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ADDIS ABABA INSTITUTE OF TECHNOLOGY

School of Electrical & Computer Engineering

Performance Analysis of Railway Capacity of Addis Ababa Light Rail Transit

A Thesis Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirement for the Degree of Master of Science in Electrical Engineering for Railway Systems.

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Abstract

Railway capacity, improvement and route capacity are currently among the most significant and prominent issue for the modern railway network. It is generally accepted that the capacity of a railway represents the number of trains that can reliably operate in a given section of track in a given time period. In this thesis the main concepts and methods to analyze performance of railway capacity are discussed. Capacity is extremely dependent on infrastructure, traffic, and operating parameters. Also there are different tools that are evaluates the performance of railway capacity such as, analytical method, optimization method and simulation method.

For this thesis, analytically by using real data from AALRT rail network, calculations are performed for the parameters that affect capacity of railway specifically breaking distance, journey time, possible speed of the train and headway time. And present their results to show how the capacity varies according to such factors. Anylogic software is used to check the validation of the calculated values and to show the performance of capacity variation in terms of speed of the train and headway time of the train for the selected station of EW, NS and bottleneck of AALRT.

Finally different factors influence railway capacity and train delays are analyzed, and then we can maximize the current practical capacity of AALRT by 40% specifically by providing better headway time (5.66min), hence, approximately 10 train can move on the track within one hour interval using advanced traveling speed than the existing AALRT operating standards for the better railway transportation quality.

Keywords :-(breaking distance, capacity, headway time, train speed, Anylogic)

Acknowledgment

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Declaration

I, Kidist Melaku Mengistu, hereby declare that this work entitled “**Performance Analysis of Railway Capacity of Addis Ababa Light Rail Transit**” is the original work of mine and has not been presented for a degree in this or any other university, and all source of materials used for the thesis have been fully acknowledged.

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Acronyms

2D	Two Dimensions
3D	Three Dimensions
AALRT	Addis Ababa Light Rail Transit
ADIF	Spanish Administration of Railway Infrastructure
ATC	Automatic Train Control
ATP	Automatic Train Protection
CAD	Computer Aid Design
DEF	Drawing Exchange Format
ERC	Ethiopia Railway Corporation
ERP	Enterprise Resource Planning
EW	East to west
HSQLDB	Hyper SQL Database
Ms	Microsoft
MRP	Manufacturing Resource Planning
MOM	Spanish name:Modulo Optimize adoredMallas).
NS	North to south
PHF	Peak Hour Factor
SRA	Strategic Rail Authority
SQL	Structured Query Language
TMS	Transcranial Magnetic Simulation
TR	Track
TXT	Technology per a Tothom
UI	User Interface
UIC	Its French name, Union Internationale des Chemins de fer, (The International union of Railway)
UK	United Kingdom

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CHAPTER ONE

1. Introduction

1.1. Background and Motivation

Railway is an attractive mode of transportation with a wide range of applications. It is used to provide high capacity local transportation of passengers in large cities, haul large quantities of ore from in land located mines to sea side ports and to connect cities by comfortable high- speed services offering short travel times from city center to city center, just to mention a few. It is energy efficient and it can be powered by renewable energy sources, hence its attractiveness is bound to increase further as awareness increase of the issues associated with air pollution and climate change [2].

The demand for railway transportation is steadily increasing around the world. The increase in demand generates increase in traffic load. Many railway lines are already used close to their maximum capacity and in order to meet the new demand, actions need to be taken. Such actions include building new railway infrastructure, upgrade existing infrastructure or use existing infrastructure more efficiently. Constructing new railway infrastructure is expensive, and it is therefore of importance that the right actions are taken at the right time. This in turn requires an understanding about how the railway system works and responds to increased capacity utilization.
Analyzing and describing railway capacity is a multifaceted task. It involves several complex systems, e.g. railway infrastructure, rolling stock, timetable and human behavior. Some of the factors influencing capacity are: number of tracks connecting the stations, station track layout, signaling system, train performance, speed difference between train services, market demand, reliability and delay acceptance of railway customers. And this all factor are generalized in three groups like this Infrastructure Parameters, Traffic Parameters and Operating Parameter.

1.2. Literature Review

There are different literatures, articles, journals that review about performance analyses of rail capacity.

One of the references about railway capacity is Burdett and Kozan (2006). They develop several approaches to calculate theoretical capacity (they call it \absolute capacity”) for railway lines and networks.

These approaches take numerous railway aspects into account; for example, mix of trains, signal locations, or dwell times. They are based on given train proportions. These proportions are used to weight the average sectional running time. This time is the key to determining the lower and upper bounds of capacity on the critical section.

Haylekiros (2016) on his Msc thesis, he tries to analyze the impact of train timetable on the traffic Management system and line capacity of AALRT. Also he designs the main parameters of the train timetable for safe, efficient, competitive and sustainable timetable for AA-LRT of phase-I in order to get good railway capacity.

Terefe (2014) also on his thesis, by choosing CTCS level 0 signaling system to implement Automatic Block Signaling, wayside signals and cab signaling systems. And he show the variation of headway time, breaking distance, traveling time and capacity of a given railway line. Braking distance of each stations are calculated so as the wayside signals are placed on safe locations. In order to calculate the operational efficiency the headway time between trains calculated. The speed limit of all necessary curves, switches and turnout are calculated and the average speed of the system is obtained.

A.H (2006) presents a new method to optimize the travel speed of trains by calculating the braking distance for trains. The braking distance is a crucial parameter to calculate the possible travel speed for a train on a certain railway line. Knowing the braking distance and the possible travel speed it is possible to determine the most suitable travel speed of the train with its capacity performance of a line,

Also the new policy of the European Union is to encourage open access to railway networks. This process has already begun in the Spanish Administration of Railway Infrastructure, ADIF, which is interested in using advanced computer tools to improve railway management. In collaboration with ADIF, they have developed a tool called MOM (acronym of the Spanish name: Modulo Optimize adordeMallas).This integrated system helps railway managers perform capacity studies to optimize their timetables and evaluate their track and station capacity in order to satisfy the demands of their customers. Several international companies are also working on similar computer-based systems:

•DEMIURGE is a software program designed to assist in making rail network capacity studies. This software can evaluate a network's capacity to absorb additional traffic, to locate bottlenecks, to assist in making decisions about infrastructure investments, to optimize current and future timetables, and to calculate the residual capacity of a timetable.

•CMS provides a system to plan the effective utilization of the railway capacity. It offers an easy "what if" scenario evaluation, automatic generation of timetables, simulation of operations to predict performance and identify remedies, identification of capacity available for sale, and usage forecasts based on improved timetables. However, CMS needs to be calibrated using updated punctuality data to ensure that its predictions are valid.

