum train separation in seconds is the minimum time from when a train starts to leave the most restrictive station, usually the maximum load point station, until the following train can berth at that station.

Controlling dwell time is based on actual station dwell time adjusted to a controlling value over the peak hour. TCRP (1996) lists design headway for different signaling system along others. Achievable capacity is the product of the design (maximum) capacity and a series of "reality" factors, which adjust the ideal capacity. These factors are not absolutes as they reflect human perception and behavior, as well as site-specific differences (expectations, cultural attitudes and the transportation alternatives). The TCQSM Manual derived these factors from observations of existing U.S. and Canadian rail rapid transit operations to create a single diversity or peak hour factor.

2.6. Signaling system

Signaling system is one of the most important systems that make up the railway industry. Railways are provided with signaling primarily to ensure that there is always enough space between trains to allow one to stop before it hits the one in front.

2.6.1. Types of rail transit train control systems

For capacity analysis purposes, rail transit control systems can be classified into:

(i) Fixed block,

(ii) Cab signaling, and

(iii) Moving block.

Rail capacity increases from fixed-block to cab-signaling to moving-block systems. (Lester, 2011: 191)

2.6.1.1. Fixed block systems

In Fixed block signaling system, the track is divided into block sections and as a train moves along the track, it will occupy blocks which prevent another train from entering that area. A mechanical or color light signals provide information to the driver on available blocks and routes whether the section ahead is clear or reserved for train.(Gregor T, 2009)

Velocities, grades, stopping areas, operational properties of the train, and location of physical elements such as switches and stations are the main factors used to calculate the block length. Once the block lengths have been calculated, signals are physically placed on the guide way to instruct the driver on scheduling and routing information. (Ludikar J, 2010)

Fixed block systems can only dictate the presence of a train within a given block but cannot tell where exactly the train is along the block. In the simplest two-aspect block system, only two indications are used—red for stop and green for go. In this case, a minimum of two blocks should be left unoccupied ahead of the train, and each block should be at least equal to the braking distance plus a safety distance. This could significantly limit the capacity of the rail line. The simplest system can accommodate a throughput approaching 24 trains per hour. (TCQSM, 2004)

Higher capacity trains use three aspect signals (red/yellow/green) with shorter block length. A three aspect, three-block system would employ three indications—red for stop, yellow for reduce speed and be prepared to stop at the next signal, and green for proceed at full speed and would use three blocks to separate trains. The addition of an extra block allows for deploying an automatic train stop device as an additional safety feature (Lester A.,2011: 191).The capacity of the line can be increased to 30 trains per hour with typical train length (TCQSM, 2004).

The capacity of the line can further be improved by using four-Aspect fixed block system. The four aspects can be implemented by using double lights, a double red indication is for stop, double green is for proceed at full speed, a red-yellow signal is for prepare to stop, and a yellow-green is for proceed at medium speed. In these systems, four blocks would separate trains, but the braking distance plus the safety distance would have to be less than or equal to the distance of two blocks and not just one. This can help increase the capacity compared to the three-aspect block system. (Lester A, 2011)

The main problem with the fixed block signaling is the length of the block increases to account for a larger stopping distance. This affects the inter-station headway. (Gregor T., 2009)

2.6.1.2. Cab signaling systems

Cab Signaling is a system of signaling whereby a set of visual display devices, fitted in the driving cab of the train, conveys instructions and information regarding the driver’s authority to proceed (Anne, 2000).The simplest systems display the track side signal aspect, indicating whether it is safe to proceed or not, display the allowable speed which is commonly called the reference speed or authorized speed, location of nearby trains and dynamic information about the track ahead (Lester A, 2011).

The authorized speed can change while traveling depending upon the location of the train ahead and allowing drivers to achieve optimum speed. In addition, cab signaling allows for mitigating the problems of external signal visibility, especially around curves and during inclement weather. Cab signaling avoids much of the capital and maintenance costs by reducing the number of color light signals. It also allows for increasing the number of aspects over what is typical for fixed-block signals. Cab-signaling systems often implement the equivalent of a five-aspect system with the following reference speeds: 80, 65, 50, 35, and 0 km/h. (TCQSM, 2004)

2.6.1.3. Moving Block systems

As signaling technology has developed, there have been many refinements to the block system but, in recent years, the emphasis has been on attempts to get rid of fixed blocks altogether. This gives the advantage of varying distances between trains according to their actual speed and their speeds in relation to each other. The moving block system is also called transmission-based or communication-based signaling systems, uses computers for continuous calculations of the safe distance based upon trains' locations, and communication of the appropriate speed, acceleration, or deceleration to each train. (TCQSM, 2004)

The system requires precise data of a train's location, speed, and length, and of fixed details of the line geometry, interlocking, and stations. Using these data, a train can keep at least a safe distance away from a disturbance or trackside object in real time. In a moving block system, this would allow a train to approach the rear of another stationed train by this calculated distance. It differs from a fixed block solution, which prevents a train from progressing into the next block if it is still occupied by another train. Therefore, the moving block implementation effectively reduces train separation, implying improved performance (Ludikar, 2010). Moving-block signals have the advantage of increasing track capacity and allowing trains to run much closer together (Lester A., 2011).

The moving block system follows the principle of separation of train by absolute braking distance in which the distance between two following trains equals the sum of braking distance of the train ahead and additional safety factor. This principle considered as the best principle for operation improvement and its only problem is the safety of the train depends on technology (Andrea M., 2007). Getting rid of fixed blocks has the advantage that distances between trains can be varied according to their actual speed and their speeds in relation to each other.

2.7. Train separation

The safety of railway system is mainly relays on the separation of trains as they operate along the track. The distance of separation is required in the design of the train vehicles, the specific type of train signaling system, and the operating rules of the property (David F., 2012). Train separation distance is a safe distance that protects a train from a collision with a train ahead operating on the same track and calculated using physical attributes of the track and train. This helps produce a time table and convey to the train operator the permission for movement and allowable maximum speed (APTA, 2012).

The low adhesion coefficient of the rail requires a longer distance to stop a moving train. This makes the braking distance much longer than the sight distance of the driver. Alternative options are required to provide safe train separation independent of the viewing range of the driver. This is satisfied with three basic theoretical principles (Andrea M. *et al*, 2007) as stated below:

a) Train separation in relative braking distance

This is a theoretical idea that leads to maximum line capacity. The separation between two trains is a relative braking distance that equals to the difference of the braking distance of the trains plus an additional safety distance.

In relative braking distance, the second train has to have a full braking distance. In case of accident happening to the first train, the second train has wide chance of colliding with the first train. Train separation in relative braking distance is only a theoretical idea with no realistic chance to be adopted in railway transportation (Daniel E., 2009).

b) Train separation in Fixed Block distance

This is the most common principle adopted worldwide. In this principle, the track is divided in block section and a block can be occupied by only one train at a time. The separation distance between two trains is the sum of the maximum braking distance, the length of block section and additional safety factor.

c) Train separation in Absolute Braking distance

This principle allows the trains to operate at closest as possible spacing considered suitable for optimal operation of railway line. The train separation distance is equal to the braking distance of the second train plus an additional safety distance. This principle depends on the technology used in the system for safe train operation. Train separation in absolute braking distance is also called moving block.

In Relative Braking Distance, the second train has to have a full braking distance. In case accident happens to the first train, the second train has a wider chance to collide with the first train. In general, train separation in relative to braking distance is only a theoretical idea with no realistic chance to be applied in railway transportation. The types of signaling system applied worldwide is based on train separation in fixed block distance and absolute braking distance (Daniel E., 2009).

All principles described above indicate that braking distance is the main component of safe train separation distance and always include additional safety distance. This safety distance accounts for the maximum distance a train can travel after it failed to act on a brake command before automatic override (or over speed) system implements emergency braking. (TCRP 1996)

A railway system should develop and implement operation rules to work in conjunction with the signaling system. One of the key principles in a signaling system is the ability to calculate the distance necessary between operating trains in a real time environment. Different Manuals develop methodologies and procedures for determining the minimum train separation for different train control systems.

2.8. Station Dwell Time

In urban public transportation, Station dwell time is a key factor that affects the travel time, performance and capacity of the system. In rail transit systems, trains are scheduled to stop at station with sufficient dwell time for passengers boarding and alighting. The provision of inadequate dwell time would cause train delays and excessive dwell time may lead to inefficient operation. Therefore, the determination of station dwell time is crucial in optimization of the capacity of rail transit system. (Jong J., 2011)

In general, dwell time is defined as the time during which a train remains stopped at a railway station, primarily to allow passengers to board and alight. It consists of the time passengers flow occurs, the additional time before the doors are closed and then a time while waiting to depart after the doors are closed (TCRP, 1996)

Station dwell time is the major component of headways at frequencies and in particular it is a main factor in capacity when it combines with minimum operating headway to create a constraining headway bottleneck in the system. For reliable estimations of train running times on main lines, it is necessary to obtain accurate estimations of dwell times at stations on the railway line. As an illustration, under the research undertaken by the Metropolitan Transportation Authority (MTA) of New York to improve the dwell times at Grand Central Station, the station dwell times reduced by 10% and this led to an increase in capacity of one train/hour (i.e., 2,000 customers during the peak hour) (Andrea M,2008).

Developing analytical model was relatively simple for train's separation time since it is a function of the train's physical performance, along with other fixed characteristics. Train dwell time is one of the most unpredictable components of railway operations mainly due to the varying volumes of alighting and boarding passengers and it is a function of the number of travelers waiting at the station and their flow time which are subject to a great deal of uncertainty (Dewei L., 2015). It is also a function of some parameters that are not always controllable, such as door closing and opening mechanisms, vehicle loading conditions which depends on both the train and platform configurations, and passenger arrival rates at stations.(Andrea M,2008).This makes it difficult to calculate as same level of precision as was the case of train separation time.

In many literatures and simulations used as a reference in TCQSM Manual related to rail transit capacity, typical value of 15 to 20 seconds is assigned for small stations and 30 to 45 seconds for major stations (TCQSM, 2004).

However, a priori knowledge of station dwell time is most useful as it gives insight into the travel time and headway variations over time. In combination with other operational information, it can yield effective timetable in order to maximize the throughput of the system. Efforts can be made at critical stations to apply smaller dwell time by modifying some of the above mentioned parameters.

Station dwells are governed by several components. The factors affecting the station dwell times can be classified into five categories: passenger, vehicle type, station, operation and external factors. (Dewei L. 2015).

1. Passenger factors

Passenger factors include passenger volume (passenger crowding) which is average number of passengers boarding and alighting, passenger crowding and passenger characteristics (gender, luggage, and handicap). These factors influence the alighting and boarding time. Researches show that the number of the boarding and alighting passengers is the main determinant of the dwell time as the efficiency of pedestrian movement and is very sensitive to crowding (Dewei L., 2015).

2. Vehicle Type :Vehicle characteristics can be categorized in three groups:

a) Door operation and control system: includes door unlocking time, actual opening and closing time, door warning time and any other fixed system constraints on door operation.
b) The number, width and spacing of vehicle doors with horizontal and vertical gap between the train and platform. Low floor trains decreases passenger service time by avoiding the need to ascend and descend steps.
c) On board circulation: The interior layout of the train (seat arrangements, walkway width, and space near the door) limits the speed of alighting and boarding.

3. Station factors include:

a) Platform circulation: The size, number and location of platform entrances influence passenger distribution and clearance times and have impact on alighting and boarding time. If platforms are too narrow, or exit path limited, congestion on the platform can cause delays in unloading a train.

b) Platform layout: influences headway between consecutive trains. Single platform with door operation on a single side is the norm. However, some systems configure busy stations with platforms on both sides of a train.

4. Railway operation such as train delay, train overtake or meet, train couple and decouple, time for passenger connection, and operation margin can also bring extra waiting times to a train.

5. External factors include weather conditions; traffic conditions at level crossings near the platform would also have an influence on train dwell times. (Dewei L., 2015)

Determination of the minimum headway of a railway system requires knowledge of station dwell times over the peak hour, which is information only available for existing systems or for new lines. Alighting and boarding passenger volume can be analyzed. (TCQSM, 2002)

In calculation of the total station dwell time due to the factors mentioned above, the duration can be classified into three constituents of dwell time as follows:

a) The time passenger flow occurs,
b) A further time before the doors are closed, and
c) Time while waiting to depart with the doors closed (TCRP, 1996).

To analyze the durations simply, the station dwell time is divided into three parts as the dwell time is the time interval between train arrival and departure as shown in figure 2.1. . (Jong J, 2011)

a) Type I Lost Time: The time interval between train stop and door open.
b) Passenger Flow Time: The time interval for alighting and boarding of passengers
c) Type II Lost Time: The time interval between doors closed and train start.

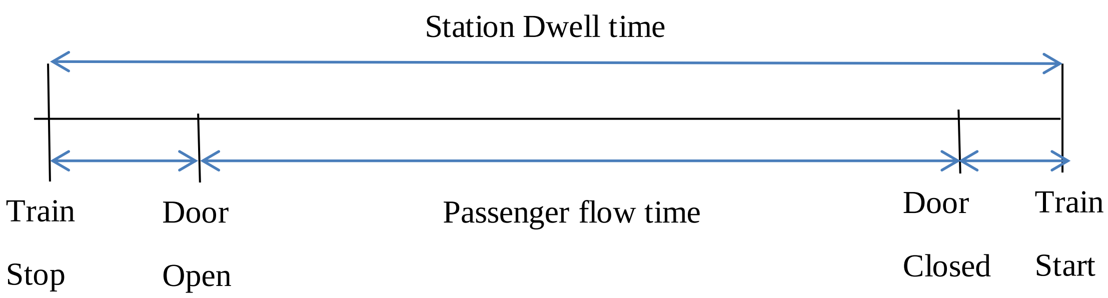

Figure 2. 1: Events during train dwell time

In an existing railway system, Type I lost time can be obtained by computing the time difference between train stop and door opened. Similarly, Type II lost time can be calculated by calculating the difference between train start and door closed.

Methods of calculating station dwell time for a new system can be categorized into two (TCQSM, 2004). The first method is simply assigning a reasonable figure to the headway critical station using the value recommended by different manuals and literatures. This method is mostly applicable at planning level where information on passenger flows is not available. In the observation made at the existing rail transit systems in North America, the station dwell times over the peak hour ranges from 30 to 50 seconds: occasionally with exceptional situations. A tighter range of dwell time values of 35 to 45 seconds is used in planning procedures and can be used together with more accurate calculation of the minimum train separation (TCQSM, 2004).

For complete alighting and boarding operation, the maximum number of passenger flow of LRT in Edmonton city is 72 per door and this requires 24 seconds plus door opening and closing time of 6 seconds. It is unlikely to have a smooth alighting and boarding but for time table purposes, it is customary to use 30 second station dwelling time depending on the particular station and time of a day (Robert R., 1984). Experience has shown that the station dwell time for grade-separated Light rail operating at or close to capacity during the peak hour ranges between 30 and 50 seconds (Lester A., 2011).

For new lines in cities with existing rail transit system, the dwell time can be estimated from the headway critical stations similar to the one being analyzed. When there are additional extensions of railway line added to an existing system, the dwell time at headway critical station of the existing system can be used to estimate the station dwell time.

The second method is calculating of dwell time from station passenger flow. This method uses a mathematical approach of determining station dwell times based on passenger volume and flow time. The method suited to new systems in location where data on hourly, directional flow at each station is available (TCRP, 1996). Dwell time distributions on existing rail systems can be measured directly and this data can be used in planning new systems (Jack R., 2011).

The duration of time for passenger flow, is the major component of dwell time which requires a detail analysis. The development of a passenger flow time model for existing railway station depends on accurate field data .The data can be collected using labor intensive field surveys, transaction log data from automatic fare collection (AFC) systems and automatic passenger counting (APC), using sensors placed on top of the doors to detect the passage and direction of people. The total passenger flow time is usually estimated by calculating the time interval between the last passenger to board and the first passenger to alight and the average flow time for each passenger is then calculated by the total flow time divided by the number of passengers (Jong P., 2011).

In the technique applied to intercity and commuter trains operated by the Taiwan Railway Administration (TRA), linear regression models was developed from the data collected to estimate total passenger flow time by using the number of passengers (Jong P., 2011). Gerry Weston (2007) developed a dwell time model, which is known as LUL method, as part of a Train Service Model for London Underground (Douglas E., 2012).

Puong (2000) proposed equation for estimation of dwell time from the number of alighting and boarding passengers per door and number of standees per door. Researches under the Transport Research Board (TRB) in north America developed a relatively simple regression equations that covert station peak hour alighting and boarding passenger volumes and flow times into total doorway use times and then into dwell times. (TCRP, 1996)

2.9. Operating Margin time

In calculation of minimum headway of rail transit system, Operating Margin time is the last component included to count for unpredicted service situation. It is an extra time allocated in case of small delay or temporary speed restriction and other routine irregularities. It allows dwell time variability without disrupting scheduled operating time. Operating margin is sometimes also called as recovery time or Buffer time. Operating margin is a time that is added to the sum of minimum train separation time and maximum load point station dwell time to create a minimum headway. A provision of suitable operating time is an important component in determining the maximum capacity and incorporating timetables are very important to reduce train delays (TCQSM, 2004).

In estimation of station capacity, an operating margin can be considered as a buffer to allow for random variation in dwell time (Jack R., 2011). In preparation of time tables of existing transit line, the determination of operating margin is mainly based on rules of thumb and sometimes validated by simulation and statistical analysis of real operations data. The estimation of operating margin based on observed running time and station arrival and departure time at major station improves the operation and time table quality of the railway line.

The operating margin typically ranges between 15 and 25 seconds (Lester A., 2011). The average dwell times, based on North American experience, ranges from 30 to 50 seconds and the coefficient of variation ranges from 0.25 to 0.70 (Jack R., 2011). Incorporating operation margin into the determination of maximum achievable capacity, it is recommended to consider values surveyed from similar existing line. Transit Capacity and Quality Service Manual recommends the provision with the range between 15, 20, or 25 seconds of operating Margin in estimating achievable capacity (TCQSM, 2004).

The recommended procedure is to use the capacity for 25 seconds at planning stage or when demand is unknown and revise the output with 20 seconds or even to 15 seconds if necessary to provide sufficient service to meet the estimated demand.

2.10. Headway

Headway is an elapsed time between trains passing a fixed point in the same direction over the same track. It is usually expressed in minutes, example "trains were running at 4-minute headway". Minimum headway for light rail system depends on signaling system, train length, platform and car design (high floor versus low floor), fare collection method (prepayment versus pay on train) (HCM, 2000). Under Block signaling system, headway of 2 minutes are possible and shorter headways can be used with moving block signal. Most North American light rail systems are signaled for a minimum headway of 3 minutes (HCM, 2000). Headway is used in calculating the number of trains required for a particular service and this helps to decide the train performance requirements and signaling.

2.11. Turn backs

There are different ways of turning a train requiring reversing its direction at the end of a trip. The simple way of changing direction where driving cabs are available at both end of the train is using typical turn back of far side crossover beyond the station is used. Trains arrive and depart on separate tracks/platforms and all the passenger and crew activities happen during the time the train stays on the platform. The arriving train pulls into switches of one of the tail tracks, changes direction, and then returns to pick up passengers from the other platform. This way is the most popular and simple reversal procedure since it uses least space and takes reasonably short time (Zhibin *et al*, 2015: 2). Figure 2.11.1 shows turnover far-side crossovers.

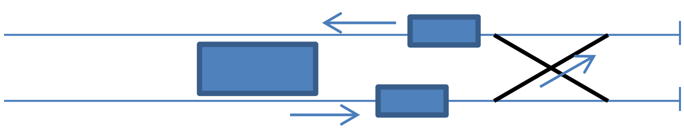

Figure 2. 2 Typical Turnover far-side crossovers

In a reversing type turn back, the train deposits arriving passengers in one platform and goes forward to the siding where it changes direction and then proceeds into a departure platform.

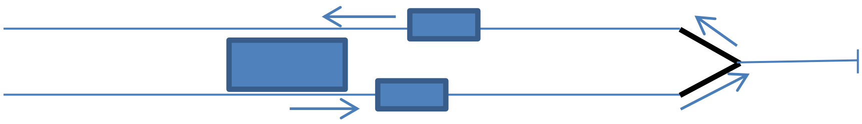

Figure 2. 3 Reversing type turn back

The design and operation of turn backs have a major contribution for the capacity of the system as, the amount of time required to board and alight passengers and for the operator to change ends and inspect the train will be longer than the headway between trains (TCQSM, 2004). Layover time is the time between the scheduled arrival and departure of a vehicle at Turn backs.

2.12. Passengers Loading Level

Train vehicle capacity is described by the number of passengers carried by the vehicle. Train vehicle capacity depends on train length and width, number of rail cars per train and passenger loading standards. Usually, the capacity of allowable crowding during the busiest 15 or 20 minutes during the peak hour is considered. The passenger loading level is expressed as passenger per meter by dividing vehicle capacity with interior length of the train (Jack R., 2011).

Provision of passengers loading level is the final step in determining rail transit capacity. After the maximum number of trains of a given system in peak hour is known, the capacity of the line to transport passenger depends on the train length and loading level.

In transit systems of different cities around the world, wide range of loading levels are used and the selection of loading level is a policy issue depending on the quality and level provided by the service. If the line for which the capacity is being determined is an addition to an existing system, it is recommended to select from the available existing loading policies of the closest matching line based on 15-minute peak period (TCQSM, 2004).

This research attempts to review standard used in existing rail transit system in different cities. In the United States and Canada, a range of passenger loading levels from 5 to 9 passengers /m length for light rail and 7 to 11 passengers /m length for heavy rail are provided. An attempt is made to provide a better quality of service based on the commonly suggested medium comfort of a minimum of 6 passengers /m using area of 0.5m^2 per passenger (TCQSM, 2004).

In table 2.1 below shows the the resulting vehicle capacity per train for a variety of rail transit lines in some developed cities of the world by using different loading standards of standing passengers per square meter and the number of seats (Jack R., 2011).

Table 2. 1 Train capacity using different loading standard in different cities

City	Train length (m)	Cars	Total Seats	Loading Standard (passengers/m^2)
Bangkok	65	3	126	8
Guanzhou	59	3	142	6
Shanghai	140	6	288	6
Singapore	138	6	300	6
Shenzen	140	6	288	6

Mexico City's Metro experiences a loading level of 0.125 m^2 per passengers. The standard body space area per passenger of selected heavy light rail systems of different cities in North America over the peak 15 minutes are shown below in Table 2.2

Table 2. 2 Passenger Spacing in different cities of North America

Passenger Space (based on gross floor space)			
City	**Area Per Passenger (m^2 /p)**	**City**	**Area Per Passenger (m2 /p)**
New York	0.38	Washington	0.50-1.11
Chicago	0.67	Atlanta	0.63-0.71
Philadelphia	0.77	Toronto	0.42-0.56
Boston	0.50	Montréal	0.31-0.38
San Francisco	0.53-0.83		

2.13. Peak hour Factor or passenger loading diversity factor

In planning transit systems, projected hourly passenger volumes must be increased to compensate for peaking within the hour. Peak hour factors are used in capacity analyses which select 15 minute flow rates as the basis for its procedures. The peak hour factor is used to adjust the hourly capacity from the 15 minutes passenger flow in peak hour which was used in calculation of the passenger loading levels. It shows the diversity of Peak hour from that of Peak 15-Minute Loading. The summary of results for North American Light rail systems are described as shown below in Table 2-3 (TCQSM, 2004).

Passengers do not load evenly into cars and trains over the peak hour. The unevenness is loading could be passenger loading in a trains within the peak-hour trains,within cars of a train or within a car it self. The peah hour factor which is eqaul to loading diversity factor accounts all the three uneveness condition.It is also used to adjust passenger volumes from the estimated design capacity to a more practical achievable capacity.

Table 2. 3 Peak hour factors form North America Light Rail System

City	Peak Hour Factor	City	Peak Hour Factor
Calgary	0.62	Philadelphia	0.75
Denver	0.75	Portland	0.80

3.0. METHODOLOGY

3.1. Introduction

In an effort to increase the overall capacity of a transit system, this study examines feasible approaches that can calculate the capacity of a given railway system. This section summarizes the methodology and steps followed to develop analytical method of calculating railway capacity of a transit system. The method is used to evaluate the capacity of the Addis Ababa Light rail Transit.

The methodology is developed for Planning and detailed design stage of new rail transit system and mainly applicable for light rail transit system similar to the ongoing Addis Ababa Light rail transit system. At the detailed design stage, the capacity of railway line is determined using input data that include horizontal and vertical alignment (curve, gradient), station locations, and dwell times at stations, signaling system, type and size of locomotive, etc. The developed methodology for detailed design stage can be applicable at planning stage depending on the available data. Planners need to estimate the capacity of the transit line and the number of trains or passengers that can be transported per hours especially for budgeting purposes. To accomplish this, methodologies that reasonably estimate the railway line capacity are required.