•RAILCAP measures how much of the available capacity issued by a given operation program in a straight forward way, and it offers a very detailed analysis of bottlenecks. However, it has one major disadvantage since the modeling requires a great deal of effort. RAILCAP requires detailed descriptions of the tracks, switches, crosses, signals and speed limits.

•VIRIATO is mainly used for adapting infrastructure to future service concepts and coordinating several operators or products that share the same infrastructure. It allows the user to determine the amount of saturation of a specified line. It compresses a given timetable, and determines the saturation rate of a line or a part of a line as a percentage. This method leads to varying results for the same line, depending on the length of the section under consideration.

•CAPRES is a model for the elaboration and saturation of timetable variants. Through the use of iterations, this model determines all available extra train paths, given all the constraints and interconnections between lines. A disadvantaged of this model is that the traditional network and operational data have to be completed with the information about where, when and how the network capacity must be used.

•FASTTRACK is a computer-based train dispatching and meet-pass model that is capable of producing a feasible train dispatching plan for a user selected corridor, given a set of proposed train schedules and a corridor's track configuration. It can be used to examine the feasibility of asset of proposed train schedules, test the impact of proposed changes in operating policies on train service, and measure both the theoretical and practical line capacity.

1.3. Statement of the Problem

Railway capacity is not static. It is extremely dependent on how it is used. Railway lines often suffer from lack of capacity. These problems can traditionally be solved by improving the infrastructure or bundle the trains for better utilization of the capacity and for the effective usage of energy consumption. But the physical and dynamic variability of train characteristics makes capacity dependent on different parameter of traffic, operation and infrastructure of railway system and the order in which the trains run on the line.

These are some of the fundamental parameter that affects it:

i. Infrastructure Parameters:-block and signaling system, Single/double tracks definition of routes line, network effects, track structure and speed limits, length of the subdivision.
ii. Traffic Parameters:-train mix, regular timetable, traffic peaking factor, priority.
iii. Operating Parameters:-track interruptions, train stop time, and maximum trip time threshold, quality of service, reliability, or robustness.

In AALRT case the problem of lack of capacity causes delay, longer waiting time of passenger and Journey time of the train, high energy consumption, maximum headway time and lower traveling speed of the train. These are the main problem outcomes due to lack of capacity.

In this thesis, we try to focus on the above parameter to see how their variations affect the performance of capacity of the railway system on both EW and NS direction and also shared station of AALRT railway system by using a dwell time different from the current dwell time value. Breaking distance, the possible traveling speed and headway time also calculated by the formula that are compatible with AALRT standards in order to get efficient utilization of capacity.

1.4. Objective

1.4.1. General Objective

The main objective of this research work is to analyze the performance of railway capacity of AALRT and determines how different factors affect railway capacity and its operation.

1.4.2. Specific Objectives

Specific objectives of this thesis are to:-

- ✓ Increase possible speed of the train
- ✓ Decrease the current headway time of AALRT
- ✓ Minimize waiting time of passenger at the station
- ✓ Decrease delays and better punctuality
- ✓ Get better energy consumption
- ✓ Sustain availability of infrastructure.

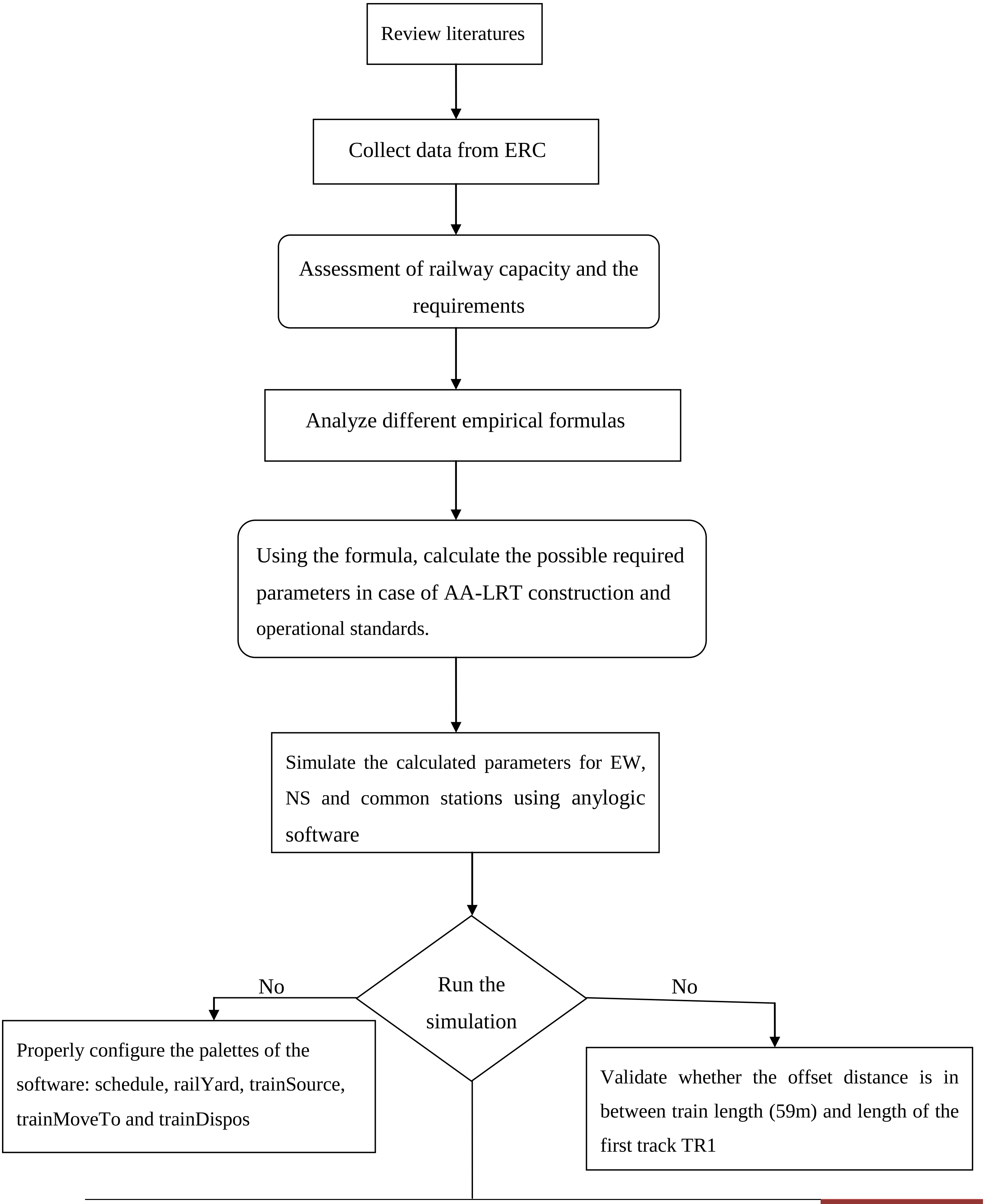
1.5. Scope of Work

The scope of this work is:

- ✓ Calculate capacity affecting parameter by its own formula.
- ✓ compare the values of the parameters with the existing value of AALRT
- ✓ Finally simulate the parameter by varying its value using anylogic.

1.6. Methodology

Using the following methodology this thesis work is performed as follows. First different literatures including journals, conference reports and different PhD thesis work related to railway capacity are reviewed. Assessment of railway capacity and its requirement is a mandatory task in order to analyze the performance of railway capacity. Then, by analyzing various empirical formulas and by collecting data's from ERC capacity and its related parameters such as breaking distance, speed of the train and headway time are calculated for EW, NS and common station of the line. Finally we simulate such parameters using anylog software to see their effect on the performance of railway capacity.


Review literatures
Collect data from ERC
Assessment of railway capacity and the requirements
Analyze different empirical formulas
Using the formula, calculate the possible required parameters in case of AA-LRT construction and operational standards.
Simulate the calculated parameters for EW, NS and common stations using anylogic software
Run the simulation
No
No
Properly configure the palettes of the software: schedule, railYard, trainSource, trainMoveTo and trainDispos
Validate whether the offset distance is in between train length (59m) and length of the first track TR1

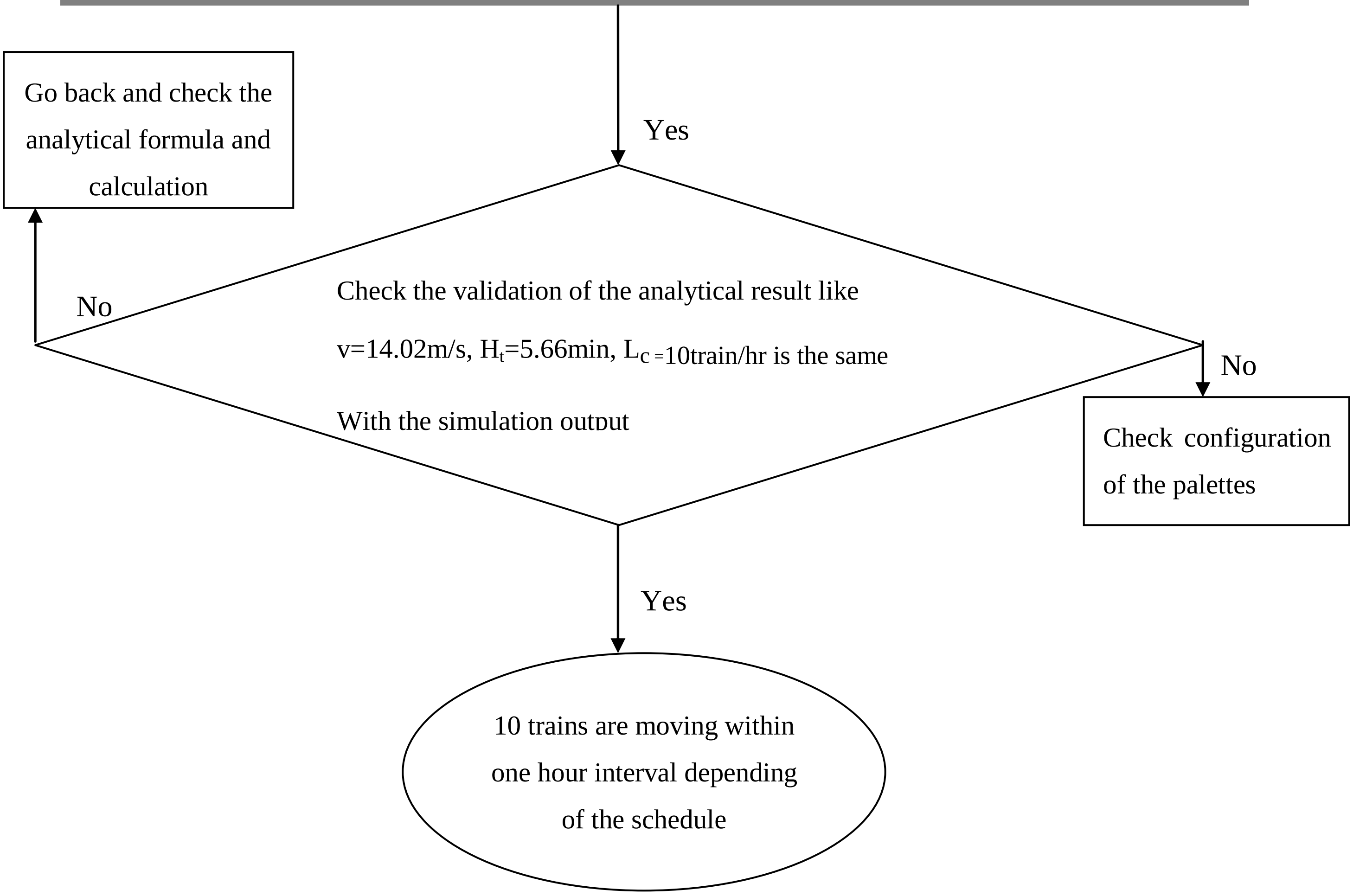


Figure 0.1: Research Methodology

1.7. Thesis Organization

This thesis work is organized in 6 chapters like this; chapter one includes introduction, which provides clear information about the background and motivation of the thesis work. Chapter two presents methods to evaluate railway capacity and its affecting parameters. Chapter three explains the overview of AALRT system and introduction of light rail capacity.

In chapter four, several analytical and empirical capacity analyses and calculations are performing on the real networks of AALRT for both directions. Chapter five, present the effect of different parameters on railway capacity using anylogic simulation software, and finally in chapter six conclusion and recommendation are present.

CHAPTER TWO

2. Railway Capacity

2.1. Definition of Railway 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 objective and quantifiable measures. It is a complex term that has numerous meanings and for which numerous definitions have been given. When referring to a rail context, it can be described as follows:

"Capacity is a measure of the ability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific service plan"[17].

Some authors also give a good general definition of railway capacity that includes the most important aspects:

"The number of trains that can be incorporated into a timetable that is conflict free, Commercially attractive, compliant with regulatory requirements, and can be operated in the face of anticipated levels of primary delays whilst meeting agreed performance targets"[17].