3.2. TCQSM Transit Capacity and Quality of Service Manual

In the literature review, different analytical methods and procedures that can be applicable in the calculation of railway capacity, particularly for urban transit systems were assessed. In this study, set of procedures provided by Transit Capacity and Quality of Service Manual for calculating the main constituents in determination of capacity are found to be convenient to apply to Ethiopian condition depending on data availability. The document does not represent a standard. It is analytical method that contains both procedures and data tables to assist in transit capacity and quality of service analysis.

The Transit Capacity and Quality of Service Manual (TCQSM) was published by the Transportation Research Board (TRB) of the United states of America. Transportation Research Board (TRB) is well known for its Highway Capacity Manual (HCM) which was developed by the researchers and practitioners of the National Academy of Sciences to provide consistent set of procedures to assess the throughput capacity of various elements of a highway system. The equivalent volume for public transport was developed in 1999 through the support of the TRB. The Transit Capacity and Quality of Service Manual (TCQSM) is now in its third printing process with an update which was published in 2013.

The main reasons for selecting the procedures of this manual are:

- Most of the analysis can be simply computed and presented using Microsoft Excel spreadsheet without applying simulation tools. This fits with the scope and budget of the research.
- The manual contains data tables that summarize empirical observations of the US and Canadian practices which is very important for comparing results of the analysis with actual conditions.
- The Manual provides default values for initial transit system design and operational analysis which is necessary for Ethiopian condition where there are no available studies and existing infrastructure of transit system.
- TCQSM Manual was developed for North American condition where condition there is quite different from the Ethiopian one. However, the analytic equations are developed using basic distance, time and speed equation used in general law of motion which can be directly applicable in Ethiopia. The equations can be simply modified with actual condition of the project. The input parameters of the equations are taken from the actual design of AALRT.

A model is developed for its utilization in Ethiopia by applying Excel spreadsheet using the analytical equations of the constituents which is required in determination of capacity. In the Excel Spreadsheet, the computations of each constituent are linked so that the resulting change in capacity of the system can be evaluated due to the change in the values of each parameter. This helps the planner or designer to optimize each element of the system and provide different alternative scenarios as an option to maximize the line capacity of a railway system.

3.3. Design Approaches used in determination of capacity

In determination of urban transit system capacity, two types of analysis approach are used:

3.3.1. Determination of capacity based on passenger volume

In this approach, the capacity of the line is determined based on the peak hour passenger volume at critical station or point. The capacity of the line is designed economically for the minimum planned train headway rather than the minimum possible train headway. The system is designed using planned headway calculated based on the frequency of service required at critical station with the highest number of passenger volume at peak hours, even if minimum headway values can be accommodated by the system. The headway computed by this approach is used to determine the number of train required by the service. The capacity of the system can be further increased by using smaller value of headway but it may not be economical.

3.3.2. Determination of achievable capacity based on the maximum throughput of the system.

In this case, the railway system is designed for maximum capacity. The line capacity is directly related to the signaling constraint to be built in the system and person capacity is then directly related to the line capacity and the size of the vehicles. Minimum headway achieved by the minimum train separation is used to optimize the capacity of the railway system.

This approach is used to analyze the additional traffic volume that could be handled by the system. It is also used to revise the capacity and level of service determined by the above method, using passenger volume.

3.4. Determination of capacity based on passenger volume

3.4.1. Total Passenger volume at stations

The capacity of a transit system can be determined based on the passengers demand along the system. For existing lines, such data may have already been available or can be analyzed using the actual field survey data on the railway system. For a new system like AALRT, an estimation of the passenger volume at each station which involves forecasting of the total passenger volume and analysis of passenger cross-section flow during peak hour of the day is required. For planning and design of a new railway system, such data are crucial in deciding the capacity of the system.

The following data are required for each station:

- Passengers boarding on trains in each direction;
- Passengers alighting from trains in each direction;
- Passengers riding on trains between stations for each direction; and
- Passengers transferring from line to line at interchange stations (if any).

3.4.2. Train Vehicle capacity

Train vehicle capacity is the passenger carrying capacity of a train vehicle during peak hours which is determined by the number of standing and seating passengers in the vehicle. Vehicle capacity depends on; the interior dimension of each car in the train, number of cars per train and passenger loading standards.

The interior dimensions of each car are determined by taking actual measurements of interior dimensions of the vehicles or by deducting the wall thicknesses from the exterior dimension of the vehicle. Then, the number of seats can be determined by dividing the interior length of the vehicle depending on seating arrangement. Finally, standing capacity of individual vehicle can be calculated using interior space usage by deducting the space occupied by seats. The capacity is based on the transit agency loading standard for passengers per square meter of standing space plus the number of seat.

The Transport Research Board (TRB) of North America, in its Transit Capacity and Quality of Service Manual, proposed a straight forward equation to vehicle capacity. In this study, the simplified form of this equation is used as shown in equation 3.1 and illustrated in Figure 3.1 subsequently.

$$C_v = \frac{L_c W_C}{S_{sp}} + N\left(1 - \frac{S_a}{S_{sp}}\right)\left(\frac{(L_c - D_n D_w - 2D_n S_b)}{S_w}\right) \qquad \text{Equation 3.1}$$

Where

C_v = Vehicle capacity (Passenger)

L_c = Interior length (m)

W_C= Interior width (m)

N=Seating Arrangement

S_{sp}= space per standing passenger (m^2)

S_a= Area of single seat (m^2)

D_w = Door Width (m)

D_n= Number of double stream doors

S_b = Single Setback allowance (m) assuming two setback allowances at each door

S_w = Seat pitch, depending on seating arrangement

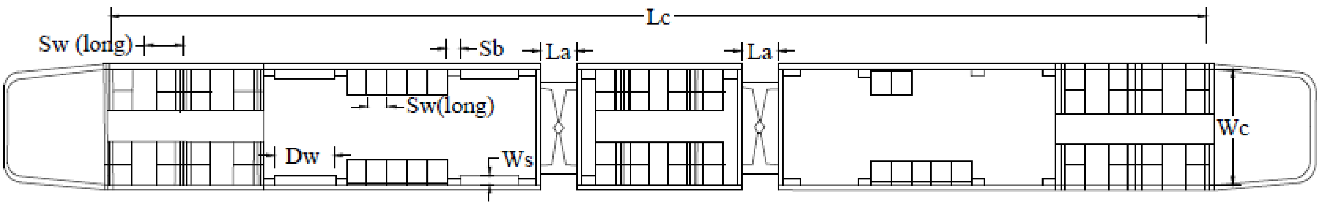

Figure 3. 1 Dimensions of articulated vehicle used in equation 3.1

In this study, the following procedures are applied in determining the vehicle capacity using equation 3.1

1. Propose vehicle type,
2. Divide the interior area of each car into sections depending on seating arrangements.
3. Determine the interior dimension of the sections in Vehicle car, L_C and W_C
4. Determine the free wall lengths of the sections by deducting the sum of the door widths, plus a setback allowance of per double stream door from the interior length.

Free wall length = Interior length – (door width*number of double stream door - setback allowance * number of double stream door), that is

$$L_w = L_c - D_w * D_n - 2 * D_n * S_b \qquad \text{Equation 3.2}$$

Where,

L_c = Interior Wall Length (m)

L_w = Free Wall Length (m)

D_w = Door Width (m)

D_n= Number of double stream doors

S_b = Single Setback allowance (m) assuming two setback allowance in each door

In articulated light rail vehicles, if seating is allowed in the articulated sections, the length of these sections should be included within the free wall length.

5. Set a seating arrangement in each section.

Seating arrangement is described by N where

N = 2 for longitudinal seating:
N = 3 for 2+1 transverse seating:
N = 4 for 2+2 transverse seating:
N = 5 for 2+3 transverse seating

6. Seating can then be allocated to Free Wall Length by dividing with the seat pitch as formulated in Equation 3.3

$$\text{Allocated seating} = \frac{L_w}{S_w} \qquad \text{Equation 3.3}$$

Where

L_w = Free wall length

S_w = Seat pitch which depend on seating arrangements

7. The result of the allocated seating, in lowest whole numbers, should then be multiplied by seating arrangement and the result gives the total number of seats.

The total number of seats =Allocated seating* N Equation 3.4

8. The floor space occupied by seats can then be calculated by multiplying the number of seats by area of single seat depending on seating arrangement.

Area occupied by seats =Total number of seat * Area of single seat (S_a) Equation 3.5

9. The residual floor area can now be assigned to standing passengers. In light rail vehicles step wells areas and the opening space in the articulated sections may be used by standing passengers in peak hours.

10. The number of standing passengers can be calculated by dividing the available area with the space per standing passenger, S_{sp}

Space per standing passenger (S_{sp}) is determined depending on the quality of the service and the number of passengers considered in one meter square.

11. The vehicle capacity is then the sum of seats and number of standing passengers, C_v

3.4.3. Passenger loading diversity factor or Peak hour factor

No train will fill with passengers equally from end to end and passengers will not arrive at stations in steadily flowing numbers throughout each hour. In planning transit systems, projected hourly passenger volumes must further increased to account for vehicle capacity utilization through the load factor. A specific figure of peak hour factor is used from similarly operated existing system. These actually convert the projected hourly passenger volume into the offered capacity required to serve that volume. In general form the survey carried out in North America cities, a value of 0.75 is recommended for light rail system for calculation of achievable capacity. In this study, the diversity factor of 0.9, that can be applicable for developing cities, is used.

3.4.4. Planned line capacity

Planned line capacity is described as number of trains per hour and determined by dividing the number of passengers at critical station with that of vehicle capacity. It is the way of expressing the frequency of service required per hour during peak hour at the busiest section of the line.

$$N = \frac{P_{max}}{C_v \times PHF} \qquad \text{Equation 3.6}$$

Where,

P_{max} =Maximum passenger peak hour cross-section flow (Passenger per hour)

C_V = Vehicle Capacity

PHF=Passenger load factor or Peak hour factor

3.4.5. Headway

The planned Headway in which the railway line operate can be computed from the number of train passing a given control point per hour. It describes the difference in time between two consecutive trains to pass a given control points.

$$Headway(H) = \frac{60}{N} \qquad \text{Equation 3.7}$$

Where,

H= Headway (min),

N= number of trains per hour

3.4.6. Total Round Trip Time

Round trip time is a total travel time of a train from the starting to end point of the railway line and then return back to the starting point, including the dwell times at each station and Layover time of Turn back time at ends of the line. The determination of round trip time requires the estimation of dwell time at each station and calculation of travel time between stations.

3.4.6.1. Travel time between stations

The travel time is a time required by a train to travel from station to station. This includes the time to accelerate from departing station, decelerate to arrival station, and time of travel with allowable uniform speed in between. In addition, deceleration and acceleration time to keep the allowable speed at turnouts and at-grade crossings. Such computations require to model the geometric design and elements of the infrastructure which is efficiently performed using software or simulation tools as it incorporate so many factors like the geometry of the line, (curve radius, gradients), station locations, locations of turnout and crossings and the performance of the train to be used. For this study, simple analytic procedures are followed to calculate the travel time between station since the utilization of simulation tools are beyond the scope and budget of the research. Most analyses of travel time are performed through the basic variables of motion of vehicle which are distance, speed and time.

For most transit operations, the station-to-station movement represented by the motions of accelerating vehicle travel from standing to speed V, the movement of vehicle in constant speed and then deceleration or braking of vehicle from speed V to a stop. The relationship between station to station distance S and travel time T_S depends on whether a transit vehicle can reach its maximum allowable speed or not. The maximum speed is determined by the geometric design and physical constraints of the line.

In this study, the three basic cases of station to station travel, which is proposed by Vukan, are considered (Vukan, 2007). If we designate $\boldsymbol{S_c}$ as critical distance that is required for a train to accelerate to V_{max} and then immediately decelerate to stop by applying brake and **S** as clear distance between the platform of the stations, the cases of station to station travel can be described as follows:

a) Case A: Station to station distance $\boldsymbol{S'} = \boldsymbol{S} < S_{\boldsymbol{c}}$

The Station to station distance $\boldsymbol{S}$ is shorter than the critical distance $\boldsymbol{S_c}$ and the train fails to reach the maximum allowable speed V_{max} due to the short distance between stations. The maximum speed reached is designated as V' and $V' < V_{max}$. In this case, the travel consists of acceleration and deceleration only and the velocity. The distance graph of this case is shown in Figure 3.2 as illustrated by Vukan (Vukan, 2007).

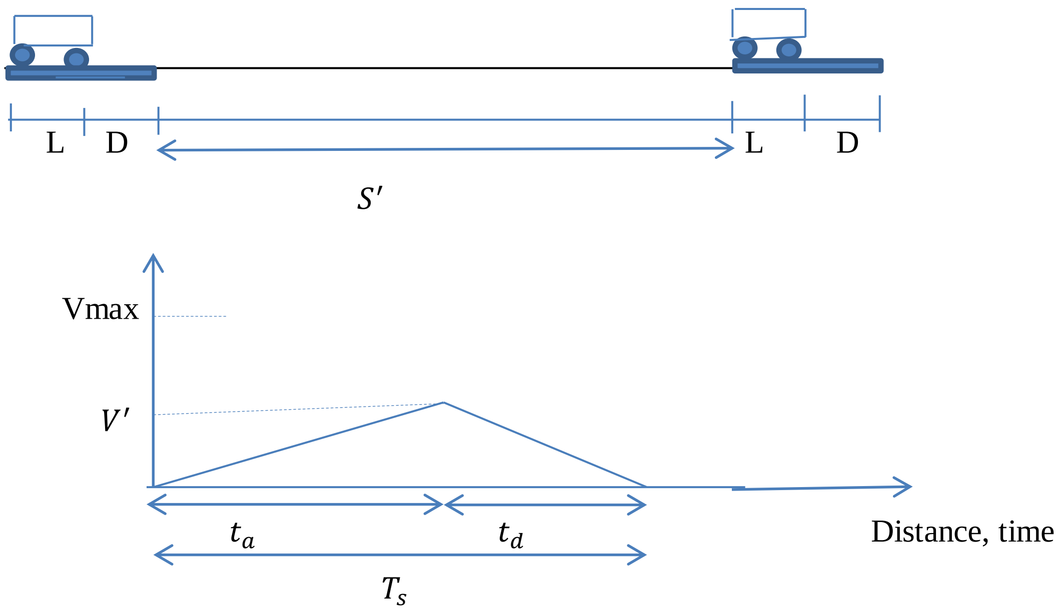

Figure 3. 2 Travel time for case A

Where

t_a= time to accelerate to the maximum speed V'

t_d= time for braking or deceleration

S'= distance between stations

T_s = station-to-station travel time

V'= achievable speed b/n stations

V_{max} =Mmaximum speed

The distance between stations can be expressed using the following formula as developed by Vukan (Vukan, 2007)

$$S' = \frac{1}{2}at_a^2 + \frac{1}{2}dt_d^2 = \frac{1}{2}at_a^2, \qquad \text{Equation 3.8}$$

Where $t_a = \frac{V'}{3.6a}$ and $t_d = \frac{V'}{3.6d}$ Equation 3.9

a = train acceleration rate (m/s^2)

d = train deceleration rate (m/s^2)

V'= maximum achievable speed b/n stations (km/hr)

S'= distance between stations (m)

t_a= time to accelerate to the maximum speed V'

t_d= time for braking or deceleration

From above equations, the maximum achievable speed V' and station to station time are also derived as shown in Equation 3.10 and Equation 3.11 (Vukan, 2007)

$$V' = 3.6 \times \sqrt{\frac{2a \times d \times S'}{a+d}}$$ Equation 3.10

V'= maximum achievable speed b/n stations (km/hr)

$$T_s = t_a + t_d = \sqrt{\frac{2(a+d)s'}{ab}}$$ Equation 3.11

Where

S'= distance between stations (m)

T_s = station-to-station travel time (sec)

Using equation 3.8, the critical distance, $\boldsymbol{S_c}$**,** which is designated for distance that is required for a train to accelerate to V_{max} and then decelerate to stop is computed by substituting V by V_{max} as shown below as developed by Vukan(2007)

$$S_c = \frac{V_{max}^2}{2}\left(\frac{1}{a} + \frac{1}{d}\right)$$ Equation 3.12

Where V_{max} in m/s

Similarly, the travel time at the critical distance is calculated as follows: (Vukan, 2007)

$$T_c = V_{max}\left(\frac{1}{a} + \frac{1}{d}\right)$$ Equation 3.13

Where V_{max} in m/s

b) Case B: Station to station distance $\boldsymbol{S} > S_c$

When station to station distance is greater than critical distance, train speed can reach the maximum speed allowed at the section, V_{max} and keep the speed until braking is applied to stop at the next station. The velocity-distance diagram is shown in Figure 3.3 below as illustrated by Vukan(2007)

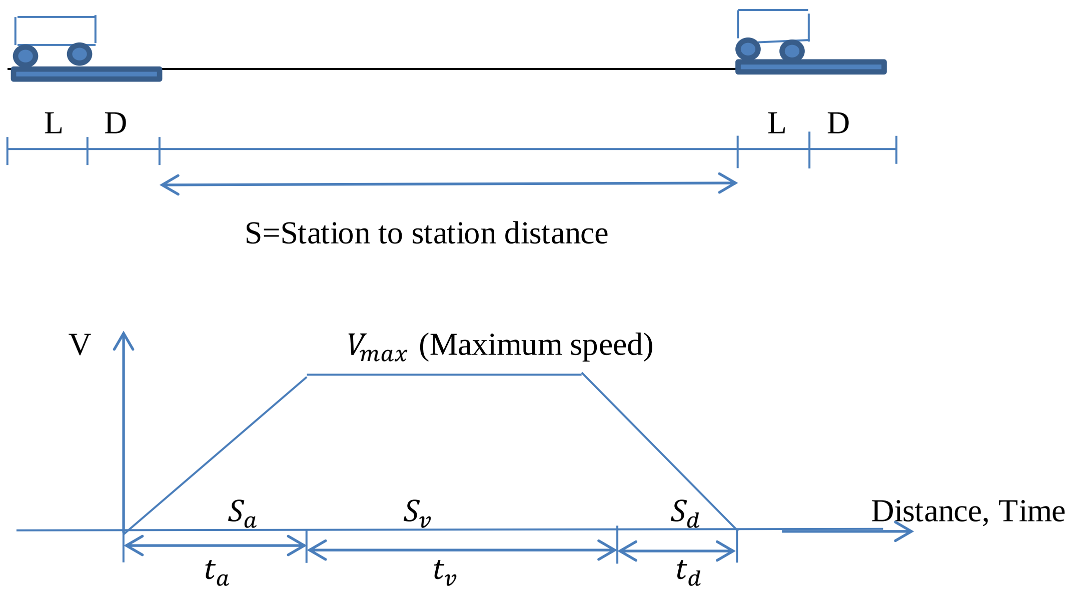

Figure 3. 3 Travel time for case B

Where

S_a = distance to accelerate (m/s^2)

S_d = distance to decelerate (m/s^2)

S_v = distance traveled at constant (maximum) speed (m/s^2)

t_a=time to accelerate to the maximum speed V_{max}

t_v= time to travel with constant speed V_{max}

t_d= time for braking or decelerating from V_{max}

The critical distance S_c which is given in Equation 3.13 is also expressed as follows:

$$S_c = S_a + S_d \qquad \text{Equation 3.14}$$

(Vukan, 2007)

This shows that the distance traveled at constant speed S_v can be calculated as

$$S_v = S - S_c = S - S_a - S_d \qquad \text{Equation 3.15}$$

(Vukan, 2007)

Then, the travel time between stations is derived from equation 3.12 and 3.15 as shown in equation 3.16 as developed by Vukan (2007)

$$T_s = t_a + t_v + t_d = T_c + \frac{S - S_c}{V_{max}} = \frac{S}{V_{max}} + \frac{V_{max}}{2}\left(\frac{1}{a} + \frac{1}{d}\right) \quad \text{Equation 3.16}$$

c) **Case C:** Station to station distance $\boldsymbol{S} > S_c$ with level Crossing

In urban transit system, the uniform travelling speed of a vehicle is interrupted by the presence of at grade crossings with other mode of transport. In most urban systems, priority is given to rail transit lines; however, such crossings have a huge risk of accidents. For safety purpose, trains reduce their maximum speed while approaching the level crossing and pass through allowable speed. A train decelerates from its maximum speed to meet the allowable speed near turnout, junction and level crossing and then accelerate to the maximum speed after traveling short crossing L_c distance at uniform speed V_2 as shown in figure 3.4.

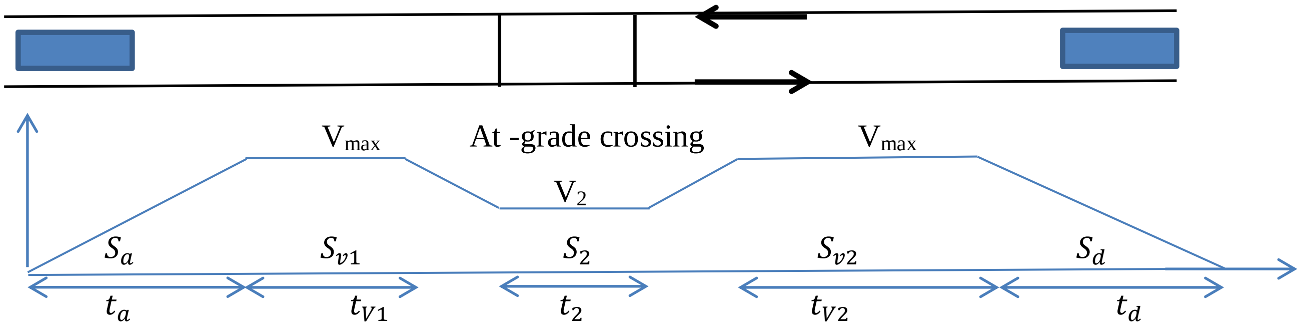

Figure 3. 4 Travel time for case C

This study considers the additional times spent in decelerating and accelerating the maximum speed to the allowable speed near turnout, junctions and level crossing and a time traveling with allowable speed near the crossings.

Following the concept used by Vukan in the preceding analysis, this study drives a simple equation of travel time between station to account for additional time required by a train while reducing its speed at at-grade crossings as shown below in Equation 3.17

$$T_s = \underbrace{\left[\frac{V_{max}}{2}\left(\frac{1}{a}+\frac{1}{d}\right)+\frac{S}{V_{max}}\right]}_{\text{The same as Case B}} + \underbrace{\left[\left(\frac{1}{a}+\frac{1}{d}\right)\left(\frac{V_{max}}{2}-V_2+\frac{V_2^2}{V_{max}}\right)+S_2\left(\frac{1}{V_2}-\frac{1}{V_{max}}\right)\right]}_{\text{additional time}}$$

Equation 3.17

Where,

a = acceleration rate (m/s^2)

d = deceleration rate (m/s^2)

V_{max} = Maximum speed of the line

V_2 = allowable speed through turnout or Junction or Level crossing

S_c = Crossing distance with constant speed V_2

S = station to station distance

T_s = travel time between stations

In this study, additional times required by a train to clear out from the platform of departing station and to travel its own length at arrival station are considered. The time required to clear out of the platform of the departing station is calculated as shown below as depicted in TCRP Manual (1996)

$$t_{p1} = \sqrt{\left(\frac{2(L+D)}{a(1-0.1G_o}\right)}$$

Equation 3.18

Where

t_{p1} = Time to clear out of the platform of departing station (sec)

L = length of the train (m)

D = distance from front of stopped train to seconds of station (m)

G_o= Gradient out of the departing station (%)

a = acceleration rate (m/s^2)

A time required by a train to travel its' own length t_{p2} at the arrival station can be approximately calculated as shown below (TCQSM, 2004)

$$t_{p2} = \frac{V_p}{2d}$$ Equation 3.19

Where

V_p = approaching Speed to station platform

d = decelerating rate

Finally in this study, the total travel time (TT) between stations is computed by adding the travel times between stations, the time to clear the platform and the time required to travel its own length at arrival station.

$$TT = T_s + t_{p1} + t_{p2}$$ Equation 3.20

Where

TT = total travel time

T_s = travel time between stations

t_{p1} = time to clear out of from the platform of departing station (sec)

t_{p2} = time required by a train to travel its' own length at the arrival station

3.4.6.2.Summary of the steps to determine Total Travel Time (TTT)

In general, the following procedures are used in calculation of travel time between stations.

a) Calculation of critical distance (S_c) using the maximum speed allowed V_{max} between stations is formulated below:

$$S_c = \frac{V_{max}^2}{2}\left(\frac{1}{a} + \frac{1}{d}\right)$$ (Using Equation 3.12 above)

b) Calculate travel time using the following cases

i) If the station to station distance $S < S_c$, Travel time between stations $T_s = t_a + t_d = \sqrt{\frac{2(a+d)s'}{ab}}$ (Using Equation 3.11 above)

The maximum achievable speed $V' = \sqrt{\frac{2a \times d \times S'}{a+d}}$ (Using Equation 3.10 above)

ii) If the station to station distance $S > S_c$ and No At-grade crossings

Travel time between stations $T_s = \frac{S}{V_{max}} + \frac{V_{max}}{2}\left(\frac{1}{a} + \frac{1}{d}\right)$ (Using Equation 3.16 above)

iii) If there are At-grade crossings, junctions, layout between stations ,the additional time is calculated as:

$$T_s = \left[\frac{V_{max}}{2}\left(\frac{1}{a} + \frac{1}{d}\right) + \frac{S}{V_{max}}\right]\left[\left(\frac{1}{a} + \frac{1}{d}\right)\left(\frac{V_{max}}{2} - V_2 + \frac{V_2^2}{V_{max}}\right) + S_2\left(\frac{1}{V_2} - \frac{1}{V_{max}}\right)\right]$$

(Using Equation 3.17 above)

iv) Calculate the time required by a train to clear out from the platform of departing station and to travel its' own length at arrival station using equation 3.18 and 3.19 respectively

$$t_{p1} = \sqrt{\left(\frac{2(L+D)}{(a-0.1G_o}\right)} \qquad t_{p2} = \frac{V_p}{2d}$$

c) Finally, calculate the total travel time between stations as follows:

$$TT = T_s + t_{p1} + t_{p2}$$ (Using equation 3.20 above)

3.4.6.3. Station Dwell time

In estimation of station dwell time, two approaches can be used as described in the literature review. The first method is assigning a reasonable value as recommended in different manuals and literatures. The second is using mathematical regression equations proposed based on out puts of different researches carried out on existing transit systems.