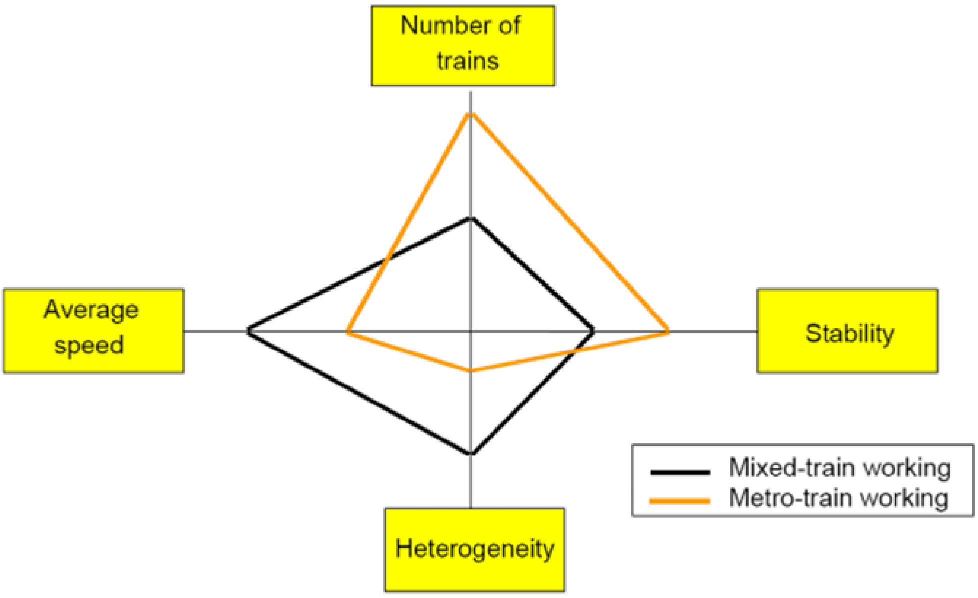


Figure 2.1: Capacity Balance [18].

There is no simple way to tell what the capacity of a railway infrastructure is because it depends to such a high degree on how it is used. Figure 2.1shows that capacity is a balance between number of trains, average speed, stability and heterogeneity. Capacity is the length of the chord connecting the four axes. It shows that railway capacity is a trade-off between quantity and quality, i.e. between number of trains that are operated and how much delays they will experience. Increased traffic load leads to higher sensitivity to delays with more secondary delays propagating from train to train.

Number of Trains

If the capacity is measured as the number of trains per hour, the capacity in a cross section can be calculated as:

$$K = q_{max}.n \qquad \text{Equation 1}$$

Where:

K = is the capacity

q_{max} = is the maximum traffic intensity [trains/h]

n = is the number of train paths

Heterogeneity

A timetable is heterogeneous or not homogeneous when a train catches up another train. The result of a heterogeneous timetable is that it is not possible to run as many train as if the timetable was homogeneous all trains running at the same speed and having the same stopping pattern.

To evaluate the heterogeneity of a timetable the SSHR and SAHR can be used [18]. SSHR Sum of Shortest Headway time Reciprocals describes both the heterogeneity of the trains and the spread of trains over the hour:

$$SSHR=\sum_{i=1}^{N}\frac{1}{h^{-}_{t,i}} \qquad \text{Equation 2}$$

Where:

ht = is the shortest headway time observed between two trains

N = is the number of trains in the cycle observed

Since fast trains can be caught behind a slower train it is important to have enough headway time at the arrival at the end of the line section to avoid secondary delays.

The SAHR Sum of Arrival Headway time Reciprocals describes the spread of trains over the hour at the arrival station.

$$SAHR = \sum_{i=1}^{N} \frac{1}{h_{t,i}^{A}}$$

Equation 3

Where:

ht^{A} = is the headway time observed between two trains at the end of the line Section

N = is the number of trains in the cycle observed

SAHR will always be smaller than or equal to the SSHR. The SAHR is only equal to SSHR in case of a homogeneous timetable and the difference will increase the more heterogeneous the timetable is. A measurement of the homogeneity can therefore be found by combining Equation 2 and Equation 3:

$$Homogeneity = \frac{SAHR}{SSHR} = \frac{\sum_{i=1}^{N} \frac{1}{h_{t,i}^{-}}}{\sum_{i=1}^{N} \frac{1}{h_{t,i}^{A}}}$$

Equation 4

The homogeneity is then equal to 1 when the timetable is completely homogeneous and opposes 0 when the heterogeneity increases.

Average Speed

A train consumes a different amount of capacity at different speeds. When a train stands still, the train consumes all the capacity since it occupies the block section for an infinite amount of time. When the train speeds up the train occupies the block section for shorter time where as more trains can pass the same block section more capacity is gained. The minimum headway time and thereby the capacity depends of the speed of the train. For railway lines with discrete automatic train control (ATC) or no ATC system the speed is even more important than continuous ATC systems since the function of the minimum headway time is discrete.

Stability

When discussing railway capacity it is important to look at the stability of the railway system too. The stability of the railway system is difficult to work out as such. The punctuality of the trains is, however, derived from the stability.

It is difficult to evaluate the stability or punctuality of a planned timetable not yet put in operation. Experienced planners might, however, have an idea of how changes in a timetable or the infrastructure might affect the punctuality. It is only possible to estimate the punctuality of smaller changes in the timetable or infrastructure using the experience. If the punctuality of larger changes in the infrastructure and/or timetable have to be estimated it is necessary to use simulation tools. Even though it is difficult to predict the future punctuality a general rule of thumb is that the punctuality will drop when the capacity utilization increases.

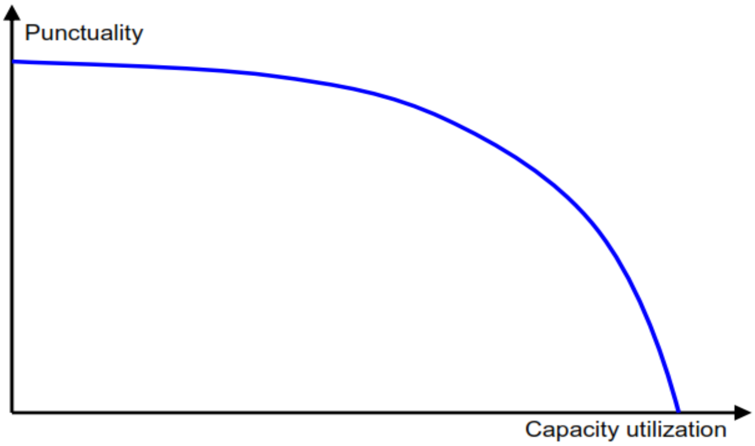


Figure 2.2: The coherence between punctuality and capacity utilization [18]

Even though it is possible to achieve higher capacity utilization on a railway line it is often said that there is no more capacity if the punctuality drops below a certain limit. Changing the timetable for the railway line examined may increase the punctuality so that it is possible to have higher capacity utilization before dropping below the punctuality level where it is said that there is no more capacity. This is due to the fact that the capacity for a given railway infrastructure is based on the interdependencies existing between the number of trains, the average speed, the stability or punctuality and the heterogeneity (differences in the speed) of the trains.

2.2. Types of Capacity

Different types of capacity are usually used in the railway environment [17].

Theoretical Capacity: It is the number of trains that could run over a route, during a specific time interval, in a strictly perfect, mathematically generated environment, with the trains running permanently and ideally at minimum headway (i.e. temporal interval between two consecutive trains).It is an upper limit for line capacity. 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 trains that can be worked mathematically.

Practical Capacity: It 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. 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: It is the actual traffic volume occurring over the network. It reflects actual traffic and operations that occur on the line. It is usually lower than the practical capacity.

Available Capacity: It is the difference between the Used Capacity and the Practical Capacity. It is an indication of the additional traffic volume that could be handled in the route. If it allows new trains to be added, it is a useful capacity; otherwise, it is lost capacity.

In the context of signaling the following definitions of railway capacity has adopted [10].

Train Following Capacity: The maximum throughput at a particular point on the railway network, such as a signal position, if all trains were to follow each other at line speed and with a minimum of braking distance separation, no allowance being made for station stops.

Point Capacity: The maximum throughput at a particular point on the railway network, such as a station platform, accounting for station stops and actual train speeds.

Theoretical Line Capacity: Indicates the theoretical maximum throughput of a railway line when all trains complete more than one round trip.

Sustainable Line Capacity: Indicates the sustainable throughput of a railway line when all trains complete more than one round trip, in accordance with the time tabled service pattern.

Optimum Line Capacity: Indicates the sustainable throughput when passenger / goods travel times and comforts are optimized.

The US Transportation Research Board introduced definitions of capacity to balance between railway capacity supply and demand, as stated below [10].

Design Capacity: The maximum number of passenger spaces past a single point in an hour, in one direction on a single track.

Achievable Capacity: 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. Both Design Capacity and Achievable Capacity are discuses more in chapter 3.

Line Capacity: The maximum number of trains that can be operated over a line in a peak hour.

Train Capacity: The product of passengers per car and the number of cars, adjusted to achievable capacity case using a diversity factor to compensate for uneven car loadings over multiple-car trains.

2.3. Parameters of Capacity

Railway capacity is highly dependent on the way it is used, and also, it varies with changes in traffic characteristics, infrastructure characteristics and operation characteristics.

These are some of the fundamental factors that affect capacity of railway [17].

• Infrastructure Parameters

Block and signaling system: The signals help extend the train driver’s visibility, so it allows greater speeds. The role of signaling is to keep trains at a safe distance. There are two types of systems: fixed and moving block signaling.

In a fixed block signaling system, the position of each train is known only by the block sections that it occupies. The separation between trains is maintained by imposing the restriction that each block section be occupied by at most one train at a time.

Block section lengths, train speeds, and train lengths are, therefore, important parameters. In a moving block signaling system, which is a modern technology, the position of each train is known continuously, thus permitting better regulation of the relative distances. This requires an efficient communication system between line signals, cabs, and control centers. In addition, speeds that can be achieved by trains can be limited in practical situations by different factors other than track geometry and signaling, such as catenaries or power traction constraints.

Single/double tracks: This has a major impact on capacity. It is not as simple as multiplying the number of tracks: two tracks usually have around four times more capacity than a single track; however, a four track line rarely increases capacity by more than 50% over a double line. Furthermore, adding a second track may not eliminate the problem because the station is the real bottleneck. Auxiliary tracks at crossing stations also increase the capacity of a single track because they allow trains to carry out crossings and overtaking.

Track structure and speed limits: The condition of the rails, ties, and ballast dictate the weight and type of equipment that can be used on the line, as well as the speeds allowed on the line. They have an important influence on the capacity. The speed limits are regulated by means of speed profiles, which take into account physics, safety, comfort, train types, etc.

- ## Traffic Parameters

Regular timetables: A specific target of the line planning and train scheduling problems is the construction of periodic timetables, which means train services of the same class departing at fixed intervals. It often represents a strong commercial constraint for train scheduling.

Traffic peaking factor: It is a measure of concentration of traffic within a short time frame. It has a significant impact on capacity because it can result in traffic levels that are higher than the network could reliably sustain. When this occurs, the effects are felt for considerable time periods into the future as the system recovers from the overload.

Priority: The priorities of trains play a vital role. Train priorities decrease capacity because priority trains are given preferential treatment over lower priority trains, which results in increased delays. This basically allows the priority traffic to move as if it were the only traffic in the network. As a rule, the greater the number of priority classes, the less capacity is available.

- ## Operating Parameters

Quality of service, reliability, or robustness: Since train operations are not perfect, and random minor disturbances and failures occur in the real management of trains during the railway operation of certain lines reducing the theoretical capacity, some buffer times must be taken into account in order to design a robust timetable. This stochastic effect is often difficult to take into account in line capacity evaluations. However, a balance between service reliability and maximum physical capacity is needed to find the economically optimal level of capacity. Therefore, increasing the number of trains over the saturation level is not profitable.

Train stop time: This parameter accounts for the amount of time trains spend stopped on a line. It is a delay that directly increases the amount of time a train takes to traverse a subdivision.

Maximum trip time threshold: This parameter represents the upper limit of acceptable trip time. It affects capacity because it restricts the number and/or length of the train stops.

Time window: The interval or unit of time that is taken as a reference for computing the desired line capacity should be defined. Traditionally, this is set either to one hour or to the whole working day.

2.3.1. Another Railway Component and Attributes with Their Impact on Improving Railway Capacity

Theoretically, improving any parameter in the list would improve capacity utilization. However, in practice, efforts are often focused on several areas that the railway industry believes to be most significant.

These are some of the attributes with their impact on improving railway capacity [10].

Platform length: improving Platform length may not directly capacity unless the existing

Platform is shorter than the requirement. However, Platform length should be taken into consideration when examining feasibility of adding more carriage to trains.

Passenger handling facilities: improving Passenger handling facilities (station gate, sign, ticketing, stairs, elevator, and escalator) may reduce dwell time and thus increase capacity.

Junction characteristics: improving Junction characteristics may ease speed limits and thus increase capacity (but only for speed <55 mph).

Distance between stations/ junctions: Distance between stations/ junctions may reduce headway time, recovery time, buffer time and waiting time thus increase capacity.

Power supply: Power supply capability will limit capacity. Upgrading will therefore have an impact in situations where the power supply is limited.

Door characteristics: improving train door characteristics such as number of doors, width of operating technology may reduce dwell time and thus increase capacity.

Breaking system (breaking rate): improving the breaking rate may reduce headway time, thus increase capacity. This is, however, controlled very strictly.

Safety rules: improving safety requirement may increase headway time and thus reduce capacity.