In this study, instead of simply assigned a reasonable values of dwell time, the results using the regression equations developed in different transit system are reviewed. The regression equations are mainly developed based on the number of boarding and alighting passengers. For example, in the model developed under Taiwan Railway Administration (TRA), the linear regression equation used the total number of boarding and alighting passengers served during arrival of each train in the station (Jong, 2011). LUL Method which was used in London Underground metro line also estimates the station dwell time using the number of alighting and boarding passengers in each train.

In this study, the simple regression equation developed by TCRP manual of Transport research board (TRB) in North America is used for estimation of dwell time of the stations. These equations are used to convert peak hour alighting and boarding passenger volumes and flow times into total doorway use times and then into dwell time (TCRP, 1996).The reason for selecting this method is that the available data for AALRT are alighting and boarding passengers volume of the stations per hour during peak hour of a day which are the input data required for the regression equation proposed by TCRP.

The resulting computational values of the equation are compared with the values recommended by different manual and literatures.

The following are the steps followed in calculating dwells from station hourly passenger flows using the regression equation proposed by TCRP.

1. Obtain peak hourly passenger volume on all stations of the railway system.
2. Select a station with the highest boarding, alighting or mixed passenger volume, $\boldsymbol{P_{max}}$ during the peak-hour movement.
3. Classify the flow as, mainly boarding, mainly alighting or mixed. For Example, All trains with greater than or equal to 70% boarding passengers were declared to be boarding.
4. Convert the passenger peak hour flow to Peak 15 minutes passenger flow using a or passenger loading factor or peak hour factor (PHF) as developed by TCRP Manual (TCRP,1996) which is shown below

$$P_{15min} = \frac{P_{max}}{4\ PHF} \qquad \text{Equation 3.21}$$

Where

P_{15min} = Passenger volume in peak 15 minutes of hour in single platform station

P_{max} = Passenger volume in peak hour in single platform station

$D_{ph} =$ PHF = Peak hour factor =Loading diversity factor

5. Calculate the number of double-stream train doors available in that of 15- min period, D_{15}.Using the following formula which was developed by TCRP Manual (TCRP,1996)

$$D_{15} = \frac{900\, D_n N_c}{t_{ts}+t_d+t_{om}}$$ Equation 3.22

Where

D_{15}= number of double-stream train doors available in the 15- min period

D_n= number of double-stream train doors per car

N_c= Number of cars per train

t_{ts}= Train Separation time

t_d=Dwell time (sec)

t_{om}= Operation Margin (Sec)

6. Calculate the passenger flows at the busiest door i.e., controlling, door of the train in the peak-within-the-peak time, F_{max} which is developed by TCRP Manual (TCRP,1996)

$$F_{max} = \frac{RP_{15min}}{D_{15}} = \frac{RP_{hour}(t_{ts}+ t_d+ t_{om})}{3600\, D_n\, N_c\, D_{ph}}$$ Equation 3.23

Where

F_{max}= Passenger flow at the busiest door of the train at peak hour

R=Ratio of busiest door usage to average door usage

7. The Transport Research Board of North America in TRCP Report developed a regression equation that relates to the passenger flows at the busiest door, F_{max} and flow time for the respective type of flow, alighting, boarding or mixed, at the maximum use door FT_{max} (seconds).The following equations illustrates the same

$$ln\left(FT_{max}^{alight}\right) = 1.440 + 0.0922F_{max}^{alight} - 0.0016\left(F_{max}^{alight}\right)^2$$ Equation 3.24

$$ln(FT_{max}^{board}) = 1.380 + 0.124F_{max}^{board} - 0.00241(F_{max}^{board})^2$$ Equation 3.25

$$ln\left(FT_{max}^{Mixed}\right) = 1.368 + 0.0948F_{max}^{alight} - 0.112(F_{max}^{board})^2 - 0.00184\left(F_{max}^{alight}\right)^2 - 0.00225(F_{max}^{board})^2$$ Equation 3.26

Where

FT_{max}= Flow time for the respective type of flow, alighting, boarding or mixed, at the maximum use door (seconds)

The dwell time relative to the respective maximum doorway flow time is given as:

$$ln(t_d) = 3.168 + 0.0254\ (FT_{max}^{mode})$$ Equation 3.27

Substituting F_{max} from equation 3.24 to 3.26 with each respective mode of Equation in to Equation 3.27 produces the following equations shown below as developed by TCRP Manual (TCRP, 1996)

$$ln(t_d) = 3.168 + 0.0254\left(e^{\left(1.380+0.124\frac{RP_{hour}(t_{ts}+\,t_d+\,t_{om})}{3600\,D_n\,N_c\,D_{ph}}-0.00214\left(\frac{RP_{hour}(t_{ts}+\,t_d+\,t_{om})}{3600\,D_n\,N_c\,D_{ph}}\right)^2\right)}\right)$$

Equation 3.28 for boarding

$$ln(t_d) = 3.168 + 0.0254\left(e^{\left(1.440+0.0922\frac{RP_{hour}(t_{ts}+\,t_d+\,t_{om})}{3600\,D_n\,N_c\,D_{ph}}-0.0016\left(\frac{RP_{hour}(t_{ts}+\,t_d+\,t_{om})}{3600\,D_n\,N_c\,D_{ph}}\right)^2\right)}\right)$$

Equation 3.29 for alighting

$$ln(t_d) = 3.168 + 0.0254\left(e^{\left(\begin{array}{l}1.368+0.0948\frac{RP_{hour}^{alight}(t_{ts}+t_d+t_{om})}{3600\,D_n\,N_c\,D_{ph}}-0.112\frac{RP_{hour}^{board}(t_{ts}+t_d+t_{om})}{3600\,D_n\,N_c\,D_{ph}}\\-0.00184\left(\frac{RP_{hour}^{alight}(t_{ts}+t_d+t_{om})}{3600\,D_n\,N_c\,D_{ph}}\right)^2-0.00225\left(\frac{RP_{hour}^{board}(t_{ts}+t_d+t_{om})}{3600\,D_n\,N_c\,D_{ph}}\right)^2\end{array}\right)}\right)$$

Equation 3.30 for Mixed

The required term, station dwell time t_d , is found in both side of the equation and solution of the each equation is solved by iterating for initial value given until the difference between the left and right side of the equation close to zero. This is computed using the Microsoft Excel goal seek feature.

The above regression equations are developed based on survey carried out in North America transit system and may or may not be applicable for Ethiopian condition. This will be reviewed after AALRT starts operation based on the survey conducted and similar regression equation can be developed .In this study, the resulting dwell time using the above regression equation is used to compared with the values recommended in manuals instead of simply assigning a recommended value.

In the capacity analysis based on passenger volume, the headway of the line is determined by using the line capacity or number of trains per hour as shown in section 3.4.4 and 3.4.5 .When the headway of a line is known, the above regression equation is expressed as shown below in Equation 3.31, 3.32 and 3.33 for alighting, boarding and Mixing respectively by substituting Headway (H) = $(t_{ts} + t_d + t_{om})$

$$ln(t_d) = 3.168 + 0.0254\left(e^{\left(1.380+0.124\frac{RP_{hour}H}{3600\,D_n\,N_c\,D_{ph}}-0.00214\left(\frac{RP_{hour}\,H}{3600\,D_n\,N_c\,D_{ph}}\right)^2\right)}\right)$$

Equation 3.31 for alighting

$$\ln(t_d) = 3.168 + 0.0254\left(e^{\left(1.44+0.0922\frac{RP_{hrH}}{3600D_nN_cD_{ph}}--0.0016\left(\frac{RP_{hrH}}{3600D_nN_cD_{ph}}\right)^2\right)}\right)$$

Equation 3.32 for boarding

$$ln(t_d) = 3.168 + 0.0254\left(e^{\left(1.368+0.0948\frac{RP_{hour}^{alight}H}{3600\,D_n\,N_c\,D_{ph}}-0.112\frac{RP_{hour}^{board}H}{3600\,D_n\,N_c\,D_{ph}}-0.00184\left(\frac{RP_{hour}^{alight}H}{3600\,D_n\,N_c\,D_{ph}}\right)^2-0.00225\left(\frac{RP_{hour}^{board}H}{3600\,D_n\,N_c\,D_{ph}}\right)^2\right)}\right)$$

Equation 3.33 for Mixed

Finally, this study develops a flow chart to describe a general steps followed in calculating station dwell time as shown below as shown in figure 3.5. After the operation of AALRT starts, the same methodology can be used by developing similar regression equations using actual survey data.

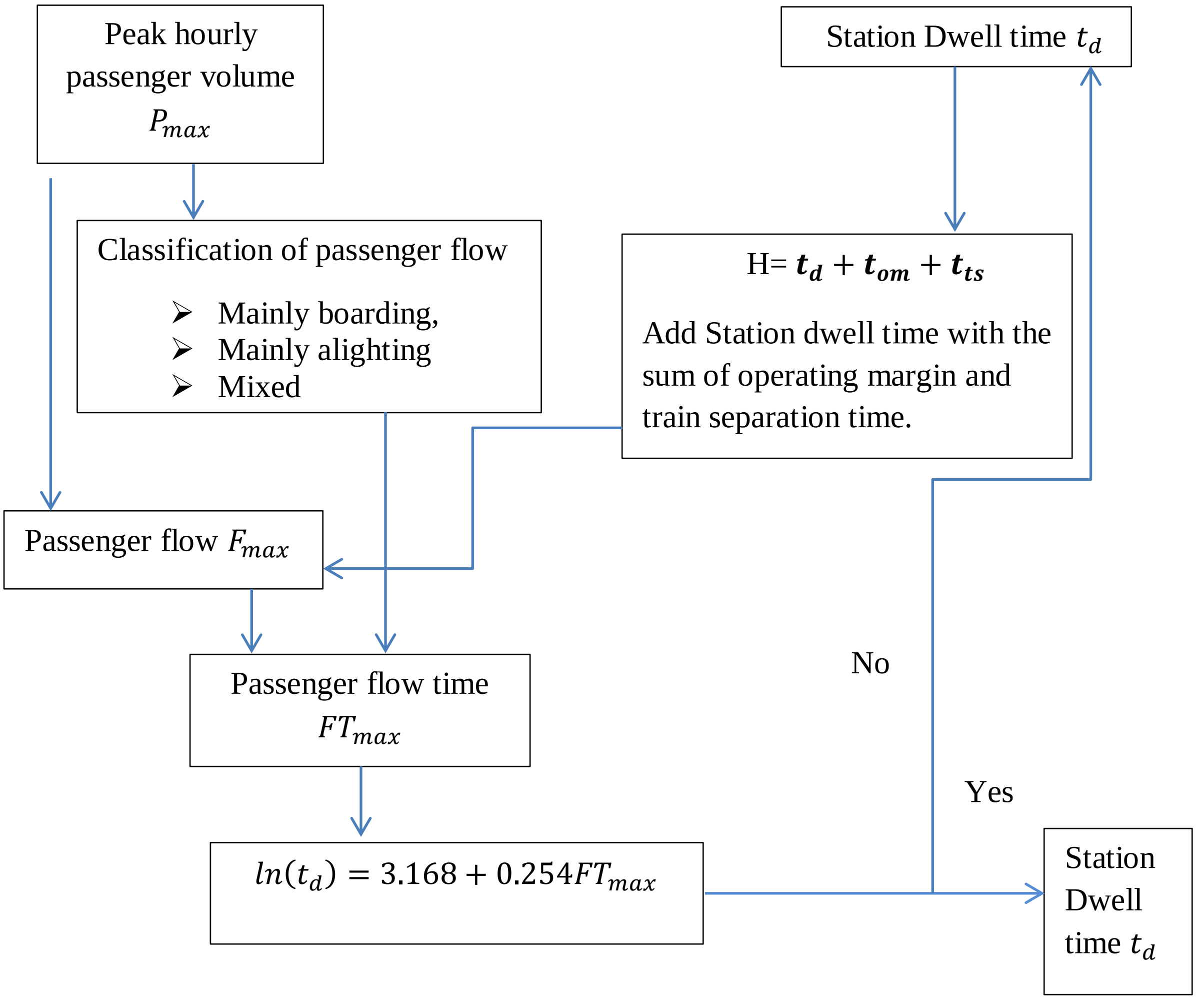

Figure 3. 5 Station dwell time analysis method

3.4.6.4. Turnaround and Layover Time at Turn-Back

Turnout layover time should be considered in the calculation of travel time at the ends of the line to account for the time required to change the direction of the train. The Turnaround and layover time must be sufficient to change direction of the train and allow for drivers to change ends and inspect the train and check trains integrity and braking. The maximum time available per track for terminal layover is given by Equation 3.34 as developed by TCQSM Manual (TCQSM, 2013)

$$t_{Lo} = \sqrt{\frac{2(L_t+f_{sa}d_{ts})}{a+d}} + \sqrt{\frac{(L_t+f_{sa}d_{ts})}{2a}} + t_s + L_t \times v \qquad \text{Equation 3.34}$$

Where

L_{Lo} =Length of the longest train

L_t =Length of the longest train

f_{sa}= Switch throw and lock time (s)

d_{ts}= track separation (m)

a = initial service acceleration rate

d= service deceleration rate

v=walking speed of the driver to change direction=1m/s

Figure 3.6. shows turn back dimensions used in equation 3.34

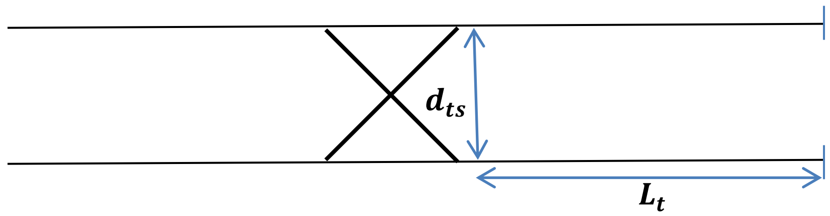

Figure 3. 6 Turn back dimensions

3.4.7. Total Round Trip time (TRTT)

The total round trip is computed by adding the sum of the travel time between stations, the sum of dwell time at each station and turnaround and layover time at turn-backs at the two ends of the line.

TRTT = $\sum TT_s + \sum t_d + \sum t_{Lo}$……………………..Equation 3.35

Where,

TT= Total Travel time between stations.

t_d = Station dwell time

t_{Lo}= Turnaround and Layover Time at Turn-backs

3.4.8. Total number of Trains (TNTR)

The next step is to calculate the number of trains required in the line. To find out how many trains are required to operate in regular interval passenger service, the following simple formula is applied:

$$Total\ Number\ of\ trains = \frac{Total\ round\ trip\ time}{headway\ of\ the\ line} \qquad \text{Equation 3.36}$$

Some railways keep a "service spare" train on standby, in case a service train becomes defective or a disruption to the service leaves a gap in the headway which needs to be filled temporarily. In this case we might plan to add one or two extra “Service Spare” to cover maintenance requirements.

3.4.9. Summary of the procedures for determination of capacity based on of passenger volume.

1) Total Passenger volume at stations: Identify station with maximum number of passenger volume per hour
2) Vehicle capacity: Determine the passenger capacity of Train Vehicle: Number of seat and standing passengers.
3) Planned Line capacity or number of Trains per hour:

$$\frac{\text{Passenger volume per hour}}{\text{Vehicle capacity}}$$

4) Planned Headway (minutes) H= $\frac{60\ minutes}{number\ of\ trains\ perhour}$
5) Round trip time (TRTT)
   a) Travel time b/n stations: Using procedures in section 3.4.6.1
   b) Station dwell time. Using Equation 3.31, 3.32 and 3.33
   c) Turn-Back Layover time : Using Equation 3.34

6) Total number of Trains required(TNTR)

$$= \frac{Total\ Round\ trip\ time}{Headway}$$

The methodology developed by this study for determining railway capacity based on Passenger volume using analytic method is presented by flow chart as shown below in figure 3.7

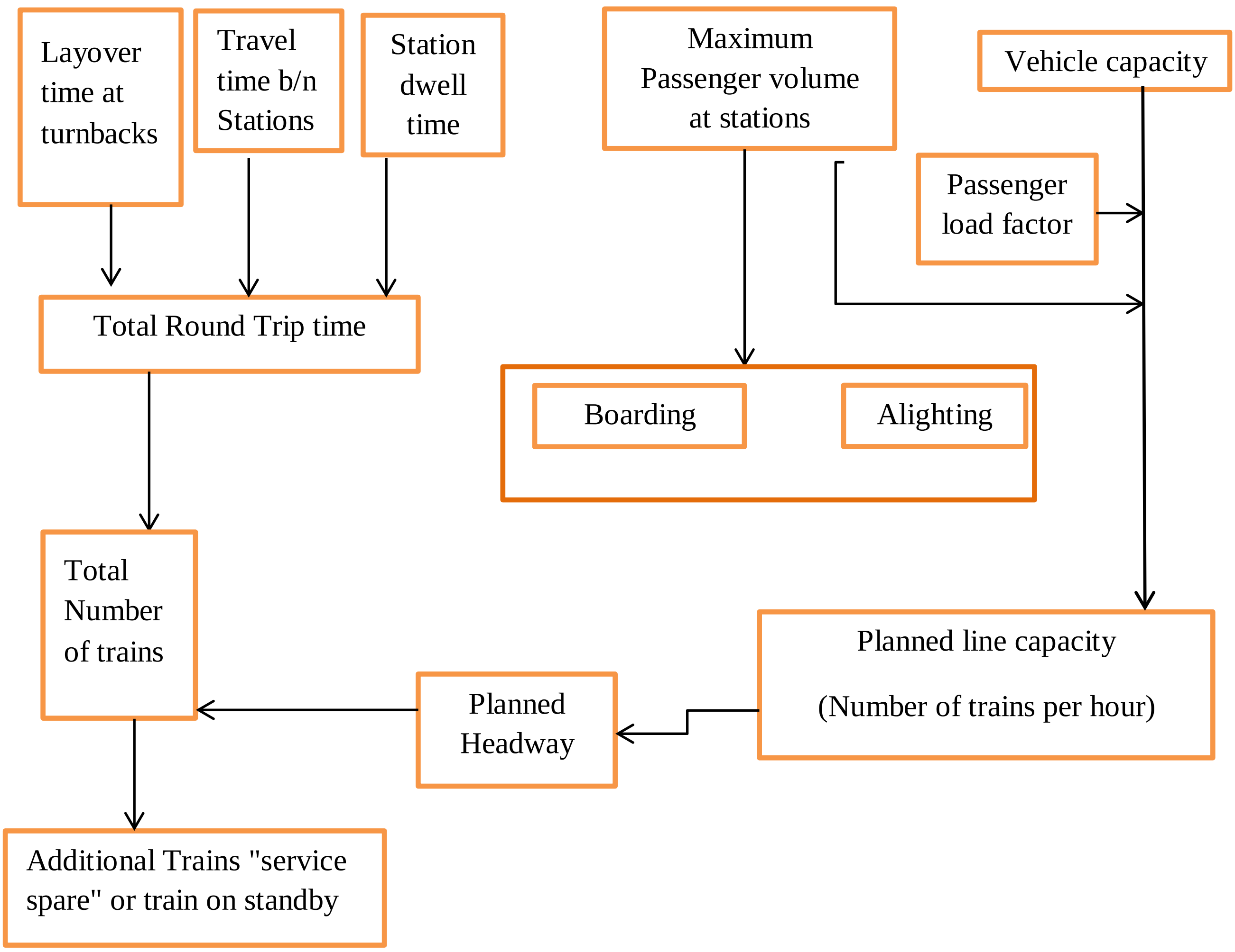

Figure 3. 7 Methodology for determination of railway capacity based on passenger volume

3.5. Determination of achievable capacity based on the maximum throughput of the system.

This method is used to calculate the maximum capacity of a railway system. The planned headway determined by above method using passenger volume can be further improved by achieving minimum train separation to optimize the capacity of the system. This minimum train separation is related to the signaling system. Therefore, this method provides an alternatives capacity options based on train separation control systems or signaling systems.

In addition, the method is useful in utilization of the unused capacity of a railway line whenever additional capacity is required in the system. Expansion work of railway infrastructure is a very costly means of increasing capacity. A more cost-effective solution is to manage the existing capacity more effectively.

3.5.1. Achievable capacity

Achievable capacity of a railway can be calculated as

$$C = \frac{\mathbf{3600}}{(\boldsymbol{t_s} + \boldsymbol{t_d} + \boldsymbol{t_{om}})} \times P_C \times N_C \times PHF \qquad \text{Equation 3.37}$$

Where:

C = achievable capacity (passenger/ h);

t_s= minimum train separation (sec);

t_d= dwell time at the controlling station (sec);

P_c= total number of passengers per car;

t_{om}=Operating Margin

N_c= Number of cars per train.

PHF = peak hour factor, H=Headway

The product of total passengers per car and number of cars per train gives vehicle capacity and is formulated as in Equation 3.38

$$\boldsymbol{C_v} = \boldsymbol{P_C} \times \boldsymbol{N_C} \qquad \text{Equation 3.38}$$

Headway of the line is calculated as

$$\text{Headway (sec)} = \quad H = t_s + t_d + t_{om} \qquad \text{Equation 3.39}$$

3.5.2. Identification of the capacity controlling section

The first step on determination of achievable capacity is the identification of the critical section or the weakest link along the rail line that will ultimately control capacity of the system .The control section could be the one with longer duration of station dwell time or where constrains like turnouts, turnbacks and junction are exist. Typically, on a new system like AALRT, the sum of the controlling dwell time, the minimum train separation, and the operating margin, which is called non-interference headway, will typically control the line capacity. A. However, the resulting headway due to the existence of turn backs and junction in the section is crosschecked and compared with the non-interference headway. The highest value of headway is used for determination of the line capacity.

3.5.3. Train separation time

3.5.3.1.Train separation principles

The distance between trains depends on the number and length of signal blocks used to separate trains. Signal spacing is a function of the stopping distance of a train operating at the maximum authorized speed.

First a basic theoretical principle to follow in provision of safe separation distance which is independent of the viewing range of the driver should be decided. As it is described in the literature review, the practical principles which are widely applicable worldwide are Train separation in Fixed Block distance and Train Separation in Absolute Braking distance. Train separation in a fixed block, the track is subdivided in blocks section and a block can be occupied by only one train at a time .Train Separation principle in Absolute braking distance is called moving block. In moving block, trains operate at closest as possible spacing with a distance equal to braking distance of the second train plus an additional safety distance.

The selection of Train Separation principle leads to the decision in selecting the type of signaling system. Under Fixed block signaling system three -aspects fixed block and multiple command cap signaling systems can be applicable. In Train Separation principle using Absolute braking distance using a moving block type of Signaling system is considered.

3.5.3.2. Train separation time

In Transit Capacity and Quality of Service Manual (2013), the minimum train control separation for fixed-block and cab signal systems is given as:

$$t_{ts} = \sqrt{\left(\frac{2(L_t+D)}{a+a_g G_o}\right)} + \frac{L_t}{v_a} + \left[\frac{1}{f_{br}} + b\right]\left(\frac{V_a}{2(d+a_g G_i)}\right) + \frac{(a+a_g G_o)\ t_{os}^2 l_v^2}{2V_a}\left(1 - \frac{V_a}{v_{max}}\right) + t_{os} + t_{ji} + t_{br}$$

(TCQSM3, 2013) …Equation 3.40

Where,

t_{ts}= Minimum train separation time (sec)

L_t =Train Length (m)

D =Distance from the front of stopped train to start of station exit block (m)

a=initial service line acceleration rate in m/s^2

a_g = Acceleration due to gravity m/s^2

d = service deceleration rate in m/s^2

f_{br} = braking safety factor (worst case service Braking of specified normal rate (decimal)

l_v =line voltage as percentage of specification. (Decimal)

t_{os}= time for overs speed governor to operate on automatic systems-to be replaced with driver sighting and reaction times on manual systems

t_{ij}= time lost to braking jerk limitation (sec)

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

G_o= Grade out of station, downgrade = negative (decimal)

G_i = Grade out of station, downgrade = negative (decimal)

V_a=Station approach speed (m/s)

V_{max}=Station approach speed (m/s)

b = separation safety factor

From Equation 3.40, $b\frac{V_a}{2(d+a_g G_i)}$ is the block length and b = separation safety factor which is equivalent to the number of braking distances or number of blocks that separate trains. For b=2.4 for three aspect fixed signaling system, 1.2 for cab signaling system and 1 for moving block system.