KPI targets: improving the key performance indicator targets e.g. punctuality and reliability may require increased recovery time, buffer time and thus reduce capacity.

Environment protection rules: rules preventing freight train frome oprating during night time becouse of noise disturbance will put these trains on day time timetable and potenstially reduce capacity.

Station stop: station stop can influence capacity. Homogeniousing the stopping pattern, as in practised in metro oprations tend to optimize the capacity.

Timetabling techniques: improving timetabling techniques may increase headway time and thus reduce capacity.

Maintenace strategy: improving infrastructure maintenace strategy may reduce special delivery time and thus reduce capacity.

2.4. Methods to Evaluate Railway Capacity

Numerous approaches have been developed to evaluate railway capacity. The most relevant methods can be classified in three levels: Analytical Methods, Optimization Methods, and Simulation Methods [14].

Analytical Methods: These are very simple models aimed at determining a preliminary solution. These methods can also be used for reference or comparison. They are designed to model the railway environment by means of mathematical formulae or algebraic expressions. They usually obtain theoretical capacities and determine practical capacities either as a percentage of the theoretical capacity or by including regularity margins when they calculate the theoretical capacity.

Analytical methods for computing railway line capacity may be a good start for identifying bottlenecks and major constraints; however, analytical results vary from one method to another depending on what type of parameters they model. Furthermore, analytical models are very sensitive to parameter input and train mix variations.

Optimization Methods: They are designed to provide more strategic methods for solving the railway capacity problem and provide much better solutions than purely analytical formulae. Optimization methods for evaluating railway capacity are based on obtaining optimal saturated timetables. These optimal timetables are usually obtained by using mathematical programming techniques such as Mixed Integer Linear Programming formulations and Enumerative algorithms.

A particular method of optimization is Saturation. This method obtains line capacity by scheduling a maximum number of additional train services in a timetable starting with either an empty timetable or with an initial base timetable.

Simulation Methods: A simulation is the imitation of an operation of a real world process or system over time. It is the representation of dynamic behavior of a system by moving it from state to state in accordance with well-defined rules. Simulation methods provide a model, which is as close as possible to reality, to validate a given timetable.

A complete analysis of the commercial simulation environments is outside the scope of this paper. Nevertheless, we give a short description of some main simulation environments:

Multi Rail (Multimodal Applied Systems) has a full train simulation capability, which shows train conflicts in detailed graphical and tabular formats. The user can define the conflict rules within the track manager, when defining the various characteristics of the track arcs and switches. Furthermore, Multi Rail has a very fast seven-day simulation algorithm called Super Sim that produces a complete trip plan for each traffic record.

Open Track (Open Track Railway Technology) is a simulation tool to answer questions about railway operations. It calculates train movements under the constraints of the signaling system and timetable. It also handles simulation where random generators produce different initial delays and station delays.

SIMONE (In control Enterprise Dynamics) is a simulation model for railway networks. It can support: determination of the robustness of a timetable, trace and quantification of bottlenecks in a network, and analysis of cause and effect relations when delays emerge.

In conclusion, analytical methods may be a good start for optimization methods. The optimization and simulation methods need to be adapted to each application environment. The three levels represent a general methodology for capacity management, where the first level represents a preliminary solution and the second level obtains a desired train schedule which is validated by means of simulation (the third level). Therefore, the current trend is to develop tools with an integrated methodology that embed analytical, optimization and simulation approaches.

2.5. Systems Views of Railway Line Capacity

In recent years, attention has been drawn to the railway capacity problem on the system scale. By considering railway capacity in systems terms, a more comprehensive picture of the factors which may affect it can be established. London Underground produced a diagram showing the factors affecting Line Capacity, as shown in Figure 2.3. The diagram clearly displays the interaction of factors, but does not distinguish operational functions from railway components. Moreover, passenger satisfaction and human factors are hardly considered in this diagram.

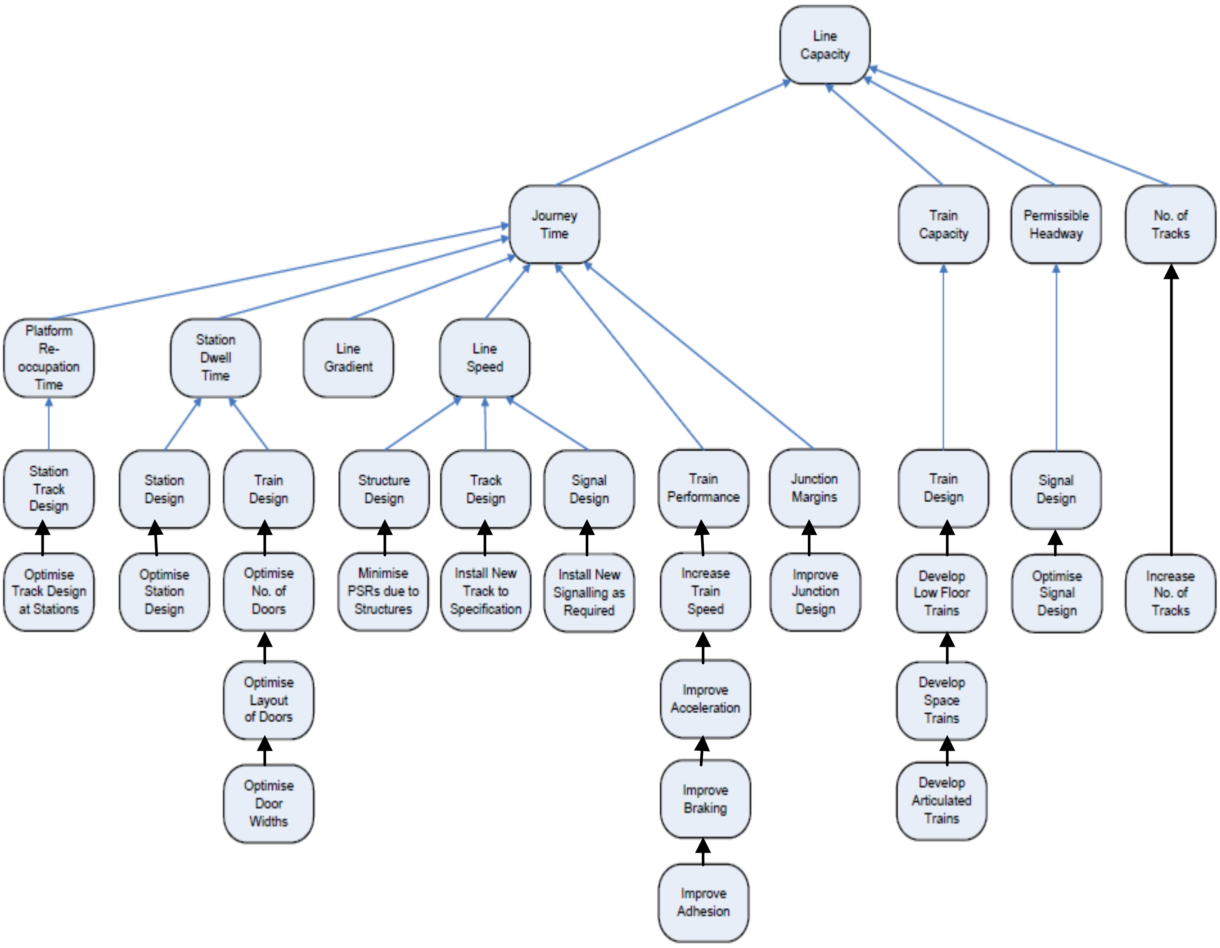


Figure 2.3: Drivers Affecting Line Capacity and Possible Technological Solutions – London Underground's Perception [10]

2.5.1. Line Capacity

Line capacity is the ability of a railway to carry a certain number of trains in one direction over a certain period. It is determined by how many trains you can run on the line in this direction in an hour and is expressed as trains per hour (tph). It can also be described in minutes or second as "headway" the time interval between successive trains.

With a defined infrastructure and a given train design line capacity will depend on the number of trains you can push along the track safely, one behind the other, in a given time. The actual number is then largely a function of the train performance and the train control system [21].

Station dwells and train control system minimum separation are the two major factors in determining line capacity [23]. In many circumstances dwells are the dominant factor. The third factor in headway is any operational allowance or margin. In some cases this margin can be added to the dwell time to create a controlling dwell time.

The three main components of dwell times are:

- ✓ passenger flow time;
- ✓ door open time after flow ceases; and
- ✓ Waiting to depart time after doors close.

2.5.2. How Can Train Control And Signaling System Affect Rail Capacity?

The characteristics of a signaling and automatic train protection (ATP) system have also a significant impact on the capacity and stability of a railway line. One way to improve railway infrastructure capacity is to update the signaling or ATP system to one that allows a closer headway between successive trains. A capacity assessment with respect to the different signaling and ATP variants then reveals how much capacity gains can be achieved. In AALRT case cab signaling, ATP and Balis are used for the signaling system.

Signaling also protect specific paths through interlocking at junctions and crossovers. Additional functions include automatic train stops should a train run through a stop signal, and speed control to protect approaches to junctions, sharp curves, and approaches to terminal stations where tracks end at a solid wall.

All urban rail transit train control systems are based on dividing the track into blocks and ensuring that trains are separated by a suitable and safe number of blocks. Train control systems are then broken down into fixed-block and moving-block signaling systems.

Fixed-Block Systems: In a fixed-block system, trains are detected by the wheels and axles of a train shorting a low-voltage current inserted into the rails. The rails are electrically divided into blocks. The blocks will be short where trains must be close together, for example in a station approach, and can be longer between stations where trains operate at speed.

The signaling system only knows the position of a train by the simple measure of block occupancy. It does not know the position of the train within the block; it may have only a fraction of the train, front or rear, within the block. At block boundaries, the train will occupy two blocks simultaneously for a short time.

Cab Signaling

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

The authorized speed can change while a train is in a block, as the train a head proceeds, allowing drivers to adjust train speed close to the optimum with less concern about overrunning a trip stop. Problems with signal visibility on curves and in bad weather are reduced or eliminated. Cab signaling avoids much of the capital and maintenance costs of multiple-aspect color light signals, although it is prudent and usual to leave signals at interlocking and occasionally on the final approach to and exit from each station.

Reducing the number of color light signals makes it economically feasible to increase the number of aspects and it is typical.

Moving Block Signaling Systems

Moving-block signaling systems are also called transmission-based or communication-based signaling systems. A moving block signaling system can be compared to a fixed block system with very small blocks and a large number of aspects.

However a moving-block signaling system has neither blocks nor aspects. The system is based on a continuous or frequent calculation of the clear (safe) distance ahead of each train and then relaying the appropriate speed, braking or acceleration rate to each train.

Train Separation

The fundamental objective of any train control system is safe but efficient train separation. To prevent collisions, trains must be kept apart and, if they are moving on the same track in the same direction, there must be enough space between them to allow the second train to stop when the first train stops. This is often referred to as the "safe braking distance" and it forms a substantial part of train separation, which increases with speed [27].

Headway

The signaling headway between the trains is defined as the time between two trains passing the same location on a railway line at a defined speed profile. Whilst there is a theoretical calculation based on the inbuilt technical capability of the system, the actual headway is dependent on various location and system specific factors including, but not limited to, differing maximum speed and braking capabilities of trains, gradients (affecting stopping distances), granularity of train detection, junctions and operational stopping patterns.

The minimum signaling headway of the route will be defined by the worst case location or condition necessary to maintain safe separation based on maximum permitted speed between trains operating at the defined operational speeds [28]. It is taken as the time between the front noses of successive trains passing any point along the line at the defined operational speed.

The practical planned maximum operational capacity is less than the sum of trains at minimum headways to allow some margin for day to day variability in operation including promptness of train dispatch, driving style etc. This is separate from timetabled allowance for delay which is captured in planned journey time, either at specific locations, principally before final destination or using the wider practice, adopted in most high speed rail operation, of timetabling trains at a percentage of maximum permitted speed.

2.6. Train/Car Capacity

Train capacity is the product of passengers per car and the number of cars, adjusted to achievable capacity using a diversity factor to compensate for uneven car loadings over multiple car trains [23].