If the block length is known, the block traveling time can be approximately as, $\frac{L_b}{V}$

where

L_b = Block length

v_a = Line speed

Similarly, train separation time for moving block signaling system is calculated as

$$t_{ts} = \frac{P_e + L_t}{v_a} + \left[\frac{1}{f_{br}} + b\right]\left(\frac{V_a}{2(d + a_g G_i)}\right) + \frac{a(1 - 0.1G_i)\, t_{os}^2 l_v^2}{2V_a}\left(1 - \frac{V_a}{v_{max}}\right) + t_{os} + t_{ji} + t_{br}$$

(TCQSM, 2013) … Equation 3.41

Where

P_e = runaway propulsion allowance for moving signaling system (m)

The above equation 3.40 and 3.41 are composed of the basic distance-speed formula and parameters influencing the movement of a train. Each component of the equation is described as follows

1) $\sqrt{\left(\frac{2(L_t + D)}{a + a_g G_o}\right)}$ is the time for a train to clear the platform
2) $\frac{L_t}{v}$ is a time a train to travel its own length while stopping.
3) $b\frac{V_a}{2(d + a_g G_i)}$ is a time to travel a block length . If block length is given, the time to travel the block length= $\frac{L_b}{v}$
4) $\left[\frac{1}{f_{br}}\right]\frac{V_a}{2(d + a_g G_i)}$ is the service breaking time
5) t_{br} *is* a train operator sighting and reaction time and/or braking system reaction time.
6) $\frac{(a + a_g G_o)\, t_{os}^2 l_v^2}{2V_a}\left(1 - \frac{V_a}{v_{max}}\right) + t_{os}$ is a time allowance for an over speed distance a train may travel until automatic break system is utilized whenever the driver is delayed to apply the breaking due to the driver's negligence or failure occurs on the braking command or due to is issued with the train in full acceleration mode. 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. l_v =line voltage as percentage of specification.

7) t_{ji} is an allowance can be added for the jerk limiting features that taper the braking rate at the beginning and end of the brake application.

3.5.4. Station dwell time

In estimation of station dwell time, the same methodology as section 3.4.6.3 is applied. In estimation of achievable capacity using the throughput of the line, the regression equation may not show reliable results when a train operates close to its maximum capacity. Different manuals recommend assigning reasonable value of dwell time when a train operates close to its maximum capacity. From the data collected from the highest use stations in North America , TCQSM manual suggests a station dwell time that ranges from 35 to 45 seconds for the train operation that close to its capacity. In this study, the results of dwell time from regression equations 3.28 to 3.30 are only accepted if it would lie between these ranges. For the result of less than or greater than the recommended ranges, the average station dwell time of 40 second is considered. (TCQSM, 2013)

3.5.5. Operating Margin

Operating margin is an extra time allocated for small delays occur during train operation. In the determination of railway capacity, it is recommended to use values surveyed from similar existing line. In most cases a typical value of operating margin that ranges from 20 to 50 seconds are used.

In this study, operating margin value recommended by Transit Capacity and Quality Service Manual from for similar LRT project in North America is used.

3.5.6. Non-interference Headway

Headway (H) of a train can be calculated as the sum of train separation time ($\boldsymbol{t_{ts}}$), station dwell time ($\boldsymbol{t_{dw}}$) and Operating Margin time (t_{om})

$$h_{ni}(\boldsymbol{sec}) = \boldsymbol{t_{ts}} + \boldsymbol{t_{dw}} + \boldsymbol{t_{om}} \qquad \text{Equation 3.42}$$

Where

h_{ni} == Non-interference Headway

$\boldsymbol{t_{ts}}$=The close-in time or Train separation time

$\boldsymbol{t_d}$ =The dwell time at this station

$\boldsymbol{t_{om}}$= operating margin,

By Substituting Equation 3.40 and 3.41 in to Equation 3.42 the following equations of non-interference headways are developed

Non-interference Headway for fixed block and cab signaling system

$$H = \sqrt{\left(\frac{2(L_t+D)}{a+a_g G_o}\right)} + \frac{L_t}{v_a} + \left[\frac{1}{f_{br}} + b\right]\left(\frac{V_a}{2(d+a_g G_i)}\right) + \frac{(a+a_g G_o)\, t_{os}^2 l_v^2}{2V_a}\left(1 - \frac{V_a}{v_{max}}\right) + t_{os} + t_{ji} + t_{br} + t_{dw} + t_{om}$$

Equation 3.43

Non-interference Headway for moving block signaling system

$$H = \frac{P_e}{v_a} + \left[\frac{1}{f_{br}} + b\right]\left(\frac{V_a}{2(d + a_g G_i)}\right) + \frac{(a + a_g G_o)\, t_{os}^2 l_v^2}{2V_a}\left(1 - \frac{v}{v_{max}}\right) + t_{os} + t_{ji} + t_{br} + \frac{L_t}{v} + t_{dw} + t_{om}$$

Equation 3.44

3.5.7. Limiting Junction Headway

A junction could be a constraint and a controlling factor on capacity of the system. At junctions, capacity is reduced due to the time required for them to be set to the correct position (Switch and lock time) and by the speed limit imposed for a speed profile that will allow trains to stop before reaching a junction. Properly designed junction operates efficiently and could not be a constraint on the capacity. The headway at junction should be computed to compare with the non-interference headway. The limiting junction headway is computed as shown below in Equation 3.45 as developed by TCQSM Manual. (TCQSM, 2013)

$$h_J = t_{cs} + \sqrt{\frac{2(L_t+2f_{sa}d_{ts})}{a}} + \frac{V_{max}}{(a+d)} + t_s + t_{om}$$ Equation 3.45

a_g = Acceleration due to gravity=

a=Service acceleration rate

d = service deceleration rate in

L_t =Train Length

d_{ts}= Track separation

f_{sa}= switch angle factor

V_{max} =70km/hr

t_S =switch throw and lock time

t_{om}= Operating Margin

The Train control separation time imposed by signaling system, t_{cs} are calculated using Equation 3.40 and 3.41

3.5.8. Controlling Headway

The controlling headway is the governing minimum headway that determines the maximum achievable capacity of the railway line. In this study, the highest of non-interference headway and limiting headway at a junction is considered as a controlling headway.

For a Light rail system in which its operation is interrupted by signals of other modes of transport near at-grade crossing, the headway imposed by the right-of-way type should be considered. In case of AALRT, the headway due to the right-of-way constraints is not considered as the operation is along exclusive lane of reserved central median and priority is given for rail line at grade crossing with other modes of transport.

3.5.9. Maximum Line Capacity

The maximum line capacity of the system is expressed as number of maximum trains that can pass a critical point of the system and computed by dividing duration of 1 hour or 3600 seconds with the minimum headway achieved in the critical section of the line.

$$Number\ of\ Train\ per\ hour(N) = \frac{3600\ sec}{H} = \frac{3600}{(t_s + t_d + t_{om})} \qquad \text{Equation 3.46}$$

Where,

H= Headway

t_{ts}=The close-in time or Train separation time (sec)

t_d =The dwell time at this station (sec)

$\boldsymbol{t_{om}}$= operating margin (sec)

3.5.10. Vehicle capacity

Calculation of Vehicle capacity involves the determination of the number of seating and standing passenger per each car for a given dimensions of vehicle. The same procedures of section 3.4.2 is applied to calculate the passenger capacity of a vehicle using equation 3.1

Most of the literatures use passenger loading level to measure the passenger capacity of a vehicle of passengers. The above vehicle capacity computed using equation 3.1 can be converted in to the passengers per unit length method as suggested by Lang and Soberman to divide into classes and then compared with actual peak-within-the-peak loading levels of other rail transit. The variation in loading levels depends on policy of the standing density used and seat spacing.

$$Passenger\ Loading\ Level = \frac{\text{Vehicle capacity}}{\text{the sum of Interior lengths of Vehicle}} \qquad \text{Equation 3.47}$$

3.5.11. Capacity of a railway system

The Capacity of the system is described as the number passengers passed a critical station of the railway system per hour during peak hour. It is computed as

$$Total\ capacity = Number\ of\ trains\ per\ hour \times Vehicle\ capacity \qquad \text{Equation 3.48}$$

(Passengers per hour per direction)

3.5.12. Calculation of total achievable capacity

The capacity of the line as the number of passenger pass the controlling station per hour is determined by equation 3.48 above.

Using the steps followed in the above methodology, the equation 3.37 can be expressed as shown as in Equation 3.49

$$\boldsymbol{C} = \frac{\boldsymbol{3600}}{\boldsymbol{H}} \times C_v \times PHF \qquad \text{Equation 3.49}$$

Where,

H=Controlling headway (seconds) determined in section 3.5.8.

C_v=Vehicle capacity determined in section 3.5.10

PHF=Peak hour factor determined in section 3.4.3

3.5.13. Summary of the procedures for determination of achievable capacity based on maximum throughput of the system

1) Identification of the critical section or the weakest link along the rail line

2) Determine train separation time on a controlling section using Equation 3.40 and 3.41 depending on train control systems or signaling system.

3) Determine station dwell time and operating margin time using the procedures and recommendation in section 3.5.4 and 3.5.5 respectively.

4) Calculate Non-interference headway of the controlling section by adding station dwell time, operating margin time and Train separation time.

$$h_{ni} = t_s + t_d + t_{om}$$

5) Calculate limiting junction Headway using Equation 3.45
6) Determine the minimum controlling headway of the line by considering the highest of Non-interference headway and limiting junction headway.

7) The line capacity or the number of trains pass a given critical section

$$N = \frac{3600}{minimum\ Headway}$$

8) Vehicle capacity: Determine the passenger capacity of Train Vehicle: Number of seat and standing passengers. (Using equation 3.1)

9) Compute Achievable Capacity of the system: Passengers per hour using Equation 3.49
10) Calculate the Round trip time using the procedures in section 3.4.6
11) Determined total number of Trains required= $\frac{Total\ round\ trip\ time}{headway}$

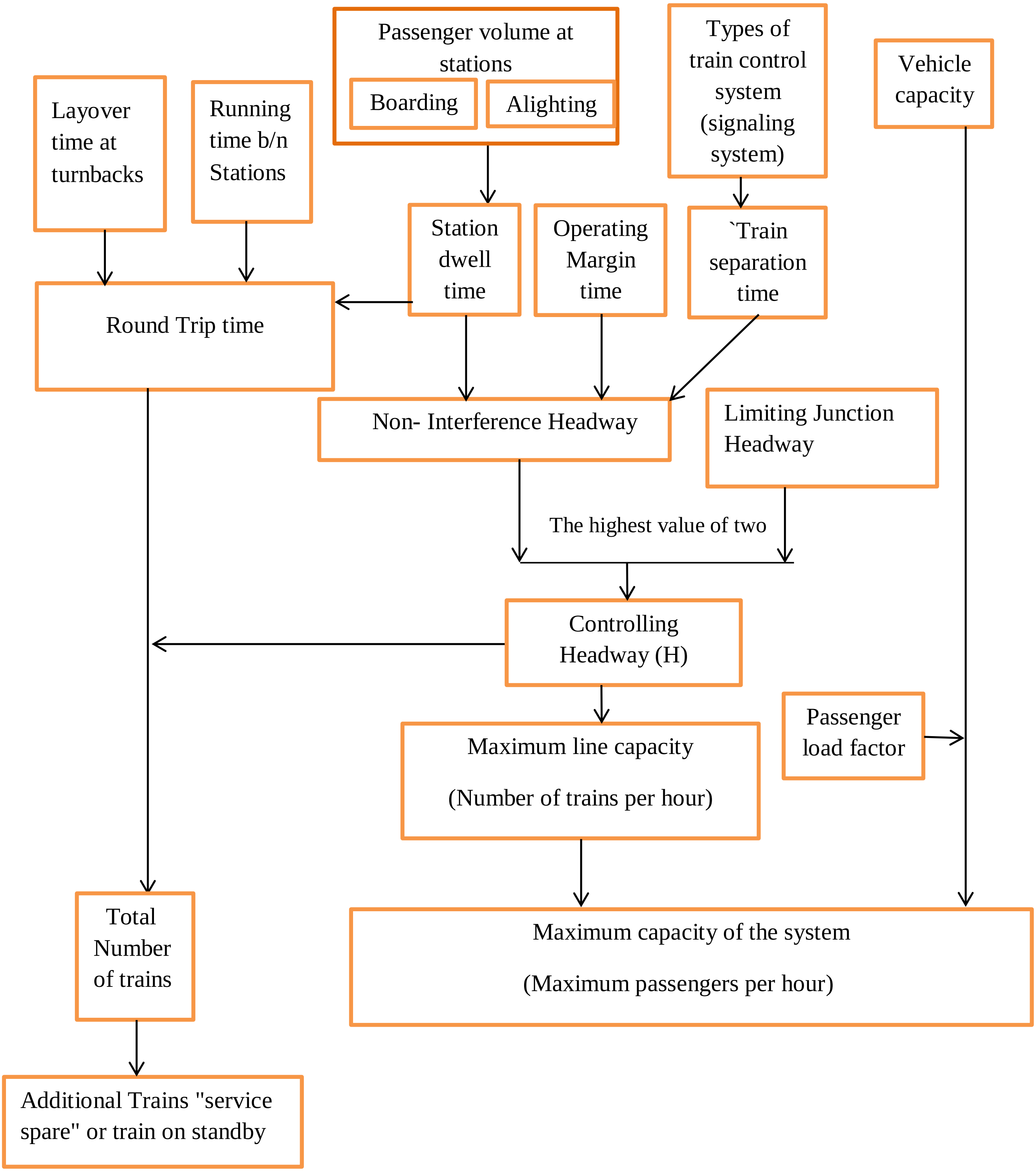

Figure 3. 8 Methodology of determining achievable capacity based on maximum throughput of the system

4.0. ANAYLISIS AND RESULTS

4.1. Estimation of AALRT Capacity based on Passenger volume

4.1.1. Capacity of East West line

4.1.1.1. Maximum passengers volume

For capacity estimation of AALRT, the data of peak hour passenger cross-section flow at the stations are taken from Schematic Design Report submitted by CREC. The total passenger flows at the stations of the East west line are forecasted in three forecast years: initial stage for 2018, Short term for 2025 and Long term for 2040. (CREC Schematic, 2012, 27-28).

The maximum passenger flow occurs in the morning and evening rush-hours. The morning rush-hour from 8:00AM to 9:00AM accounts the maximum of the daily passenger flow which is about 9%. Therefore, the peak passenger flow of the morning rush hour is used for analysis. The passenger cross-Section flow during morning rush-hour in Initial Stage, short term and Long term are presented in bar graphs as shown in figure 4.1, 4.2 and 4.3 respectively.

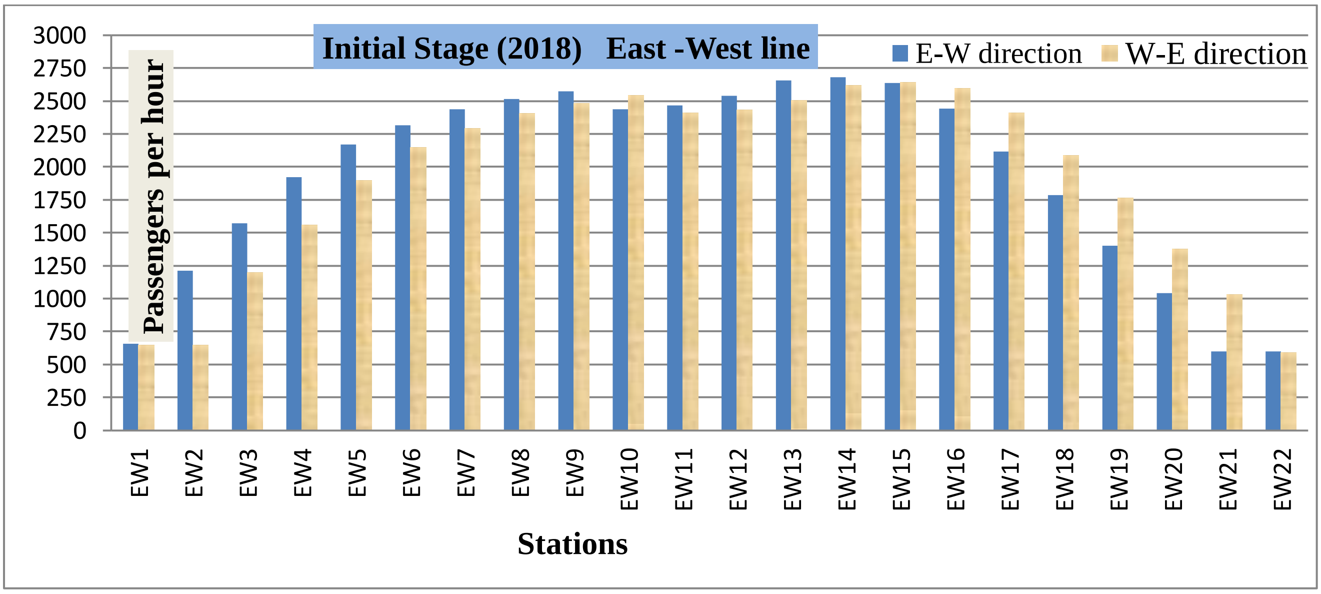

Figure 4. 1 Passenger Flow Cross-Section during Morning Rush-Hour in Initial Stage (2018)-Source CREC

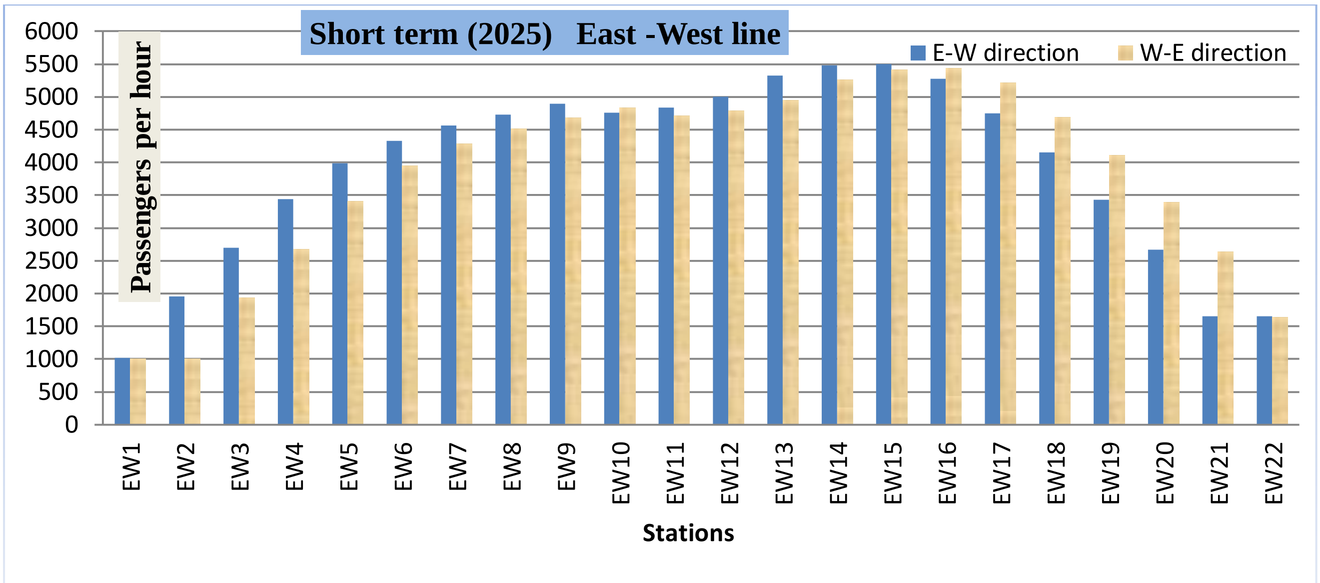

Figure 4. 2 Passenger Flow Cross-Section during Morning Rush-Hour in short term (2025)-Source CREC

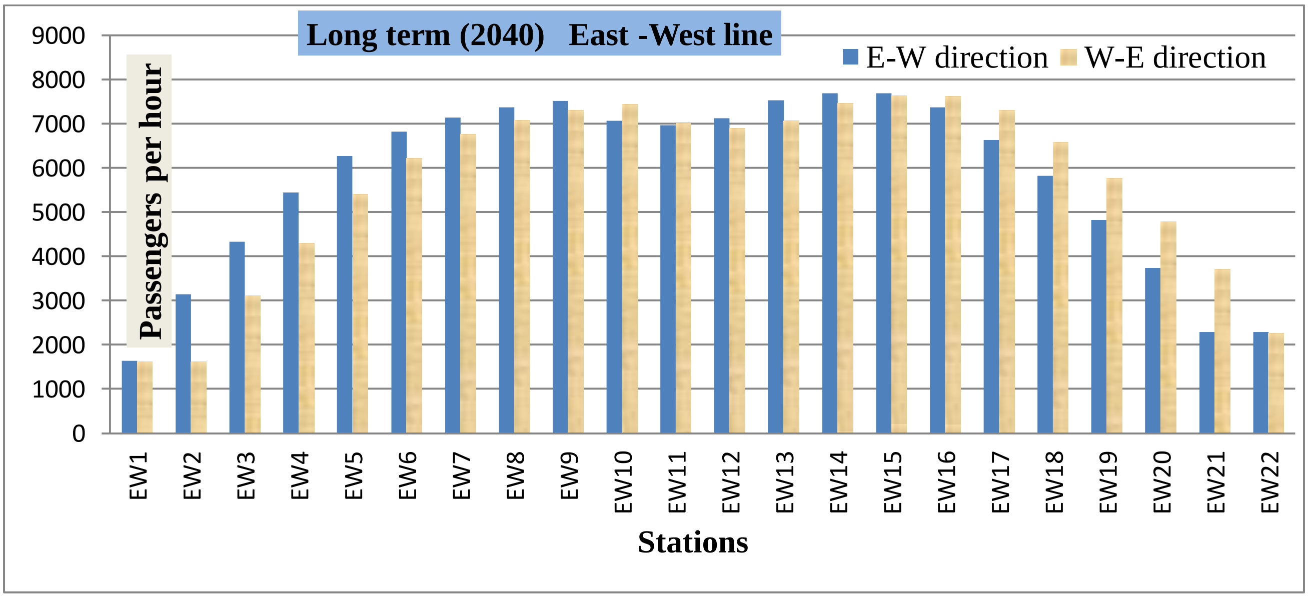

Figure 4. 3 Passenger Flow Cross-Section during Morning Rush-Hour in Long term (2040) - Source CREC

As it shown in the above bar graphs the maximum passenger flow volume of East -West line during morning peak hour in initial, short, long term is 2,679 Persons/hour located in section EW14-EW15, 5,502 Persons/hour in located section EW15-EW16 and 7,696 Persons / hour located in section EW14-EW15 (CREC Schematic, 2012, 11).

4.1.1.2. Vehicle capacity

The proposed vehicle type and size of AALRT is taken from a the report on technical specifications of the vehicles submitted by CREC in 2013.Vehicles are 70% low floor articulated 6 axle modern trams with maximum operating speed of 70km/h .Each unit of vehicle consists of three car which are bi-directional driving. Train marshaling of one unit (3 cars) in initial stage and two units of a train in short and long terms are considered in calculation of passenger carrying of the vehicles. (CREC Spec, 2013)

The procedure in 3.4.2 section is applied in calculation of the passenger carrying capacity of the vehicle .The vehicle is first divided into three sections depending on the proposed seating arrangement as it is shown in Figure 4 4. And then, the Seating is allocated to the free wall length by dividing by the seat pitch. A seat pitch (s_w) of 0.8m and 0.4m are considered for transverse seating and longitudinal seating respectively. The floor space remaining after deducting the seating space is used for standing passengers. The standing capacity of a train depends on the level of service. Taking the experiences LRT systems in developing countries, the Standing capacity of 6 passengers per m^2 and 8 passengers per m^2 can be used (Jack R., 2011). For estimation of number of trains passing a given point per hour, the worst case of a standing capacity of 6 passengers per m^2 is considered and the dimensions of internal components of the vehicle are taken from actual measurements.

As it is shown in table 4.1, the maximum passenger carrying of the vehicle at initial stage using one unit train (3 cars) is computed to be 289 and in terms of passenger loading level, it is 12 passengers per meter. The proposed capacity of the vehicle by CREC is 286 and the difference with the result of this study is small and the difference could be in measuring of dimension of the components of the vehicle. Therefore, in this study the capacity of vehicle proposed by CREC is used .Accordingly, the vehicle capacity is 286 at initial stage and 572 at short and long term are used.

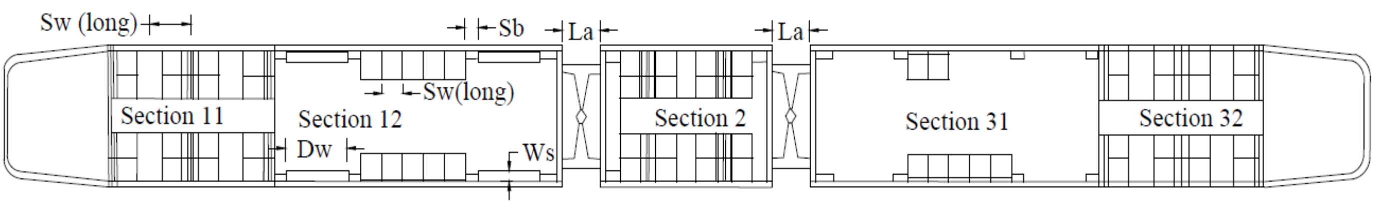

Figure 4. 4 Dimensions used in calculation of vehicle capacity

Table 4. 1 Calculation of Vehicle Passenger Carrying Capacity

Car External Wall thickness (m)	0.05	Internal Partition Wall thickness(m)	0.05	Area of single transverse seat (S_a)(m^2)	0.32	Number of Passengers per m2	6.00	Space per standing passenger (S_{sp})(m^2)	0.167
Car internal traversal Wall thickness (m)	0.05	Reduction of width in Articulation	0.4	Area of single longitudinal seat(S_a)(m^2)	0.32	Seat pitch transverse (S_w)	0.8	Seat pitch longitudinal (S_w)	0.4

N= 2 for longitudinal seating, N= 3 for 2+1 transverse seating, N= 4 for 2+2 transverse seating, N= 5 for 2+3 transverse seating

		Car 1		**Car 2**	**Car 3**		**Articulated Section**	**Total**
Exterior Dimension Per Car	Length(m)	9.55		3.6	9.55		1.6	**24.3**
	Width(m)	2.65		2.65	2.65		2.65	**2.65**
		Car 1		**Car 2**	**Car 3**		**Articulated Section**	**Total**
		Section 11	Section 12	Section 21	Section 31	Section 32		
Exterior Dimension per section of a car	Length(m)	3.5	6.05	3.6	6.2	3.35	1.6	22.7
	Width(m)	2.65	2.65	2.65	2.65	2.65	2.65	
Car Section Interior Dimension	Interior Length(m)	3.4	6	3.50	6.10	3.25	1.6	22.25
	Interior Width(m)	2.55	2.45	2.55	2.45	2.55	1.85	
Interior Area (m^2)		**8.67**	**14.70**	**8.93**	**14.95**	**8.29**	**2.96**	**55.53**

	Car 1		Car 2	Car 3		Articulated Section	Total
	Section 1-1	Section 1-2	Section 2-1	Section 3-1	Section 3-2		
Number of Double Stream Doors (D_n)	0	2	0	2	0	0	4
Door Width(D_w) in (m)	0	1.3	0	1.3	0	0	
Steep Well Width(m)	0	0	0	0	0	0	
Single setback allowance in (m)	0	0.2	0	0.2	0	0	
Length at corner that cannot be used for seating(m)	0	0.6	0	0.6	0	0	
Free wall Length cannot used for Seating (m)	3.4	2.0	3.5	2.1	3.25	1.6	
Free Width Length not used for Seating in (m)	2.45	1.95	2.45	2.45	2.45	1.85	
Is seating in Articulated section allowed? Write Yes or No in Articulated section.						No	
Seating arrangement (N)	4	2	4	2	4	0	
	Transverse	Longitudinal	Transverse	Longitudinal	Transverse		
Allocated seating	4	5	4	5	4	0	
Number of seats	16	10	16	10	16	0	
Reduced number of Seats	0	0	0	3	0	0	
Total Number of Seats	**16**	**10**	**16**	**7**	**16**	0	**65**
Total Area occupied by Seats	5.12	3.2	5.12	2.24	5.12	0.00	
Is Stranding on Steep is allowed? Write **Yes** or **No**	No Steep	No Steep	No Steep	No Steep	No Steep	No Steep	
Standing Area available on Steep Well(m^2)	0	0	0	0.0	0	0	
Total number of Standing of Passengers	21	69	22	76	19	17	224
Total Number of Seats per Car	26		16	23		0	65
Total number of Standing Passengers per Car	**90**		**22**	**95**		**17**	224
Vehicle Capacity	116		38	118		17	**289**
Passenger per meter	**12**		**10**	**12**		**10**	
	Total Vehicle Capacity		**289**	**Passengers**			
	Total Passenger per meter		**12**	**Passengers per hour**			

In addition, different options of vehicle capacity are computed by varying the number and type of seating arrangements as shown in table 4.1.1

Table4.1.1. Options of Vehicle Capacity with different Seating arrangements

Option 1	Sections	Seating arrangement (N)	Seating type	Seating number	Number of standing passengers	Total number of passengers
Car 1	Section 11	4	Transverse	16	21	37
	Section 12	2	Longitudinal	10	69	79
Car 2	Section 21	4	Transverse	16	22	38
Car 3	Section 31	2	Longitudinal	10	76	86
	Section 32	4	Transverse	16	19	35
Articulation	-	-	-	0	17	17
	Reduced number of seats			-3		
	Total number of passengers			**65**	**224**	**289**

Option 2	Sections	Seating arrangement (N)	Seating type	Seating number	Number of standing passengers	Total number of passengers
Car 1	Section 11	2	Longitudinal	18	13	31
	Section 12	2	Longitudinal	10	59	69
Car 2	Section 21	2	Longitudinal	20	10	30
Car 3	Section 31	2	Longitudinal	10	62	72
	Section 32	2	Longitudinal	18	10	28
Articulation	-	-	-	0	17	17
	Total number of passengers			**76**	**171**	**247**

Option 3	Sections	Seating arrangement (N)	Seating type	Seating number	Number of standing passengers	Total number of passengers
Car 1	Section 11	4	Transverse	16	17	33
	Section 12	4	Transverse	8	63	71
Car 2	Section 21	4	Transverse	16	18	34
Car 3	Section 31	4	Transverse	8	66	74
	Section 32	4	Transverse	16	15	31
Articulation	-	-	-	0	17	17
	Total number of passengers			**64**	**196**	**260**

Option 4	Sections	Seating arrangement (N)	Seating type	Seating number	Number of standing passengers	Total number of passengers
Car 1	Section 11	2	Longitudinal	18	13	31
	Section 12	4	Transverse	8	63	71
Car 2	Section 21	2	Longitudinal	20	10	30
Car 3	Section 31	4	Transverse	8	66	74
	Section 32	2	Longitudinal	18	10	28
Articulation	-	-	-	0	17	17
	Total number of passengers			**72**	**179**	**251**

Option 5	Sections	Seating arrangement (N)	Seating type	Seatingn umber	Number of standing passengers	Total number of passengers
Car 1	Section 11	4	Transverse	16	17	33
	Section 12	2	Longitudinal	10	59	69
Car 2	Section 21	2	Longitudinal	20	10	30
Car 3	Section 31	2	Longitudinal	10	62	72
	Section 32	4	Transverse	16	15	31
Articulation	-	-	-	0	17	17
	Total number of passengers			**72**	**180**	**252**

Option 6	Sections	Seating arrangement (N)	Seating type	Seating number	Number of standing passengers	Total number of passengers
Car 1	Section 11	2	Longitudinal	16	17	33
	Section 12	2	Longitudinal	10	59	69
Car 2	Section 21	2	Longitudinal	20	10	30
Car 3	Section 31	2	Longitudinal	10	62	72
	Section 32	4	Transverse	16	15	31
Articulation	-	-	-	0	17	17
	Total number of passengers			**72**	**180**	**252**

Option 7	Sections	Seating arrangement (N)	Seating type	Seating number	Number of standing passengers	Total number of passengers
Car 1	Section 11	4	Transverse	16	17	33
	Section 12	4	Transverse	8	63	71
Car 2	Section 21	2	Longitudinal	20	10	30
Car 3	Section 31	2	Longitudinal	10	62	72
	Section 32	2	Longitudinal	18	10	28
Articulation	-	-	-	0	17	17
	Total number of passengers			**72**	**179**	**251**

Option 8	Sections	Seating arrangement (N)	Seating type	Seating number	Number of standing passengers	Total number of passengers
Car 1	Section 11	0	Transverse	0	52	52
	Section 12	0	Transverse	0	81	81
Car 2	Section 21	0	Transverse	0	53	53
Car 3	Section 31	0	Transverse	0	83	83
	Section 32	0	Transverse	0	49	49
Articulation	-	-	-	0	17	17
	Total number of passengers			**0**	**335**	**335**

4.1.1.3.Planned Line Capacity of East West line

The line capacity is described by the number of train passed at station with large number of passenger volume per hour and computed by using Equation 3.6.as shown below.

Passenger loading diversity factorD_{ph} of 0.9 is used as described in Section 3.4.3

The number of trains per hour for E-W line in initial stage is calculated as

$$\frac{\text{maximum passenger flow volume}}{\text{Peak hour factor} \times \text{train capacity}} = \frac{P_{max}}{PHF \times C_v} = \frac{2{,}679 \text{ passeneger/hr}}{0.90 \times 286 \text{ passenger/train}}$$

$$= 10.41$$

$$\approx 11 \text{ train/hr}$$

For Short term using two unit of a train

$$\frac{P_{max}}{D_{ph} \times C_v} = \frac{5{,}502 \text{ passeneger/hr}}{0.9 \times 572 \text{ passenger/train}} = 10.69 \approx 11 \text{ trains /hr}$$

For long term using two unit of a train

$$\frac{P_{max}}{D_{ph} \times C_v} = \frac{7{,}696 \text{ passeneger/hr}}{0.90 \times 572 \text{ passenger/train}} = 14.95 \approx 15 \text{ trains /hr}$$

4.1.1.4. Planned headway of E-W line

The headway of a line is computed as shown below using Equation 3.7

For initial stage (2018)

Planned Headway = $\frac{60}{number\ of\ trains\ perhour} = \frac{3600}{11} = 327.27sec = 5.5\ minutes$

For Short term (2025)

Planned Headway = $\frac{60}{number\ of\ trains\ perhour} = \frac{3600}{11} = 327.27sec = 5.5\ minutes$

For long term (2040)

Planned Headway = $\frac{60}{number\ of\ trains\ perhour} = \frac{3600}{15} = 240\ sec$

$$= 4.0\ minutes$$

4.1.1.5. Total Round Trip Time of E-W line

4.1.1.5.1. Station dwell time

Station Dwell time is computed using equation 3.31, 3.32 and 3.33 as described in section 3.4.6.3. The hourly volume data of boarding and alighting passengers are adopted from Schematic design report submitted by the Contractor of AALRT, CREC.
(CREC Schem, 2013)

The passenger volume data are provided for the three forecasting years and station dwell time is estimated for initial stage, short term and long term as shown in section 4.1.1.1.

The analysis is executed using Microsoft Excel and the results are presented as follows from table 4.2 to 4.7 and the sum of the station dwell time at each stage is given in the bottom of each table

The description of terms used in the tables are listed below

$D_{n=}$ number of double-stream train doors per car

$N_{c=}$ Number of cars per train

D_{ph}=PHF= Peak hour factor or loading diversity factor

Flow class=Flow classification type

A =alighting

B=boarding

M=Mixed

F=number passenger flow on busiest door

FT=Passenger flow time at busiest door (sec)

Table 4. 2 Station dwell time (East-West line) - Initial Stage (2018)

R	1.2	D_n	2	N_c	2.00	PHF	0.9	Headway (minutes)				5.5
East to West							West to East					
Station No	Passenger boarding Volume	Passenger alighting Volume	Flow Class.	F	FT (sec)	Station Dwell time(sec)	Passenger boarding Volume	Passenger alighting Volume	Flow Class.	F	FT (sec)	Station Dwell time(sec)
EW1	656	0	B	21.0	31.10	**53**		648	A	20.0	16.78	**37**
EW2	556	3	B	17.0	22.87	**43**	3	553	A	17.0	14.47	**35**
EW3	370	8	B	12.0	14.72	**35**	8	370	A	12.0	10.80	**32**
EW4	368	22	B	12.0	14.72	**35**	22	362	A	12.0	10.80	**32**
EW5	288	37	B	9.0	10.97	**32**	36	285	A	9.0	8.81	**30**
EW6	183	35	B	6.0	8.00	**30**	35	179	A	6.0	7.04	**29**
EW7	168	49	B	6.0	8.00	**30**	49	165	A	6.0	7.04	**29**
EW8	129	52	B	4.0	6.40	**28**	51	127	A	4.0	5.99	**28**
EW9	312	250	M	18.0	5.33	**28**	247	305	M	18.0	6.55	**29**
EW10	572	708	M	40.0	5.34	**60**	699	566	M	40.0	3.29	**60**
EW11	561	534	M	35.0	4.82	**60**	527	552	M	34.0	5.36	**60**
EW12	283	210	M	16.0	5.13	**28**	208	281	M	16.0	6.58	**29**
EW13	311	196	M	16.0	4.76	**27**	194	307	M	16.0	7.03	**29**
EW14	206	181	M	13.0	5.35	**28**	178	203	M	13.0	5.80	**28**
EW15	192	237	M	14.0	6.14	**28**	236	189	M	14.0	5.24	**28**
EW16	167	357	M	17.0	7.90	**30**	352	165	M	17.0	4.13	**27**
EW17	106	434	A	14.0	12.22	**33**	429	105	B	14.0	17.69	**38**
EW18	39	369	A	12.0	10.80	**32**	362	39	B	12.0	14.72	**35**
EW19	20	408	A	13.0	11.50	**32**	404	20	B	13.0	16.16	**36**
EW20	8	365	A	12.0	10.80	**32**	358	8	B	11.0	13.38	**34**
EW21	3	445	A	14.0	12.22	**33**	443	3	B	14.0	17.69	**38**
EW22		599	A	19.0	16.01	**36**	591		B	19.0	26.80	**47**
Total Station Dwell Time(sec)			**1,543.00**	**25.72≈26 min**								

Table 4. 3 Station dwell time (East-West line) – Short term (2025)

R	1.2	D_n	2	N_c	4.00	D_{ph}	0.9	Headway (minutes)				5.5
East to West							West to East					
Station No	Passenger boarding Volume	Passenger alighting Volume	Flow Class.	F	FT (sec)	Station Dwell time (sec)	Passenger boarding Volume	Passenger alighting Volume	Flow Class.	F	FT (sec)	Station Dwell time(sec)
EW1	1018		B	16.0	21.04	**41**		1006	A	16.0	13.71	**34**
EW2	942	3	B	15.0	19.32	**39**	3	935	A	15.0	12.96	**33**
EW3	756	13	B	12.0	14.72	**35**	13	751	A	12.0	10.80	**31**
EW4	781	39	B	12.0	14.72	**35**	38	770	A	12.0	10.80	**31**
EW5	614	65	B	10.0	12.13	**33**	65	608	A	10.0	9.45	**30**
EW6	413	71	B	7.0	8.91	**30**	70	407	A	7.0	7.60	**29**
EW7	296	70	B	5.0	7.16	**29**	69	291	A	5.0	6.50	**28**
EW8	258	89	B	4.0	6.40	**28**	88	255	A	4.0	5.99	**28**
EW9	549	387	M	15.0	5.01	**27**	383	540	M	15.0	6.57	**28**
EW10	1084	1214	M	36.0	5.42	**60**	1201	1074	M	36.0	4.33	**27**
EW11	1113	1032	M	34.0	4.78	**60**	1021	1098	M	33.0	5.58	**27**
EW12	589	428	M	16.0	5.08	**28**	424	584	M	16.0	6.69	**28**
EW13	697	376	M	17.0	4.38	**27**	372	690	M	17.0	7.59	**29**
EW14	520	368	M	14.0	5.01	**27**	364	515	M	14.0	6.48	**28**
EW15	491	465	M	16.0	5.69	**28**	463	486	M	16.0	5.92	**28**
EW16	426	654	M	17.0	7.12	**29**	646	421	M	17.0	4.82	**27**
EW17	276	805	A	13.0	11.50	**32**	797	273	B	13.0	16.16	**36**
EW18	106	697	A	11.0	10.11	**31**	686	105	B	11.0	13.38	**33**
EW19	56	777	A	12.0	10.80	**32**	769	55	B	12.0	14.72	**35**
EW20	27	797	A	13.0	11.50	**32**	785	27	B	12.0	14.72	**35**
EW21	11	1018	A	16.0	13.71	**34**	1010	11	B	16.0	21.04	**41**
EW22		1657	A	26.0	21.18	**60**	1637		B	26.0	43.20	**71**
Total Station Dwell Time(sec)			**1494**	**24.9≈ 25 min**								

Table 4. 4 Station dwell time (East-West line) – Long term (2040)

R	**1.2**	**D_n**	**2**	**N_c**	**4.00**	**D_{ph}**	0.9	**Headway (minutes)**				**4**
East to West							**West to East**					
Station No	**Passenger boarding Volume**	**Passenger alighting Volume**	**Flow Class.**	**F**	**FT (sec)**	**Station Dwell time (sec)**	**Passenger boarding Volume**	**Passenger alighting Volume**	**Flow Class.**	**F**	**FT (sec)**	**Station Dwell time (sec)**
EW1	1635		B	19.0	26.80	**47**		1622	A	19.0	16.01	**36**
EW2	1511	6	B	17.0	22.87	**43**	6	1503	A	17.0	14.47	**35**
EW3	1210	23	B	14.0	17.69	**38**	23	1204	A	14.0	12.22	**33**
EW4	1193	68	B	14.0	17.69	**38**	67	1182	A	14.0	12.22	**33**
EW5	936	115	B	11.0	13.38	**34**	114	929	A	11.0	10.11	**31**
EW6	686	142	B	8.0	9.90	**31**	141	679	A	8.0	8.19	**30**
EW7	435	117	B	5.0	7.16	**29**	116	430	A	5.0	6.50	**29**
EW8	380	149	B	5.0	7.16	**29**	148	377	A	5.0	6.50	**29**
EW9	756	612	M	16.0	5.28	**28**	608	747	M	16.0	6.77	**29**
EW10	1469	1909	M	39.0	3.26	**60**	1895	1459	M	39.0	1.43	**60**
EW11	1513	1617	M	35.0	3.08	**60**	1605	1499	M	35.0	2.58	**60**
EW12	845	679	M	18.0	5.12	**28**	675	840	M	18.0	6.87	**29**
EW13	958	564	M	18.0	4.06	**27**	560	951	M	18.0	8.14	**30**
EW14	716	547	M	15.0	5.16	**28**	543	711	M	15.0	6.91	**29**
EW15	675	680	M	16.0	6.05	**28**	677	670	M	16.0	5.98	**28**
EW16	580	904	M	18.0	7.77	**29**	896	576	M	17.0	4.41	**27**
EW17	376	1105	A	13.0	11.50	**32**	1097	373	B	13.0	16.16	**36**
EW18	146	963	A	11.0	10.11	**31**	952	145	B	11.0	13.38	**34**
EW19	76	1072	A	12.0	10.80	**32**	1064	76	B	12.0	14.72	**35**
EW20	38	1122	A	13.0	11.50	**32**	1111	38	B	13.0	16.16	**36**
EW21	16	1472	A	17.0	14.47	**35**	1464	16	B	17.0	22.87	**43**
EW22		2284	A	26.0	21.18	**60**	2265		B	26.0	43.20	**60**
Total Station Dwell Time(sec)			**1591**	**$26.5 \approx 27\ min$**								

4.1.1.5.2. Traveling Time between Stations of East West Line

The travel time between stations is computed using the procedures described in section 3.4.6.1.depending on the cases of motion. The input parameters are taken from the actual design of AALRT.

The description of terms used and the values of parameters are shown below

TT= Total travel time (sec) (to be calculated)

T_s=travel time between stations (Sec) (to be calculated)

t_{p1} = Time to clear out the platform of departing station (sec)

t_{p2} = time required by a train to travel its' own length at the arrival station

a = service acceleration rate =1.0 m/s^2 (CREC Spec, 2013)

d = Service acceleration rate =1.1 m/s^2 (CREC Spec, 2013)

D= Distance from Train Front to end of Platform =30 m (CREC Spec, 2013)

Allowed speed near level crossing, Junction, turnout =20km/hr (AALRT design)

The travel time between stations are computed as shown in table 4.5 below.

Accordingly, the total travel time from station to station is 58 minutes

Table 4. 5 Travel time between stations of East West line

	Station Interval		Gradient out	Station to station Length (m)	Max. Speed (Km/hr)	Critical Distance	allowable average Speed (Km/hr)	Station to Station travel time (second)	Travel time at departing and arrival stations	Number of Turnout and junction	Number of level crossing	Distance travel in level crossing	additional time at crossing	Total Travel time
	From	**To**	G_o	**S**	V_{max}	S_c	**v**	T_s	$t_{p1}+t_{p2}$				t_L	**TT**
1	Start	EW1	1.00	152	**20.0**	29.46	**20.0**	32.66	**12.6**	1	0	0	5.30	50.55
2	EW1	EW2	-0.50	1200	**65.0**	311.18	**65.0**	83.70	**12.3**	1	1	30	27.26	123.30
3	EW2	EW3	-1.00	1032	**65.0**	311.18	**65.0**	74.39	**13.2**	0	1	174	31.58	119.16
4	EW3	EW4	0.60	763	**65.0**	311.18	**65.0**	59.49	**13.4**	0	0	0	0.00	72.93
5	EW4	EW5	1.00	800	**65.0**	311.18	**65.0**	61.54	**13.4**	0	1	30	13.63	88.61
6	EW5	EW6	1.00	665	**65.0**	311.18	**65.0**	54.07	**12.6**	0	0	0	0.00	66.70
7	EW6	EW7	-0.40	910	**65.0**	311.18	**65.0**	67.63	**12.3**	0	1	145	27.96	107.93
8	EW7	EW8	-1.00	1026	**65.0**	311.18	**65.0**	74.06	**12.7**	1	1	30	27.26	114.06
9	EW8	EW9	-0.20	769	**65.0**	311.18	**65.0**	59.83	**13.3**	0	0	0	0.00	73.08
10	EW9	EW10	0.70	716	**65.0**	311.18	**65.0**	56.89	**13.3**	0	0	0	0.00	70.14
11	EW10	EW11	0.70	686	**65.0**	311.18	**65.0**	55.23	**12.7**	0	0	0	0.00	67.97
12	EW11	EW12	-0.20	627	**65.0**	311.18	**65.0**	51.96	**12.3**	0	0	0	0.00	64.30
13	EW12	EW13	-1.00	974	**65.0**	311.18	**65.0**	71.18	**12.4**	0	0	0	0.00	83.57
14	EW13	EW14	-0.90	615	**65.0**	311.18	**65.0**	51.30	**12.3**	0	0	0	0.00	63.63
15	EW14	EW15	-1.00	533	**65.0**	311.18	**65.0**	46.75	**12.3**	1	0	0	13.63	72.72
16	EW15	EW16	0.00	580	**65.0**	311.18	**65.0**	49.36	**12.8**	1	0	0	13.63	75.84
17	EW16	EW17	0.20	385	**65.0**	311.18	**65.0**	38.56	**13.0**	0	0	0	0.00	51.52
18	EW17	EW18	0.40	500	**60.0**	265.15	**60.0**	45.91	**13.1**	0	0	0	0.00	58.98
19	EW18	EW19	0.20	628	**60.0**	265.15	**60.0**	53.59	**13.0**	0	0	0	0.00	66.55
20	EW19	EW20	-1.00	675	**65.0**	311.18	**65.0**	54.62	**12.3**	0	0	0	0.00	66.96

	From	To	G_o	S	V_{max}	S_c	v	T_s	$t_{p1}+t_{p2}$				t_L	TT
21	EW20	EW21	0.50	672	**65.0**	311.18	**65.0**	54.45	**13.1**	1	0	0	13.63	81.22
22	EW21	EW22	-0.85	699	**50.0**	184.13	**50.0**	63.59	**12.4**	1	0	0	10.13	86.13
23	EW22	EW21	-0.45	699	**50.0**	184.13	**50.0**	63.59	**12.6**	1	0	0	10.13	86.33
24	EW21	EW20	0.85	672	**65.0**	311.18	**65.0**	54.45	**12.6**	1	0	0	13.63	80.67
25	EW20	EW19	-0.50	675	**65.0**	311.18	**65.0**	54.62	**13.4**	0	0	0	0.00	68.06
26	EW19	EW18	1.00	628	**60.0**	265.15	**60.0**	53.59	**12.7**	0	0	0	0.00	66.33
27	EW18	EW17	-0.20	500	**60.0**	265.15	**60.0**	45.91	**12.6**	0	0	0	0.00	58.54
28	EW17	EW16	-0.40	385	**50.0**	184.13	**50.0**	40.98	**12.7**	0	0	0	0.00	53.72
29	EW16	EW15	-0.20	580	**65.0**	311.18	**65.0**	49.36	**12.8**	1	0	0	13.63	75.84
30	EW15	EW14	0.00	533	**65.0**	311.18	**65.0**	46.75	**13.4**	1	0	0	13.63	73.83
31	EW14	EW13	1.00	615	**65.0**	311.18	**65.0**	51.30	**13.4**	0	0	0	0.00	64.67
32	EW13	EW12	0.90	974	**65.0**	311.18	**65.0**	71.18	**13.4**	0	0	0	0.00	84.62
33	EW12	EW11	1.00	627	**65.0**	311.18	**65.0**	51.96	**13.0**	0	0	0	0.00	64.92
34	EW11	EW10	0.20	686	**65.0**	311.18	**65.0**	55.23	**12.5**	0	0	0	0.00	67.71
35	EW10	EW9	-0.70	716	**65.0**	311.18	**65.0**	56.89	**12.5**	0	0	0	0.00	69.37
36	EW9	EW8	-0.70	769	**65.0**	311.18	**65.0**	59.83	**13.0**	0	0	0	0.00	72.79
37	EW8	EW7	0.20	1026	**65.0**	311.18	**65.0**	74.06	**13.4**	1	1	30	27.26	114.76
38	EW7	EW6	1.00	910	**65.0**	311.18	**65.0**	67.63	**13.1**	0	1	145	27.96	108.67
39	EW6	EW5	0.40	665	**65.0**	311.18	**65.0**	54.07	**12.3**	0	0	0	0.00	66.40
40	EW5	EW4	-1.00	800	**65.0**	311.18	**65.0**	61.54	**12.3**	0	1	30	13.63	87.51
41	EW4	EW3	-1.00	763	**65.0**	311.18	**65.0**	59.49	**12.5**	0	0	0	0.00	72.03
42	EW3	EW2	-0.60	1032	**65.0**	311.18	**65.0**	74.39	**13.4**	0	1	174	31.58	119.41
43	EW2	EW1	1.00	1200	**65.0**	311.18	**65.0**	83.70	**13.1**	1	1	30	27.26	124.09
44	EW1	Start	0.50	152	**20.0**	29.46	**20.0**	32.66	**12.8**	1	0	0	5.30	50.81

Total Travel time b/n stations (min) = 57.62≈58 minutes

4.1.1.5.3. Turnaround and Layover Time at turn back

The Layover time at turn backs are calculated using equation 3.34

$$t_{Lo} = \sqrt{\frac{2(L_t + f_{sa} d_{ts})}{a + d}} + \sqrt{\frac{(L_t + f_{sa} d_{ts})}{2a}} + t_s + L_t \times v$$

The values of parameters in the equation are taken from the actual design of AALRT and some values are adopted form the TCQSM as shown below recommended

Where

L_t =Length of the longest train =60m (CREC spec, 2013)

t_s= Switch throw and lock time (s) =6 seconds (TCQSM, 2013)

f_{sa}= switch angle factor =6.09 (TCQSM, 2013)

d_{ts}= track separation (m) = 4m (AALRT design, 2013)

a = initial service acceleration rate = 1m/s (CREC spec, 2013)

d= service deceleration rate (CREC spec, 2013)

v= walking speed of the driver one side to other assuming 1m/s walking

$t_{Lo} = \sqrt{\frac{2(60+6.09*4)}{1+1.1}} + \sqrt{\frac{(60+6.09*4)}{2*1}} + 6 + 60 \times 1$= 81.45≈ 85 seconds

4.1.1.5.4. Total round Trip Time E-W line

Total round Trip time (TRTT) is the sum of total travel time between stations, dwell time at each station and layover time at the two ends of a line as shown in Equation 3.35

The total travel time between stations is 58 minutes as shown in the table 4.5.As shown in the table 4.2, 4.3 and 4.4, the total dwell time estimated is 26 , 25 and 27 minutes at initial stage, short term and long term respectively.

Turnaround and Lay overtime Time at one end of the station is 85 seconds

Therefore, total trip travel time is computed as

At initial stage (2018)

TRTT = $\sum TT_s + \sum t_d + \sum t_{Lo}$= 58 min+ 26min. + (2* 85/60) min=86.83≈ 87 minutes

At short term (2025)

TRTT = $\sum TT_s + \sum t_d + \sum t_{Lo}$= 58 min+ 25 min. + (2* 85/60) min=85.83 ≈ 86 minutes

At long term (2040)

TRTT = $\sum TT_s + \sum t_d + \sum t_{Lo}$= 58 min+ 27min. + (2* 85/60) min=87.83≈ 88 minutes

4.1.1.6. Total number of Trains required for E-W line

$$Total\ number\ of\ trains\ required = \frac{\text{total round trip time}}{\text{Headway}}$$

Accordingly, the total number of Trains for initial stage is

$$\frac{87\ min}{5.5 min} = 15.82 \approx 16\ trains$$

For short term

$$\frac{86\ min}{5.5 min} = 15.64\ \ \approx 16\ trains$$

For long term

$$\frac{88 min}{4\ min} = 22\ trains$$

4.1.2. Capacity of North South line

4.1.2.1. Maximum passengers volume

The peak hour passenger cross-Section flow during morning rush-hour in initial stage (2018), short term (2025) and long term (2040) are provided in the CREC report and the data are presented as shown in figure 4.6, 4.7 and 4.8 respectively.

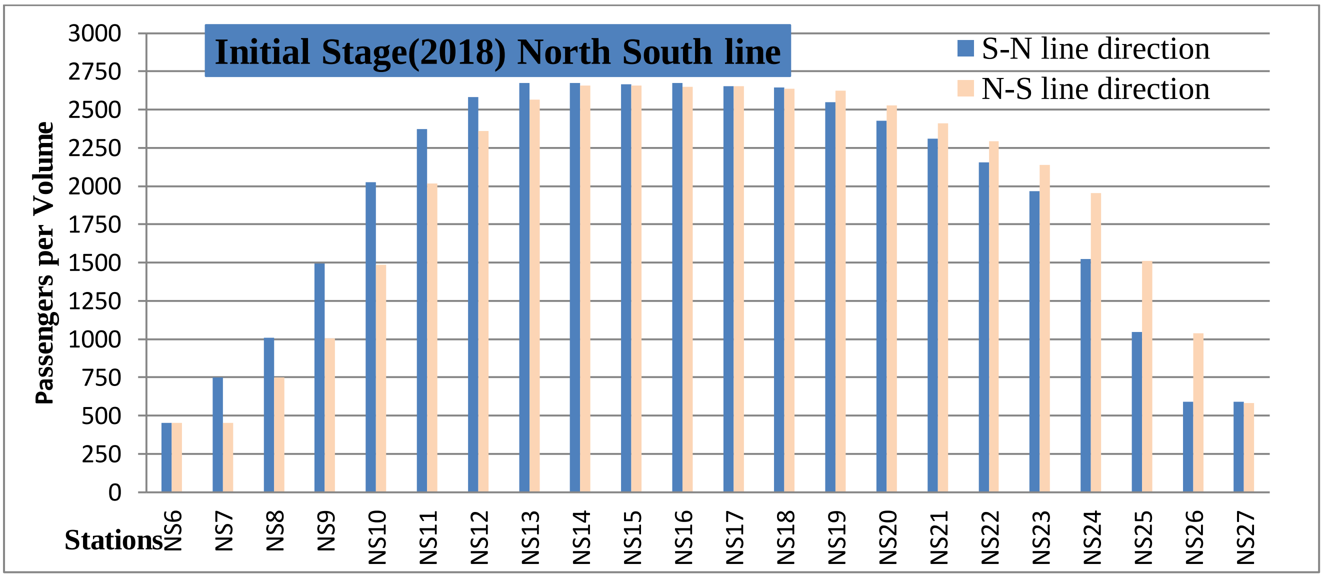

Figure 4. 5 Passenger Flow Cross-Section during Morning Rush-Hour in Initial Stage (2018)-source CREC

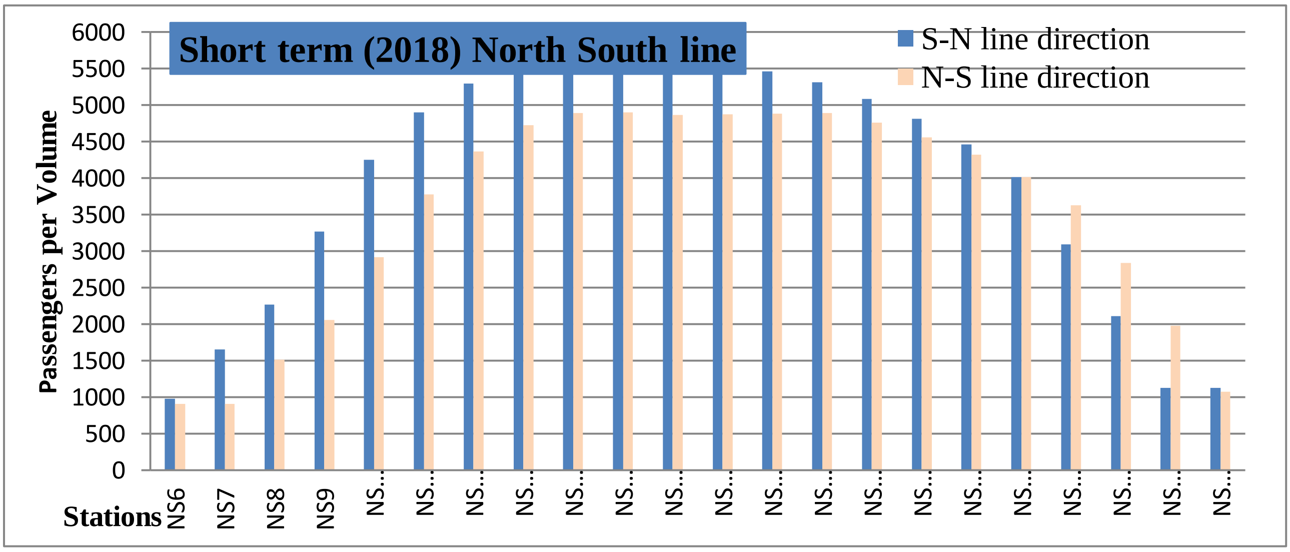

Figure 4. 6 Passenger Flow Cross-Section during Morning Rush-Hour in short term (2025)-source CREC

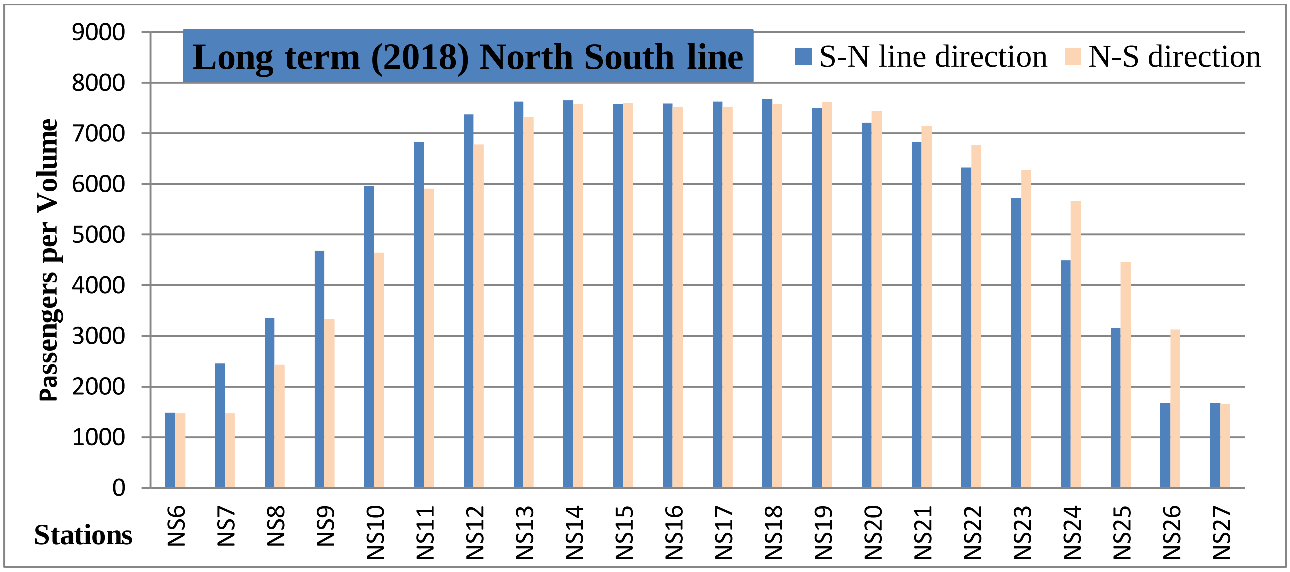

Figure 4. 7 Passenger Flow Cross-Section during Morning Rush-Hour in Long term (2040)-source CREC

As it shown in the above bar graphs, the maximum cross-section flow or maximum passenger flow volume of North-South line during morning peak hour in initial, short, long term is 2,675 Persons/hour located in section NS14-NS15, 5,491 Persons/hour in located section NS14-NS15 and 7,696 Persons / hour located in section NS18-NS19 (CREC Schematic, 2012, 19-20).

4.1.2.2. Vehicle capacity

The Maximum Vehicle capacity calculated in table 4.1 is also applied here. The maximum passenger carrying of the vehicle in initial stage using one unit train is 286 and in terms of passenger loading level, it is 11 passengers per meter. For short and long term using two units of a train, the maximum passenger capacity becomes 572.

4.1.2.3. Planned Line Capacity of N-S line

The number of trains per hour for N-S line in initial stage is calculated as

$$\frac{\text{maximum passenger flow volume}}{\text{Peak hour } \times \text{factortrain capacity}} = \frac{P_{max}}{D_{ph} \times C_v} = \frac{2{,}675 \text{ passenger/hr}}{0.90 \times 286 \text{ passenegr/train}} = 10.39$$

$$\approx 11 \ trains/hour$$

For short term

$$\frac{\text{maximum passenger flow volume}}{\text{Peak hour} \times \text{factortrain capacity}} = \frac{P_{max}}{D_{ph} \times C_v} = \frac{5491 \text{ passenger/hr}}{0.90 \times 572 \text{ passenegr/train}} = 10.67$$

$$\approx 11\ trains/hour$$

For long Term

$$\frac{\text{maximum passenger flow volume}}{\text{Peak hour} \times \text{factortrain capacity}} = \frac{P_{max}}{D_{ph} \times C_v} = \frac{7696 \text{ passenger/hr}}{0.90 \times 572\text{passenegr/train}} = 14.95$$

$$\approx 15\ trains/hour$$

4.1.2.4. Planned Headway

Headway in initial stage

$$\frac{60}{number\ of\ trains\ perhour} = \frac{3600}{11} = 327.27 sec = 5.5\ minutes$$

Headway in Short term

$$\frac{60}{number\ of\ trains\ perhour} = \frac{3600}{11} = 327.27\ sec = 5.5\ minutes$$

Headway in Short term

$$\frac{60}{number\ of\ trains\ perhour} = \frac{3600}{15} = 240\ sec = 4.0\ minutes$$

4.1.2.5. Round Trip Time of N-S line

4.1.2.5.1. Station dwell time

Station Dwell time is computed using Equation 3.31, 3.32 and 3.33 as described in section 3.4.6.3. The hourly volume data of boarding and alighting passengers are adopted from Schematic design report submitted by the Contractor of AALRT, CREC. (CREC Schem, 2013)

The dwell time for each station are computed as shown below in table 4.6, 4.7 and 4.8

Table 4. 6 station dwell time in stations of North South line at initial stage

R	**1.2**	**D_n**	**2**	**N_c**	**2.00**	**D_{ph}**	**0.9**	**Headway (minutes)**				**5.5**
	South to North						**North to South**					
Station No	**Passenger boarding Volume**	**Passenger alighting Volume**	**Flow Class.**	**F**	**FT (sec)**	**Station Dwell time (sec)**	**Passenger boarding Volume**	**Passenger alighting Volume**	**Flow Class.**	**F**	**FT (sec)**	**Station Dwell time(sec)**
NS6	455		B	14.0	17.69	**38**		452	A	14.0	12.22	**33**
NS7	297	1	B	10.0	12.13	**33**	1	299	A	10.0	9.45	**31**
NS8	260	4	B	8.0	9.90	**31**	4	262	A	9.0	8.81	**30**
NS9	513	26	B	16.0	21.04	**41**	26	507	A	16.0	13.71	**34**
NS10	596	65	B	19.0	26.80	**47**	65	593	A	19.0	16.01	**36**
NS11	434	86	B	14.0	17.69	**38**	85	429	A	14.0	12.22	**33**
NS12	333	124	B	11.0	13.38	**34**	123	330	A	11.0	10.11	**31**
NS13	232	143	M	13.0	4.73	**27**	142	230	M	13.0	6.38	**28**
NS14	213	210	M	14.0	5.65	**28**	209	209	M	14.0	5.67	**28**
NS15	164	172	M	12.0	5.49	**28**	171	164	M	12.0	5.35	**28**
NS16	412	406	M	26.0	5.83	**60**	404	407	M	26.0	5.94	**60**
NS17	440	458	M	28.0	5.91	**60**	456	439	M	28.0	5.56	**60**
NS18	387	397	M	25.0	6.05	**28**	394	385	M	25.0	5.86	**28**
NS19	295	392	M	22.0	7.07	**29**	389	293	M	21.0	5.04	**28**
NS20	198	316	M	17.0	7.11	**29**	317	197	M	17.0	4.72	**27**
NS21	77	194	A	6.0	7.04	**29**	192	76	B	6.0	8.00	**30**
NS22	58	213	A	7.0	7.60	**29**	213	57	B	7.0	8.91	**30**
NS23	33	222	A	7.0	7.60	**29**	217	33	B	7.0	8.91	**30**
NS24	42	486	A	15.0	12.96	**34**	484	41	B	15.0	19.32	**39**
NS25	14	492	A	16.0	13.71	**34**	485	14	B	15.0	19.32	**39**
NS26	3	458	A	14.0	12.22	**33**	458	3	B	14.0	17.69	**38**
NS27		590	A	19.0	16.01	**36**		584	A	18.0	15.24	**35**
Total Station Dwell Time(sec)			**1531sec**	**25.5 ≈ 26 min**								

Table 4. 7 station dwell time in stations of North South line at short term

R	1.2	D_n	2	N_c	4.00	D_{ph}	0.9	Headway (minutes)				5.5
	South to North						North to South					
Station No	Passenger boarding Volume	Passenger alighting Volume	Flow Class.	F	FT (sec)	Station Dwell time (sec)	Passenger boarding Volume	Passenger alighting Volume	Flow Class.	F	FT (sec)	Station Dwell time(sec)
EW1	980	0	B	15.0	19.32	**39**		908	A	14.0	12.22	**33**
EW2	675	3	B	11.0	13.38	**33**	3	604	A	10.0	9.45	**31**
EW3	624	10	B	10.0	12.13	**32**	10	557	A	9.0	8.81	**30**
EW4	1052	53	B	17.0	22.87	**42**	52	910	A	14.0	12.22	**33**
EW5	1106	124	B	17.0	22.87	**42**	122	986	A	16.0	13.71	**34**
EW6	821	169	B	13.0	16.16	**36**	167	753	A	12.0	10.80	**32**
EW7	633	235	B	10.0	12.13	**32**	232	592	A	10.0	9.45	**31**
EW8	453	270	M	12.0	4.68	**27**	267	433	M	12.0	6.24	**28**
EW9	486	474	M	16.0	5.76	**28**	390	403	M	13.0	5.67	**28**
EW10	447	496	M	15.0	6.05	**28**	408	377	M	13.0	5.45	**28**
EW11	898	892	M	28.0	5.70	**60**	702	710	M	22.0	6.06	**28**
EW12	908	902	M	28.0	5.68	**60**	777	784	M	24.0	5.99	**28**
EW13	786	773	M	25.0	5.88	**28**	664	676	M	22.0	6.08	**28**
EW14	519	673	M	19.0	6.81	**28**	649	513	M	18.0	5.29	**28**
EW15	369	596	M	16.0	6.99	**28**	566	365	M	15.0	4.83	**27**
EW16	184	454	A	7.0	7.60	**29**	420	182	M	10.0	4.28	**27**
EW17	126	484	A	8.0	8.19	**29**	436	125	B	7.0	8.91	**30**
EW18	71	516	A	8.0	8.19	**29**	448	70	B	7.0	8.91	**30**
EW19	77	1000	A	16.0	13.71	**34**	868	76	B	14.0	17.69	**38**
EW20	27	1013	A	16.0	13.71	**34**	888	26	B	14.0	17.69	**38**
EW21	6	989	A	16.0	13.71	**34**	916	6	B	14.0	17.69	**38**
EW22		1125	A	18.0	15.24	**35**	1070		B	17.0	22.87	**43**
Total Station Dwell Time(sec)			**1458**	**24.3≈ 25 min**								

Table 4. 8 Station dwell time in stations of North South line at Long term

R	1.2	D_n	2	N_c	4.00	D_{ph}	0.9	Headway (minutes)				4
South to North							North to South					
Station No	Passenger boarding volume	Passenger alighting volume	Flow Class.	F	FT (sec)	Station Dwell time (sec)	Passenger boarding volume	Passenger alighting volume	Flow Class.	F	FT (sec)	Station Dwell time(sec)
EW1	1480		B	17.0	22.87	**43**		1468	A	17.0	14.47	**35**
EW2	977	4	B	11.0	13.38	**34**	4	973	A	11.0	10.11	**31**
EW3	918	18	B	11.0	13.38	**34**	18	915	A	11.0	10.11	**31**
EW4	1411	87	B	16.0	21.04	**41**	86	1398	A	16.0	13.71	**34**
EW5	1475	196	B	17.0	22.87	**43**	195	1464	A	17.0	14.47	**35**
EW6	1152	273	B	13.0	16.16	**36**	271	1141	A	13.0	11.50	**32**
EW7	917	372	B	11.0	13.38	**34**	369	909	A	11.0	10.11	**31**
EW8	682	427	M	13.0	4.70	**27**	424	677	M	13.0	7.28	**29**
EW9	646	622	M	15.0	5.89	**28**	618	638	M	15.0	6.12	**28**
EW10	654	730	M	17.0	6.42	**28**	724	650	M	17.0	5.63	**28**
EW11	1094	1082	M	26.0	5.04	**60**	1073	1083	M	25.0	5.18	**28**
EW12	1220	1182	M	28.0	4.43	**60**	1174	1213	M	28.0	4.80	**60**
EW13	1046	1002	M	24.0	5.13	**28**	994	1038	M	24.0	5.58	**28**
EW14	794	973	M	20.0	6.71	**29**	965	788	M	20.0	4.90	**27**
EW15	579	870	M	17.0	7.60	**29**	866	574	M	17.0	4.55	**27**
EW16	325	706	M	12.0	7.89	**30**	700	323	M	12.0	4.11	**27**
EW17	213	708	A	8.0	8.19	**30**	704	212	B	8.0	9.90	**31**
EW18	120	735	A	9.0	8.81	**30**	726	119	B	9.0	10.97	**32**
EW19	121	1345	A	15.0	12.96	**34**	1335	120	B	15.0	19.32	**39**
EW20	43	1386	A	16.0	13.71	**34**	1372	42	B	16.0	21.04	**41**
EW21	10	1485	A	17.0	14.47	**35**	1477	10	B	17.0	22.87	**43**
EW22	1675		B	19.0	26.80	**47**	1661		B	19.0	26.80	**47**
Total Station Dwell Time(sec)			**1538**	**25.6 ≈ 26 min**								

4.1.2.5.2. Travel time between stations in North south line

Table 4. 9 Travel time between stations of North South line

	Station Interval		Gradient out	Station to station Length (m)	Max. Speed (Km/hr)	Critical Distance	allowable Speed (Km/hr)	Station to Station travel time (second)	Travel time at departing and arrival stations	Number of Turnout and junction	Number of level crossing	Distance travel in level crossing	additional time at crossing	Total Travel time
	From	**To**	G_o	**S**	V_{max}	S_c	**v**	T_s	$t_{p1}+t_{p2}$				t_L	**TT**
1	Start	NS6	0.10	84.0	**20.0**	29.46	**20.0**	20.42	**12.9**	1	0	0	5.30	38.63
2	NS6	NS7	0.50	890.0	**65.0**	311.18	**65.0**	66.53	**13.1**	0	0	0	0.00	79.66
3	NS7	NS8	1.00	785.0	**65.0**	311.18	**65.0**	60.71	**13.4**	0	1	30	13.63	87.78
4	NS8	NS9	1.00	475.0	**65.0**	311.18	**65.0**	43.54	**13.4**	0	0	0	0.00	56.98
5	NS9	NS10	1.00	935.0	**65.0**	311.18	**65.0**	69.02	**13.4**	1	1	54	30.25	112.71
6	NS10	NS11	0.50	801.0	**65.0**	311.18	**65.0**	61.60	**13.1**	0	0	0	0.00	74.73
7	NS11	NS12	-0.80	1909.0	**60.0**	265.15	**60.0**	130.45	**12.4**	0	0	0	0.00	142.88
8	NS12	NS13	0.80	495.0	**45.0**	149.15	**45.0**	51.53	**13.3**	0	0	0	0.00	64.85
9	NS13	NS14	1.00	550.0	**65.0**	311.18	**65.0**	47.70	**13.4**	0	0	0	0.00	61.14
10	NS14	NS15	1.00	403.0	**65.0**	311.18	**65.0**	39.55	**13.4**	0	0	0	0.00	53.00
11	NS15	NS16	0.20	848.0	**50.0**	184.13	**50.0**	74.31	**13.0**	2	2	121	60.19	147.46
12	NS16	NS17	0.20	385.0	**65.0**	311.18	**65.0**	38.56	**13.0**	0	0	0	0.00	51.52
13	NS17	NS18	0.40	500.0	**60.0**	265.15	**60.0**	45.91	**13.1**	0	0	0	0.00	58.98
14	NS18	NS19	0.20	628.0	**60.0**	265.15	**60.0**	53.59	**13.0**	0	0	0	0.00	66.55
15	NS19	NS20	-1.00	675.0	**65.0**	311.18	**65.0**	54.62	**12.3**	0	0	0	0.00	66.96
16	NS20	NS21	0.50	531.0	**50.0**	184.13	**50.0**	51.49	**13.1**	2	0	0	20.27	84.89
17	NS21	NS22	0.50	679.0	**35.0**	90.23	**35.0**	79.12	**13.1**	0	0	0	0.00	92.25
18	NS22	NS23	1.00	751.0	**65.0**	311.18	**65.0**	58.83	**13.4**	0	0	0	0.00	72.27
19	NS23	NS24	1.00	607.0	**50.0**	184.13	**50.0**	56.96	**13.4**	0	1	30	10.13	80.54

	From	To	G_o	S	V_{max}	S_c	v	T_s	$t_{p1}+t_{p2}$				t_L	TT
20	NS24	NS25	0.00	553.0	**65.0**	311.18	**65.0**	47.86	**12.8**	0	0	0	0.00	60.71
21	NS25	NS26	-1.00	885.0	**65.0**	311.18	**65.0**	66.25	**12.3**	0	0	0	0.00	78.59
22	NS26	NS27	0.40	683.0	**50.0**	184.13	**50.0**	62.43	**13.1**	0	0	0	0.00	75.51
23	NS27	End	-0.20	63.0	**15.0**	16.57	**15.0**	19.10	**12.7**	0	0	0	0.00	31.84
24	End	NS 27	0.20	63.0	**15.0**	16.57	**15.0**	19.10	**13.0**	0	0	0	0.00	32.06
25	NS 27	NS 26	0.20	683.0	**50.0**	184.13	**50.0**	62.43	**13.0**	0	0	0	0.00	75.39
26	NS 26	NS 25	-0.40	885.0	**65.0**	311.18	**65.0**	66.25	**12.6**	0	0	0	0.00	78.89
27	NS 25	NS 24	1.00	553.0	**65.0**	311.18	**65.0**	47.86	**13.4**	0	0	0	0.00	61.30
28	NS 24	NS 23	0.00	607.0	**50.0**	184.13	**50.0**	56.96	**12.8**	0	1	30	10.13	79.94
29	NS 23	NS 22	-1.00	751.0	**65.0**	311.18	**65.0**	58.83	**12.3**	0	0	0	0.00	71.17
30	NS 22	NS 21	-1.00	679.0	**35.0**	90.23	**35.0**	79.12	**12.3**	0	0		0.00	91.46
31	NS 21	NS 20	-0.50	531.0	**50.0**	184.13	**50.0**	51.49	**12.6**	2	0	0	20.27	84.34
32	NS 20	NS 19	-0.50	675.0	**65.0**	311.18	**65.0**	54.62	**12.6**	0	0	0	0.00	67.20
33	NS 19	NS 18	-1.00	628.0	**60.0**	265.15	**60.0**	53.59	**12.3**	0	0	0	0.00	65.93
34	NS 18	NS 17	-0.20	628.0	**60.0**	265.15	**60.0**	53.59	**12.7**	0	0	0	0.00	66.33
35	NS 17	NS 16	-0.40	385.0	**50.0**	184.13	**50.0**	40.98	**12.6**	0	0	0	0.00	53.61
36	NS 16	NS 15	-0.20	848.0	**50.0**	184.13	**50.0**	74.31	**12.7**	2	2	121	60.19	147.25
37	NS 15	NS 14	-0.20	403.0	**65.0**	311.18	**65.0**	39.55	**12.7**	0	0	0	0.00	52.30
38	NS 14	NS 13	-1.00	550.0	**65.0**	311.18	**65.0**	47.70	**12.3**	0	0	0	0.00	60.03
39	NS 13	NS 12	-1.00	495.0	**45.0**	149.15	**45.0**	51.53	**12.3**	0	0	0	0.00	63.87
40	NS 12	NS 11	-0.80	1909.0	**60.0**	265.15	**60.0**	130.45	**12.4**	0	0	0	0.00	142.88
41	NS 11	NS 10	0.80	801.0	**65.0**	311.18	**65.0**	61.60	**13.3**	0	0	0	0.00	74.91
42	NS 10	NS 9	-0.50	935.0	**65.0**	311.18	**65.0**	69.02	**12.6**	1	1	54	30.25	111.86
43	NS 9	NS 8	-1.00	475.0	**65.0**	311.18	**65.0**	43.54	**12.3**	0	0	0	0.00	55.88
44	NS 8	NS 7	-1.00	785.0	**65.0**	311.18	**65.0**	60.71	**12.3**	0	1	30	13.63	86.68
45	NS 7	NS 6	-1.00	890.0	**65.0**	311.18	**65.0**	66.53	**12.3**	0	0	0	0.00	78.87
46	NS 6	Start	-0.50	84.0	**20.0**	29.46	**20.0**	20.42	**12.6**	1	0	0	5.30	38.31
										Total Travel time(min)				**56.06**

4.1.2.5.3. Total round Trip Time N-S line

Total round Trip time is the sum of travel time between stations dwell time at each station and Turnaround and Layover time at turn backs. The total travel time between stations is 56.06 minutes as shown in the table 4.9 and the total dwell time is 26, 25 and 26 minutes at initial stage, short term and long term as shown in tables 4.6, 4.7 and 4.8 respectively. The turn back layover time of 85 seconds which is calculated in section 4.1.1.5.3 is used here.

Therefore, the total round trip time of N-S line is computed as

At initial stage

TRTT = $\sum TT_s + \sum t_d + \sum t_{Lo}$=56.06 min+26 min+ (2*85/60) =84.89 ≈ 85 minutes

For short Term

TRTT = $\sum TT_s + \sum t_d + \sum t_{Lo}$=56.06 min +25 min+ (2*85/60) =83.89 ≈84 minutes

For long Term

TRTT = $\sum TT_s + \sum t_d + \sum t_{Lo}$=56.06 min +26 min+ (2*85/60) =84.89 ≈85 minutes

4.1.2.5.4. Total number of Trains required for N-S line

$$Total\ number\ of\ Trains\ required = \frac{\text{Total Round trip time}}{\text{Headway}}$$

Accordingly, the total number of Trains for initial stage is

$$\frac{85\ min}{5.5\ min} = 15.5 \approx 16\ trains$$

For short term

$$\frac{84 min}{5.5\ min} = 15.3 \approx 16\ trains$$

For long term

$$\frac{85\ minutes}{4} = 21.21 \approx 22\ trains$$

4.1.3. Summary of the results for capacity of AALRT based on Passengers volume

The summary of the result for capacity of AALRT based on passenger volume and the total numbers of trains required for AALRT are shown below in table 4.10 and 4.11.

Table 4. 10 Summary of the results for capacity of AALRT

Line	East West			North South		
Forecasting Period	Initial Stage	Short term	Long Term	Initial Stage	Short term	Long Term
Forecasted Passenger volume (Passenger/hr.)	2679	5502	7696	2675	5491	7696
Line Capacity Trains/hr.	11	11	15	11	11	15
Headway(min)	5.5	5.5	4.0	5.5	5.5	4.0
Total Round trip Time(min)	87	86	88	85	84	85
Total number of Trains Required	16	16	22	16	16	22

Table 4. 11 Number of trains required for AALRT

	Total Number of Trains		
	Initial stage	Short Term	Long Term
East West line	16	16	22
North South line	16	16	22
Total number of trains required for operation	32	32	44
Standby and maintenance cars	4	4	4
Total Number of trains required	36	36	48

This study focus on the number of trains required for the operation to fulfill the passenger volume at peak hour .The number of Standby trains or the trains that stop for maintenance activities conducted during operation is assumed to be 2 for each line as considered by CREC report.

4.2.Determination of achievable Capacity of AALRT based on maximum throughput of the system

4.2.1. Maximum load point station or control section

The control section could be the one with longer duration of station dwell time or where constrains like turnouts, Turn-backs and junction are exist. Typically, on a new system like AALRT, the sum of the controlling dwell time, the minimum train separation, and the operating margin, which is called non-interference headway, will typically control the line capacity. A. However, the resulting headway due to the existence of turn backs and junction in the section is crosschecked and compared with the non-interference headway. The highest value of headway is used for determination of the line capacity.

As it is described in sections, 4.1.1.1 and 4.1.2.1 the maximum passenger flow occurs in the section between stations of EW14-EW15 for East West line and NS14-NS15 for North South line. Therefore, these sections are considered as a controlling section to calculate Non-interference headway that determines the line capacity.

4.2.2. Train Separation time

Train Separation time for three aspect-fixed block and cab signaling system is given as in Equation 3.40

$$t_{ts} = \sqrt{\left(\frac{2(L_t+D)}{a+a_g G_o}\right)} + \frac{L_t}{v_a} + \left[\frac{1}{f_{br}} + b\right]\left(\frac{V_a}{2(d+a_g G_i)}\right) + \frac{(a+a_g G_o)\; t_{os}^2 l_v^2}{2V_a}\left(1 - \frac{V_a}{v_{max}}\right) + t_{os} + t_{ji} + t_{br}$$

And for Moving block signaling system in Equation 3.41

$$t_{ts} = \frac{P_e+L_t}{v_a} + \left[\frac{1}{f_{br}} + b\right]\left(\frac{V_a}{2(d+a_g G_i)}\right) + \frac{(a+a_g G_o)\; t_{os}^2 l_v^2}{2V_a}\left(1 - \frac{V_a}{v_{max}}\right) + t_{os} + t_{ji} + \; t_{br}$$

Most of the input parameters of the Equation 3.40 and 3.41 are taken from the actual design of AALRT and Technical Specifications of the Vehicles (CREC, 2013). For parameters which are not available in the design, the recommended values in TCQSM are adopted as shown below

t_{ts}= Minimum train separation time (sec) –To be calculated

L_t =Train Length =30m (CREC Spec, 2013)

D =Distance from the front of stopped train to start of station exit block =30m (CREC Spec, 2013)

a=initial service line acceleration rate in =1 m/s^2 (CREC Spec, 2013)

a_g = Acceleration due to gravity=10 m/s^2 (CREC Spec, 2013)

d = service deceleration rate in=1.1 m/s^2 (CREC Spec, 2013)

f_{br} = braking safety factor (worst case service braking of specified normal rate =0.75 (75%) (TCQSM, 2013)

l_v =line voltage as percentage of specification =0.9 (90%) (TCQSM, 2013)

t_{os}= time for over speed governor to operate on automatic systems-to be replaced with driver sighting and reaction times on manual systems =3seconds (TCQSM, 2013)

t_{ij}= time lost to braking jerk limitation =1.5 seconds (TCQSM, 2013)

t_{br}= operator & brake system reaction time= 0.5seconds (TCQSM, 2013)

G_o= Gradient out of station = downward negative (decimal) (AALRT Design, 2013)

G_i = Gradient in to the station = downward negative (decimal) (AALRT Design, 2013)

V_{max}=Maximum speed of the line (m/s) (AALRT Design, 2013)

P_e= runaway propulsion allowance or Positioning Error Moving block only =6.25m

B = separation safety factor-equivalent to number of braking distances (surrogate for blocks) that separate trains =2.4 Three aspect Fixed block, 1.2 for Cab signaling and 1 for moving block.

In solving the minimum value of train separation, the station approach speed V_a is required. The optimum approach speed to station of 47km/hr for three aspect fixed block signaling and 52km/hr for cab and moving block signaling systems are used as recommended by TCRP manual .(TCRP,1996)

Substituting the above values in equations of 3.40 and 3.41, the result of Train Separation times for corresponding control systems are summarized as shown in table 4.12 and 4.13

Using gradient of near Station EW14

G_o= Gradient out of station = downward =-1%= -0.01 (decimal) (AALRT Design, 2013)

G_i = Gradient in of station = upward =1.2%= 0.012 (decimal) (AALRT Design, 2013)

Table 4. 12 Train Separation time of the controlling section systems of East West line for different Train control systems

Train control System	B (Separation safety factor)	Train Separation time t_{ts} (Second)
Three Aspect Fixed Block System	2.4	38.86
Cab Signaling system	1.2	32.43
Moving block system	1	22.10

Using gradient of near Station NS14

G_o= Gradient out of station = downward =1%= 0.01 (decimal) (AALRT Design, 2013)

G_i = Gradient in of station = upward =5.5%= 0.055(decimal) (AALRT Design, 2013)

Table 4. 13 Train Separation time of the controlling section systems of North South line for different Train control systems

Train control System	B (Separation safety factor)	Train Separation time t_{ts} (Second)
Three Aspect Fixed Block System	2.4	32.61
Cab Signaling system	1.2	27.87
Moving block system	1	19.84

4.2.3. Station dwell time and operating Margin

Station well time calculated using the regression equation of 3.28, 3.29 and 3.30 for the maximum load point stations of the two lines, EW 14 and NS 14 is 28 seconds. The literature references used in this study related to rail transit capacity recommends the a typical value of station dwell time ranges from 35 sec to 45 sec for calculating of line capacity of the system. In this study the above results of station dwell time using the regression equation used for comparison and the average recommended value of 40 seconds of average dwell time is used in calculation of non-interference headway of the two lines.

When trains operate at close distance near its capacity, there are more chance of occurrence of delay on service due to additional station dwell time and delay of a train ahead. To account this condition, an operation time of 25 second is considered as recommended by TCQSM manual.

4.2.4. Non-interference headway

Non-interference headway is calculated as the sum of train separation time, station dwell time and selected operating margin as shown in section 3.5.6.

$$h_{ni} = t_{ts} + t_d + t_{om}$$

The computed values of non-interference headway of the two lines are presented in the table 4.14 and 4.15 as shown below

Table 4. 14 Non-interference headway of East west line

Train control System	Train Separation time t_{ts} (Second)	Station Dwell Time (Seconds)	Operating Margin (Seconds)	Non-interference headway (Seconds)
Three Aspect Fixed block Signaling	38.86	40	25	103.9
Cab Signaling	32.43	40	25	97.43
Moving Block	22.10	40	25	87.10

Table 4. 15 Non-interference headway of North south line

Train control System	Train Separation time t_{ts} (Second)	Station Dwell Time (Seconds)	Operating Margin (Seconds)	Non-interference headway (Seconds)
Three Aspect Fixed block Signaling	32.61	40	25	97.61
Cab Signaling	27.87	40	25	92.87
Moving Block	19.84	40	25	84.84

4.2.5. Limiting Junction Headway

Limiting Junction headway is calculated as

$$h_J = t_{cs} + \sqrt{\frac{2(L_t + 2f_{sa}d_{ts})}{a}} + \frac{V_{max}}{(a+d)} + t_s + t_{om}$$

Train control separation time imposed by signaling system, t_{ts} which are calculated in table 4.10 and 4.11 are used in calculation of limiting junction headway.

a_g = Acceleration due to gravity=10 m/s^2 (CREC Spec, 2013)

a=Service acceleration rate=1 m/s^2

d = service deceleration rate in=1.1 m/s^2 (CREC Spec, 2013)

L_t =Train Length =30m (CREC Spec, 2013)

d_{ts}= Track separation

f_{sa}= switch angle factor =6.09 for #7 turnout (TCQSM, 2013)

V_{max} = 70km/hr (CREC Spec, 2013)

t_s=switch throw and lock time=6 second (TCQSM, 2013)

t_s= Operating Margin=25 sec

Limiting Junction headway is calculated as shown in table 4.16 and 4.17 for the East West line and North East line respectively.

Table 4. 16 Limiting Junction headway of East west line

Train control System	Train Separation time t_{ts} (Second)	Limiting Junction headway (Seconds)
Three Aspect Fixed block Signaling	38.86	91.65
Cab Signaling	32.43	85.22
Moving Block	22.10	74.89

Table 4. 17 Limiting Junction headway of North South line

Train control System	Train Separation time t_{ts} (Second)	Limiting Junction headway (Seconds)
Three Aspect Fixed block Signaling	32.61	85.40
Cab Signaling	27.87	80.66
Moving Block	19.84	72.63

4.2.6. Controlling Headway

The controlling headway will be the highest of the non-interference headway and limiting headway at a junction. Accordingly, the Controlling headway of East -West line and North - south line are given as shown below in table 4.18

Table 4. 18 Controlling headway

Train control System	Controlling Headway East-West line (seconds	Controlling Headway North – south line (seconds)
Three Aspect Fixed block Signaling	103.9 ≈ 104	97.61 ≈ 98
Cab Signaling	97.43 ≈ 98	92.87 ≈ 93
Moving Block	87.10 ≈ 88	84.84 ≈ 85

4.2.7. Achievable Line capacity of AALRT

The maximum achievable capacity of AALRT can be calculated as

$$\text{Line capacity} = \text{number of trains per hour(Trains/hr)} = \frac{3600}{\text{Minimum Headway(sec)}}$$

The line capacity of East West line and North south line is computed as shown in Table 4.19 below

Table 4. 19 Line capacity of East-West line and North -South line

Train control System	Controlling Headway East-West line (seconds	Line Capacity of East West line(Trains/hr)	Controlling Headway of North - East line (seconds)	Line Capacity of North South line(Trains/hr)
Three Aspect Fixed block Signaling	104 sec =1.73 min	60/1.73 = **35**	98 sec=1.63 min	60/1.63 = **37**
Cab Signaling	98 sec =1.63 min	60/1.63 = **37**	93 sec =1.55 min	60/1.55 = **39**
Moving Block	88 sec = 1.47 min	60/1.47 = **41**	85 sec = 1.42 min	60/1.42 = **43**

4.2.8. Number of trains

The maximum number of trains accommodated by the line can be computed by dividing the total trip time with the minimum headway of the line. The maximum number of trains of East-West line and South East line for a given Train control system is computed as shown in the table 4.20

Table 4. 20 Number of Trains of East-West line and North -South line

Train control System	Minimum Headway of East-West line (seconds)	Total Trip time of East-West line (min)	Max. Number of Trains in East-West line	Minimum Headway of North South line (seconds)	Total Trip time of North-South line (sec)	Max. Number of trains in North-South line	Max. number of Trains accommodated by AALRT line
Three Aspect Fixed block Signaling	104 sec = 1.73 min	87	**51**	98 sec= 1.63 min	85	**53**	**104**
Cab Signaling	98 = 1.63min	86	**53**	93 sec= 1.55 min	84	**55**	**108**
Moving Block	88 = 1.47 min	88	**60**	85se = 1.42 min	85	**60**	**120**

4.2.9. The total achievable capacity of AALRT

Achievable capacity of a railway can be calculated using Equation 3.5.12

$$\mathbf{C} = \frac{\mathbf{3600}}{(\boldsymbol{t_s} + \boldsymbol{t_d} + \boldsymbol{t_{om}})} \times \boldsymbol{P_C} \times \boldsymbol{N_C} \times \boldsymbol{PHF} = \frac{\mathbf{3600}}{\boldsymbol{H}} \times \boldsymbol{C_v} \times \boldsymbol{PHF}$$

Where: $\boldsymbol{C_v} = \boldsymbol{P_C} \times \boldsymbol{N_C}$ and $H = t_s + t_d + t_{om}$

C = achievable capacity (passenger/ h);

t_s= minimum train separation (sec);

t_d= dwell time at the controlling station (sec);

P_c= total passengers per car;

t_{om}=Operating Margin

N_c= Number of cars per train.

C_v= Vehicle capacity

PHF = peak hour factor.

H=Headway

The vehicle capacity C_v depends on the number of passengers standing per meter square and the number of cars used by a train

The achievable capacity of the East west line and North South line are computed for the type of Signaling system as shown below in table 4.21 and 4.22

Table 4. 21 Achievable capacity of East-West line

Train control System	Minimum Headway of East-West line (seconds)	Vehicle Capacity at initial stage using 6 passenger/m2	Vehicle Capacity in short and long term using 6 passenger/m2	Achievable capacity per direction of North-south line at initial stage. (Passengers/hr. Using PHF=0.9	Achievable capacity per direction of North-south line in short and long term (Passengers/hr.)using PHF=0.9
Three Aspect Fixed block Signaling	98	286	572	9,456	18,911
Cab Signaling	93	286	572	9,964	19,928
Moving Block	85	286	572	10,902	21,803

Table 4. 22 Achievable capacity of North South line

Train control System	Minimum Headway of East-West line (seconds)	Vehicle Capacity at initial stage using 6 passenger/m2	Vehicle Capacity in short and long term using 6 passenger/m2	Achievable capacity per direction of East-West line at initial stage. (Passengers/hr.) Using PHF=0.9	Achievable capacity per direction of East-West line in short and long term (Passengers/hr.)Using PHF=0.9
Three Aspect Fixed block Signaling	104.0	286	572	8,910	17,820
Cab Signaling	98.0	286	572	9,456	18,911
Moving Block	88.0	286	572	10,530	21,060

4.3. Evaluation of the proposed capacity of AALRT

4.3.1. Total Passenger flow of AALRT and the proposed Design Capacity of AALRT

In the Schematic Design report submitted by CREC, the total passenger volume and passenger cross-section flow at the stations of the two lines which are forecasted in three forecast years are given as shown in section 4.1.1.1 and 4.1.2.1.

In the report ,it is describes that the train operation plan and routing design is considered based on the passenger flow forecast as design principles in order to fulfill passengers' trip needs. In addition, it is also stated that the system traffic efficiency is undertaken into consideration (CREC Schematic, 2012).Accordingly, the approximate values of maximum cross-section flow of East -West line during morning peak hour in initial, short, long term is 2700 persons/h, 5,500 persons/h and 7700 persons / h and for North-South line, 2700 persons / h, 5500 persons / h and 7700 persons/h respectively are used for estimation of the capacity of the line (CREC Schematic, 2012).

The detail capacity calculation and the method used to analysis of the data are not given in the report submitted by CREC. However, the output of the results of the design transport capacity and train allocation of the project are given as shown below in the tables 4.23 and 4.24.

Table 4. 23 Proposed Design Capacity and Train Allocation of E-W Line

Design Year Index		Initial Stage	Short term	Long term
Operating Length (km)		17.1	17.1	37.8
One-way maximum cross-section flow during morning rush-hour(10,000 persons-times/h)		0.27	0.55	0.77
Train marshaling		One unit	Two unit	Two unit
Capacity(Passengers /train)		286	572	572
Number of passed cars during rush-hour (pairs/h)		10	11	15
Minimum headway(min)		6	5.4	4
Transport capacity (10,000 persons-times/h)		0.29	0.63	0.86
Allocation (per train)	Cars in service	19	20	59
	Standby and maintenance cars	2	2	6
	Total	**21**	**22**	**65**

Table 4. 24 Proposed Design Capacity and Train Allocation of N-S Line

Design Year Index		Initial Stage	Short term	Long term
Operating Length (km)		16.2	16.2	36
One-way maximum cross-section flow during morning rush-hour(10,000 persons-times/h)		0.27	0.55	0.77
Train marshaling		One unit	Two unit	Two unit
Capacity(Passengers /train)		286	572	572
Number of passed cars during rush-hour (pairs/h)		10	11	15
Minimum headway(min)		6	5.4	4
Transport capacity (10,000 persons-times/h)		0.29	0.63	0.86
Allocation (per train)	Cars in service	18	18	56
	Standby and maintenance cars	2	2	6
	Total	20	20	62

4.3.2. Evaluation of the Proposed line Capacity of AALRT

The computation of line capacity of AALRT is not shown in the report submitted by CREC. However, by seeing the input data and results, one can understand the proposed line capacity given in table 4.19 and 4.20 are computed by dividing the maximum passenger volume of one way cross-section flow during morning peak-hour(Passenger per hour) with the Vehicle passengers carrying capacity (Passenger per train).

For example, the number of train passed per hour on E-W line in initial stage is calculated as

$$\frac{\text{maximum cross section flow}}{\text{train capacity}} = \frac{2700\ \text{Passenger/hr}}{286\ \text{passeneger/train}} = 9.44 \approx 10\ \text{train/hr}$$

This shows that in calculating the line capacity a passenger load factor of 1 is used .This means a uniform arrival of passengers with in a peak hour and uniform distribution of passenger with in the vehicle are assumed.

Similarly, the proposed number of trains passing during peak hour for East- west line is 11 trains /hr in the short term and 15 trains/hr in the long term .The same number of trains per hour are proposed for North-South line at all stages as the maximum one way cross-section flow during morning peak-hour of the line is almost the same as that of East- west line.

The design capacity of line is calculated as the product of number of passed trains during peak-hour (trains/h) and train Capacity (Passengers /train). For example, the transport capacity of East West line in initial stage is computed as:

$$\begin{aligned}\text{Transport capacity} \\ &= \text{number of passed trains during peak hour(trains/hr)} \\ &\times \text{train Capacity (Passengers /train)} \\ &= 10\ \text{train/hr} \times 286\ \text{passeneger/train} = 2860\text{passenger/hr} \\ &\approx 2900\text{passengers/hr}\end{aligned}$$

Following this steps, the transport capacity or line capacity in short and long term for both lines can be calculated as 6300 passengers/hr and 8300 passengers per hour as it shown in Tables 4.19 and 4.20

The number of trains that passes a given point is calculated as 3600/Minimum Headway

$$\text{Number of trains per hour(Trains/hr)} = \frac{3600}{\text{Minimum Headway(sec)}}$$

From this equation the proposed minimum headway of the line can be computed. For example, the minimum headway of the E-W line in initial stage is equal to 3600 /number of trains per hour (trains/hr)

$$\begin{aligned}\text{Minimum headway} &= \frac{3600}{\text{number of trains per hour (trains/hr)}} = \frac{3600}{10\text{(trains/hr)}} \\ &= 360\ sec = 6\ minutes\end{aligned}$$

Then following the same procedures the minimum headway of both lines in short and long term is calculated as

$\frac{3600}{11(\text{trains/hr})} = 327\ sec = 5.4min$, at short term and

$\frac{3600}{15(\text{trains/hr})} = 240\ sec = 4min$, at long term

These result are shown in table 4.23 and 4.24

The number of trains required for a particular service is calculated based on the proposed headway and round trip time. The value of total round trip time which is a main factor in deciding the number of trains is not clearly provided in CREC report. However, from the headway and number of trains given the total round trip time used in estimation of number of trains is computed.

For example, in initial stage Headway and number of trains for East-West line are proposed to be 6 minutes and 19 trains respectively. Therefore, the total round time trip is computed from the equation below

$$Number\ of\ trains = \frac{Total\ round\ trip\ time}{headway}$$

Total round trip time (TRTT) =Headway× Number of trains

The numbers of trains are given in table 4.23 and 4.24 above

Accordingly, the total round trip times at each stage of the two lines are computed as follows:

a) East- West line

Initial stage

Total round trip time (TRTT) = 6min × 19 = 114 min= 1hour and 54 minutes

Short term

Total round trip time (TRTT) = 5.4min × 20 = 108min= 1hour and 48 minutes

Long term

Total round trip time (TRTT) = 4 min × 59 = 236 min=3 hour and 56 minutes

b) North- South line

Initial stage

Total round trip time (TRTT) = 6min × 18 = 108 min = 1hour and 48 minutes

Short term

Total round trip time (TRTT) = 5.4min × 18 = 97.2 min =1hour and 37.2 minutes

Long term

Total round trip time (TRTT) = 4 min × 56 = 224 min=3 hour and 44 minutes

In the report submitted by CREC, the numbers of trains are calculated for the long term is using a one way length of 36.0km including the extension sections of AALRT which is incorporated in Phase II construction. Therefore, in this study the number of trains, total round trip time and capacity of AALRT at long term is not evaluated.

5.0. DISCUSSIONS ON THE RESULTS

In the report submitted by CREC, the line capacity is computed simply by dividing the hourly passenger volume of the controlling station by the passenger carrying capacity of the vehicle. This shows that in the proposed design of AALRT, a load factor of 1 is used. This implies that a uniform arrival of passengers within the peak hour and uniform distribution of passengers within the vehicle are assumed. This leads to inadequate estimation of the frequency of service or number of trains per hour required in the controlling station.

In this study, a load factor of 0.9 is used in the computation of capacity using passenger volume. Load factor should be applied to account for variations in train loading within the peak hour due to the diversity of passengers arriving to the station within the peak hour. In addition, the train vehicle cannot exactly fits with its carrying capacity as passengers are not uniformly distributed with in the vehicle. Especially, on LRT system with short frequency and short dwell time, passengers do not get enough time to rearrange themselves within the available space.

For example in the design of CREC, the line capacity of East-West line at initial stage is proposed to be 10 trains per hour as shown in section 4.3.2. By applying a load factor of 0.9 and a vehicle capacity of 286, the line capacity becomes 11 trains per hour. This leads to a change in headway from 6 minutes to 5.5 minutes.

Assuming the same total round trip time proposed by CREC for initial stage which is 114 minutes and 5.5 minutes of headway computed by using 0.9 passenger loading factor ,the number of trains required for East West line is computed as:

Number of trains= $\frac{Total\ travel\ time}{Headway} = \frac{114\ minutes}{5.5\ minutes} = 20.72 \approx 21\ trains$

This shows that additional 2 trains are required for East-West line at an initial stage assuming the round trip time of 114 minutes as proposed by CREC.

In the design report submitted by CREC, an average travelling speed of 20km/h and average dwelling time of 30 seconds at each station are assumed (CREC, 2012, 32).This shows that the total round trip time is calculated using average speed of approximately 20 km/hr and uniform dwelling time of 30 seconds at each station. As a total round trip time is a main factor that determines the number of the trains required for a given line, detailed calculation of total round trip time is crucial for reasonable capacity analysis of a railway line.

In this study, the dwell time of each station is computed in detail depending on the headway of the line .The total travel time between stations are calculated incorporating the physical constraints that affects the motion of the vehicle. In addition, the turnaround and layover time that required for changing the direction of a train at the ends of the lines is also considered. This results a better estimation of total round trip time along the two lines.

In this study, the headway of 5.5 minutes is computed for East-West line by using a load factor of 0.9 and vehicle passenger carrying capacity of 286 passengers as shown in section 4.1.1.2 .The total round trip time is estimated to be 87 minutes. Therefore, the total number of trains required is computed as:

$$\text{Number of Trains required} = \frac{\text{Total round trip time}}{\text{Headway}} = \frac{87}{5.5} = 15.8 \approx 16$$

A total of 16 trains are required to operate with headway of 5.5 minutes on East –West line. This means the number of train required for operation with headway of 5.5 minutes is less than with that of proposed by CREC with headway of 6 minutes. This shows that in this study, smaller numbers of trains are estimated by using a reliable estimation of the total round trip time and smaller headway even if a load factor of 0.9 is applied.

Similarly, the comparison of the proposed capacity of the two lines at initial stage and at short term period by CREC with the results computed in this study are presented in Tables 5.1 and 5.2.below. The number of trains proposed by CREC for long term is calculated considering the extension lines of AALRT which are included in the second phase. Therefore, the number of trains computed in this study cannot be compared with the one proposed by CREC for the long term.

Table 5. 1 Comparison of capacity proposed by CREC and this Study for East West line

		Proposed by CREC (East West line)				Proposed by this study (East West line)				Difference in Headway (min)	Difference in Number of trains	Difference in total round trip time (min)
	Passenger Volume/hr.	Line capacity	Headway	Number of trains	Total Travel time (min)	Line capacity	Headway	Number of trains required	Total Travel time (min)			
Initial Stage	2679	10	6.0	19	114	11	5.50	16.00	87.00	- 0.5	-3.00	-27
Short term	5502	11	5.4	20	108	11	5.50	16.00	86.00	+ 0.1	- 4.00	-22
Long term	7696	15	4.0	59	236	15	4.0	22.00	88.00	0.0	Cannot be compared	Cannot be compared

Table 5. 2 Comparison of capacity proposed by CREC and this study for North-South line

		Proposed by CREC (North South line)				Proposed by this study (North South line)				Difference in Headway (min)	Difference in Number of trains	Difference in total round trip time (min)
	Passenger Volume/hr	Line capacity	Headway	Number of trains	Total Travel time (min)	Line capacity	Headway	Number of trains required	Total Travel time (min)			
Initial Stage	2675	10	6.0	18	108	11	5.5	16	85	- 0.5	-2.00	-23.00
Short Term	5491	11	5.4	18	97.2	11	5.5	16	84	- 0.1	- 2.00	-13.2
Long term	7678	15	4.0	56	224	15	4.0	22	85	0.0	Cannot be compared	Cannot be compared

The estimation of capacity based on passenger volume is an economical method of determining headway, the frequency of service and total number of trains along the line. However, this method is applicable when a train operates far below its capacity and the effect of train controlling system and the train separation time is negligible. When a train operates closer to its capacity this method fails to show the capacity related to the train controlling signaling system or trains separation time and station dwell time.

When more frequency of train service with small headway time is required, the estimation should be analyzed with a method of estimating achievable capacity using the throughput of the line. This method relates to the capacity of the line with the allowable train separation time, station dwell time and train controlling system by computing the necessary number and length of blocks required.

As it is shown in the analysis, the controlling headways in both lines are non-interference headways. In East-West line, the controlling headways are approximately 104 seconds, 98 seconds and 88 seconds for Fixed Three Aspect block, Cab and Moving block signaling systems respectively as shown in Table 4.18. Similarly, in the case of North-South line, the controlling headways are approximately 98, 93 and 85 seconds for Fixed Three Aspect block, Cab and Moving block signaling systems respectively.

In estimation of the achievable capacity, the vehicle carrying capacity is calculated with assumption of 6 passengers/m^2 .The total vehicle capacity of 286 which is used with load factor of 0.9. For two unit of train, the vehicle capacity is 572 in short and long term.

In this study, the achievable capacity is defined as the maximum number of trains or the maximum number of passenger passes at controlling point or station per peak hour. With the headway values and two unit of vehicle capacity 572, a maximum capacity of 21,060 and 21,803 passengers per hour per direction can be achieved in East-West and North-South line respectively using Moving block signaling system.

The total achievable capacity of the East-West line and North-South line is summarized as shown in tables 5.3 and 5.4.

Table 5. 3 The total achievable capacity of East West line

Train Control system	Achievable capacity per direction of East-West line at initial stage. (Passengers/hr.) Using PHF=0.9	Achievable capacity for two direction of East-West line at initial stage. (Passengers/hr.) Using PHF=0.9	Achievable capacity per direction of East-West line in short and long term (Passengers/hr.) Using PHF=0.9	Total Achievable capacity in two directions of East-West line in short and long term (Passengers/hr.) Using PHF=0.9
Three Aspect Fixed block Signaling	8,910	17,820	17,820	35,640
Cab Signaling	9,456	18,912	18,911	37,822
Moving Block	10,530	21,060	21,060	42,120

Table 5. 4 The total achievable capacity of North-South line

Train Control system	Achievable capacity per direction of East-West line at initial stage. (Passengers/hr) Using PHF=0.9	Achievable capacity two direction of North-South line at initial stage. (Passengers/hr) Using PHF=0.9	Achievable capacity per direction of North-South line in short and long term (Passengers/hr.) Using PHF=0.9	Achievable capacity in two direction of North-South line in short and long term (Passengers/hr.) Using PHF=0.9
Three Aspect Fixed block Signaling	9,456	18,912	18,911	37,822
Cab Signaling	9,964	19,928	19,928	39,856
Moving Block	10,902	21,804	21,803	43,606

The sum of achievable capacity of the two lines which are shown in tables 5.3 and 5.4 are presented in table 5.5 below as total achievable capacity of AALRT for the type of controlling system

Table 5. 5 Total Capacity of AALRT in terms of passenger per hour

Train Control system	Total Achievable capacity of AALRT at initial stage (Passengers/hr.) Using PHF= 0.9	Total Achievable capacity of AALRT in short and long term (Passengers/hr.) Using PHF= 0.9
Three Aspect Fixed block Signaling	36,732	73,462
Cab Signaling	38,840	77,678
Moving Block	42,864	85,726

The line capacity of the two lines in trains per hour and the total maximum number of trains accommodated by AALRT is summarized as shown in table 5.6

Table 5. 6 Summary of the maximum line capacity of East-West line and North-South line and the maximum total number of trains required for AALRT

Train Control system	Line capacity of East-West line	Line capacity of North-South line	Maximum number of trains operated East-West line	Maximum number of trains operated North-South line	Maximum number of trains operated by AALRT
Three Aspect Fixed block Signaling	35	37	51	53	104
Cab Signaling	37	39	53	55	108
Moving Block	41	43	60	60	120

The estimation of capacity using passenger volume depends on the passenger volume data forecasted at each station during peak hour. In the developing cities like Addis Ababa, where frequently reviewed travel demand model are not easily available, the predicted passenger volume at design stage may not reflect the actual demand to use on LRT line after the operation starts. Therefore, the two approaches which are proposed in this study to estimate capacity can be used in conjunction for decision of the minimum headway, train separation time and number of trains required.

For a given data of passenger volume per hour of the controlling station, the planned headway and economical capacity of a line can be computed using the first approach of capacity estimation based on passenger volume .For any capacity required between this value, due to the increase in passenger volume or the requirement of level of service, the maximum achievable capacity can be computed using the maximum throughput of line. Decision makers of a railway project may be interested to see the alternatives of capacity options and the train separation time to decide the type of signaling system and the number of trains required for each value of headway. Therefore, using the headway computed using the first approach using passenger volume can be used to calculate the train separation time and number of trains required.

An example of this is shown below in table 5.7 for East-West line. The headway for a given different passenger volume is computed using a vehicle capacity of 289 and passenger load factor of 0.9. This headway is used to calculate the train separation time and number of trains required for a given total round trip time and average station dwell time with operating margin.

The decision of type of signaling system is a broad topic to discuss. However, such options could lead to the possible type of signaling system to use. For example, for headway value of 6 minutes computed from the passenger volume given, the train separation time is 295 seconds or 4.9 minutes. Trains separated with 4.9 minutes have a low chance of appearing at the same time between two stations like AALRT with average distance between stations is 0.8 km. As a result, a Three Aspect Fixed block signaling system with a block length equal to station to station distance is enough to efficiently operate the trains as it is now used in AALRT system. However, when the demand increases or there is a need for smaller headway due to the improvement of service frequency, the train separation time become smaller. For example, for proposed headway of 1.5 minutes, the train separation time is 25 seconds and 58 trains are required for operation as shown in table 5.7. For trains separated by only 25 seconds, the chance of two trains appears at the same time between two stations is high. For such condition, number of blocks used between stations and the option of moving block signaling system may be considered.

Train separation time and number of trains required for a different headway values at initial stage are given in Table 5.7 and 5.8 for East-West line and North East line respectively.

Table 5. 7 Train separation time and number of trains required for a different headway values at initial stage for East West line

	Passengers load Factor		0.90	Vehicle Capacity (Passengers)			286
				Total Round time (minutes)			87
	Passenger Volume	Line capacity	Headway (minutes)	Station Dwell time (sec)	Operating Margin (Sec)	Train Separation time (sec)	Number of trains required
1	2000	8	7.50	40	25	385.00	12
2	2250	9	6.67	40	25	335.00	14
3	2500	10	6.00	40	25	295.00	15
4	2750	11	5.45	40	25	262.27	16
5	3000	12	5.00	40	25	235.00	18
6	3250	13	4.62	40	25	211.92	19
7	3500	14	4.29	40	25	192.14	21
8	3750	15	4.00	40	25	175.00	22
9	4000	16	3.75	40	25	160.00	24
10	4250	17	3.53	40	25	146.76	25
11	4500	18	3.33	40	25	135.00	27
12	4750	19	3.16	40	25	124.47	28
13	5000	20	3.00	40	25	115.00	29
14	5250	21	2.86	40	25	106.43	31
15	5500	22	2.73	40	25	98.64	32
16	5750	23	2.61	40	25	91.52	34
17	6000	24	2.50	40	25	85.00	35
18	6250	25	2.40	40	25	79.00	37
19	6500	26	2.31	40	25	73.46	38
20	6750	27	2.22	40	25	68.33	40
21	7000	28	2.14	40	25	63.57	41
22	7250	29	2.07	40	25	59.14	43
23	7500	30	2.00	40	25	55.00	44
24	7750	31	1.94	40	25	51.13	45
25	8000	32	1.88	40	25	47.50	47
26	8250	33	1.82	40	25	44.09	48
27	8500	34	1.76	40	25	40.88	50
28	8750	34	1.76	40	25	40.88	50
29	9000	35	1.71	40	25	37.86	51
30	9250	36	1.67	40	25	35.00	53
31	9500	37	1.62	40	25	32.30	54
32	9750	38	1.58	40	25	29.74	56
33	10000	39	1.54	40	25	27.31	57
34	10250	40	1.50	40	25	25.00	58
35	10500	41	1.46	40	25	22.80	60

Table 5. 8 Train separation time and number of trains required for a different headway values at initial stage for North South line

	Passengers load Factor		0.90	Vehicle Capacity(Passengers)			286
				Total Round time (minutes)			85
	Passenger Volume	Line capacity	Headway	Station Dwell time (sec)	Operating Margin (Sec)	Train Separation time (sec)	Number of trains required
1	2000	8	7.50	40	25	385.00	12
2	2250	9	6.67	40	25	335.00	13
3	2500	10	6.00	40	25	295.00	15
4	2750	11	5.45	40	25	262.27	16
5	3000	12	5.00	40	25	235.00	17
6	3250	13	4.62	40	25	211.92	19
7	3500	14	4.29	40	25	192.14	20
8	3750	15	4.00	40	25	175.00	22
9	4000	16	3.75	40	25	160.00	23
10	4250	17	3.53	40	25	146.76	25
11	4500	18	3.33	40	25	135.00	26
12	4750	19	3.16	40	25	124.47	27
13	5000	20	3.00	40	25	115.00	29
14	5250	21	2.86	40	25	106.43	30
15	5500	22	2.73	40	25	98.64	32
16	5750	23	2.61	40	25	91.52	33
17	6000	24	2.50	40	25	85.00	34
18	6250	25	2.40	40	25	79.00	36
19	6500	26	2.31	40	25	73.46	37
20	6750	27	2.22	40	25	68.33	39
21	7000	28	2.14	40	25	63.57	40
22	7250	29	2.07	40	25	59.14	42
23	7500	30	2.00	40	25	55.00	43
24	7750	31	1.94	40	25	51.13	44
25	8000	32	1.88	40	25	47.50	46
26	8250	33	1.82	40	25	44.09	47
27	8500	34	1.76	40	25	40.88	49
28	8750	34	1.76	40	25	40.88	49
29	9000	35	1.71	40	25	37.86	50
30	9250	36	1.67	40	25	35.00	51
31	9500	37	1.62	40	25	32.30	53
32	9750	38	1.58	40	25	29.74	54
33	10000	39	1.54	40	25	27.31	56
34	10250	40	1.50	40	25	25.00	57
35	10500	41	1.46	40	25	22.80	59
36	10750	42	1.43	40	25	20.71	60

During the research period of this study, the proposed 41 trains for the initial stage are purchased and ready for operation. Allowing two trains to stop as standby or for maintenance for each line, the number of trains available for operation are 19 and 18 for East -west line and North -East line respectively. The headway proposed for these trains is 6 minutes. As described earlier, this study proposed 16 trains to operate with 5.5 minutes of headway. However, the excess number of trains can be utilized to increase the number of frequency of service by reducing headway.

Accordingly, with the estimated round trip time of each line, the minimum headway that can be applicable to the lines can be computed as shown below.

The minimum headway that can be applied in east west line at initial stage is

$$\text{Minimum headway} = \frac{Total\ round\ trip\ time}{number\ of trains} = \frac{87\ minutes}{19} = 4.6 \text{ minutes}$$

The minimum headway that can be applied in North south line at initial stage is

$$\text{Minimum headway} = \frac{Total\ round\ trip\ time}{number\ of trains} = \frac{85\ minutes}{18} = 4.7 \text{ minutes}$$

The train separation time can be estimated by referring the tables 5.7 and 5.8 .Accordingly, the available number of trains in AALRT the train separation time of 211.92 and 223.46 seconds respectively.

The number frequency of the service or the number of trains per hour becomes 13 trains per hour for both lines as shown below

$\frac{60}{4.6} = 13.04 \approx 13 trains\ /hr$, for East West line and

$\frac{60}{4.7} = 12.8 \approx 13\ trains\ /hr$, for North south line

6.0. CONCLUSIONS AND RECOMMENDATIONS

6.1.Conclusions

The estimation of capacity using passenger volume is an economical way of calculating capacity based on hourly passenger volume. In calculation of the frequency of service required at highest loading point of a line, a reasonable value of load factor should be applied to account for unevenly distribution of passengers arriving at a station within the peak hour and within the vehicle itself. This study recommends to uses a load factor of 0.9 for AALRT line at detailed design level in a condition where there is no existing similar infrastructure to compare and available data to compute such factor. In the proposed design of AALRT by CREC, the number of trains per hour at the controlling station is computed by using a load factor of 1 assuming a uniform distribution of passengers within the peak hour. This may leads to insufficient estimation of frequency of service with in the peak hour.

By applying a load factor of 0.9 on the maximum forecasted passenger volume given in CREC report, the trains should be operated with a headway of 5.5 at both initial stage (2018) and short term (2025) .The headway of 4.0 minutes can be used at long term (2040).Using the estimated total round trip time under this study, the number of trains required at both initial stage and short term is 16. During the research period of this study, 19 trains for East-West line and 18 trains for North south line have already been deployed for trial operation as proposed by CREC at initial stage. The numbers of trains are more than the required amount for the proposed headway of 6 minutes. Such excess numbers of trains are due to the estimation of relatively longer round trip time. For Example, the operation of 19 trains with headway of 6 minutes requires a round trip time of 114 minutes or 1 hour and 54 minutes which is a long duration for a 17km line. For efficient utilization of the system, the reduction of total round trip time is crucial. In this study, the total round trip time is computed using analytical equations and the results are a maximum of 87 minutes for East west line and 85 minutes for North South line. This results a smaller number of trains.

The excess numbers of trains can be directly used when the passenger volume is found to be greater than the forecasted one after the operation starts. However, with the forecasted volume of passengers, the excess numbers of trains can be used to increase the frequency of service by reducing the headway .Therefore, this study recommends that with the available number of trains, an operation of using a minimum headway of 4.7 minutes can be achieved. This headway increases the line capacity to 13 trains per hour.

In capacity estimation of AALRT, the two analytical methods developed in this study can be applied in both planning and detailed design stages. The methodology of estimating capacity using passenger volume is used to estimate the capacity of a line by using the forecasted passenger volume data. The methodology of estimating achievable capacity using the throughput of the line is applied to estimate the maximum achievable capacity of the system and the capacity of the line for a given value of headway even though the passenger volume is not known.

The forecasted passenger volume and the location of the critical or controlling station may be found to be different after the operation starts. In such conditions, the proposed methodologies can be used to estimate the capacity of the line and the number of trains required based on the actual survey data collected from the lines. The capacity of the line at a given passenger volume can be easily referred from table 5.7 and 5.8. In addition, these tables can be used as a quick reference for planners to provide different options of capacity at different value of headway for decision makers.

In AALRT, a maximum capacity of 73,462, 77,678 and 85,726 passengers per hour can be achieved using a Three Aspect Fixed Block signaling, Cab signaling and Moving Block signaling system respectively.

6.2. Recommendations of Further Studies

In determination of the frequency of service at controlling station of a railway line, a reasonable value for passenger loading diversity factor that represent uneven distribution of passengers using AALRT during peak hour and within the vehicle itself is required. This is determined by carrying out actual survey in the operation of AALRT. In this study, passenger diversity factor based on the practice of other countries is used and a further detailed study on passenger loading diversity factor based on passenger characteristics on AALRT is recommended.

Station dwell time is one of the major components of headway that affects the capacity and total round trip time of a railway line. Estimation of station dwell time is a challenging practice that requires knowledge of station passenger movement. Many studies developed a complex mathematical regression and logarithmic equations that relates the passenger volume and flow time to station dwell time. The regression equation used in this study is convenient for AALRT as it uses the available input data of hourly passenger volume and its reliability need to be checked during the operation of AALRT. Station dwell time depends on operation practice of a system and passengers characteristics. Therefore, a further study on determining station dwell time based on actual passengers characteristic and condition of AALRT is recommended.

Travel time is an important issue in transportation network planning and traffic operations. The efficient utilization of AALRT calls upon reducing the total round trip time. The travel time between stations is a major component of total round trip time that determines the number of trains required for a given headway. Analytical methods of calculating travel time are less precise as average values are considered. A realistic method of calculating travel time is required using simulation tools considering all factors affecting the motion of vehicle. A further detail study of travel time between stations of AALRT is recommended for efficient utilization of the line and for better estimation of the number of trains required.

In general, analytic methods are mainly used at planning stage where most of the factors shaping up the capacity of a railway line are not known. At detailed design stage, the methods are relatively produce reliable results, especially on a simple rail network like AALRT. The upcoming national railway lines call upon for efficient utilization of the service. For efficient utilization, the capacity of the line needs to be determined. For reliable estimation of railway capacity, further studies on simulation methods are recommended.

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