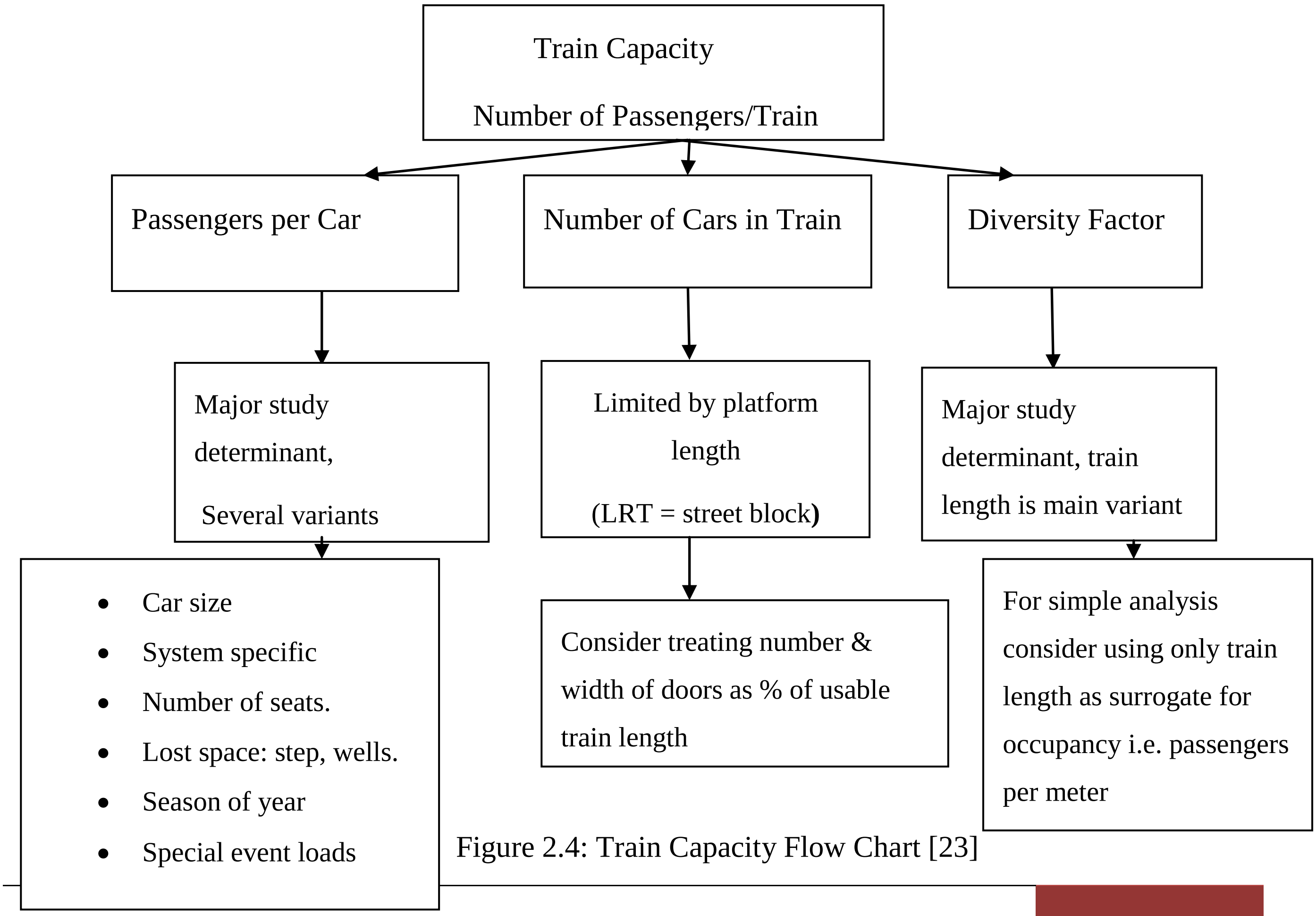


Figure 2.4: Train Capacity Flow Chart [23]

The only true means of measuring achievable car capacity is on those systems where pass ups occur. That is where passengers wait for the next train rather than crowd onto the one in their station. Determining full car capacity and pass-up capacity depends on interior arrangements, type of system, old or new, and time of peak loading.

Car Capacity

There are two approaches to calculation and evaluation of car capacity: design specific and a generic average based on car length.

Design-Specific Capacity

If a specific car design has already been chosen, capacity calculation is relatively straightforward. Space used for seats, cabs, wheelchair, stroller or bicycle positions, baggage racks, step wells, and other equipment is deducted from the interior floor area and the remaining, “standing” space assigned an appropriate standing density.

Train Length Alternative

This alternative offers the simplest method of establishing capacity per unit of car length based on policy decisions of seating type and quantity, and standing density.

2.7. Capacity in Different Traffics

Capacity of an infrastructure varies widely with differences in traffic distribution [14].

2.7.1. Capacity of a Line with Homogeneous Traffic

Computing the capacity for a line where all trains run at the same speed and have identical stop patterns is straightforward. In a space-time diagram, train paths are homothetic. In this case, capacity is the inverse of the minimum headway, i.e. the smallest time interval that should exist between 2 consecutive train paths.

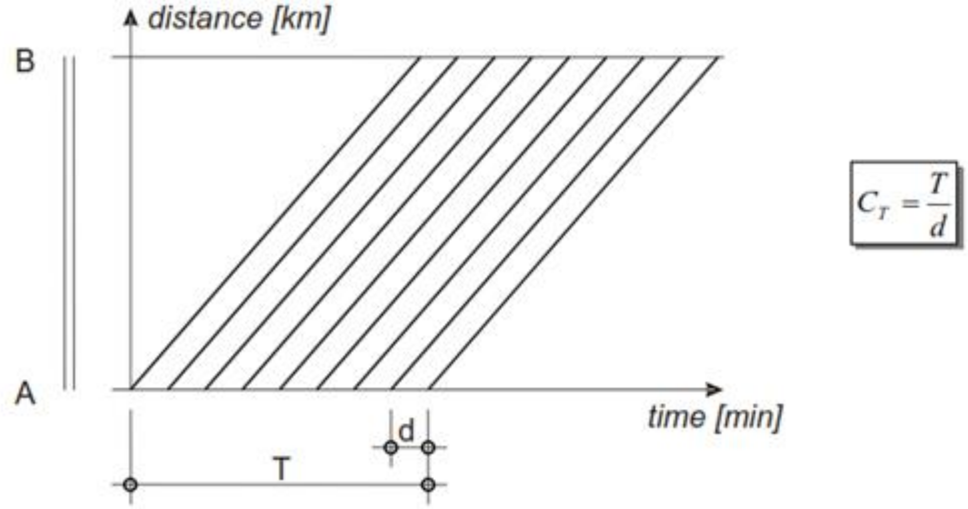


Figure 2.5: Capacity of a Line with Homogeneous Traffic

Actually, this simple formula may be misleading. When intermediate stations have a single platform for train stops, overall capacity of the line may be set by the station capacity: following trains cannot enter the station until the previous one leaves. Stop duration, and therefore passengers’ exchange, may be a critical factor in determining minimum headway.

Metro lines are a classical example of lines with homogeneous traffic. Rapid regional services around major conurbation are also mostly operated with identical train paths. The same goes for heavily loaded sections of national networks. This is the configuration of operations that maximizes capacity, as long as network effects do not induce extra constraints at the ends of the most loaded section.

2.7.2. Capacity of a Line with Mixed Traffic

Nevertheless, most of rail lines support mixed traffic, with several type of trains running, providing different services with different stopping patterns. Commercial speed is not uniform and train paths on the space-time diagram are not homothetic. In those cases, two more factors at least enter the game of determining capacity:

- ✓ Distance between consecutive stations where a faster train may overtake a slower one
- ✓ Sequence of the train paths i.e. the order in which the train paths are scheduled

Capacity cannot be calculated anymore by means of a single formula. To determine capacity, design of the timetable becomes unavoidable, as shown in Figure below, where 2 different train sequences lead to 2 different values of capacity for the same section.

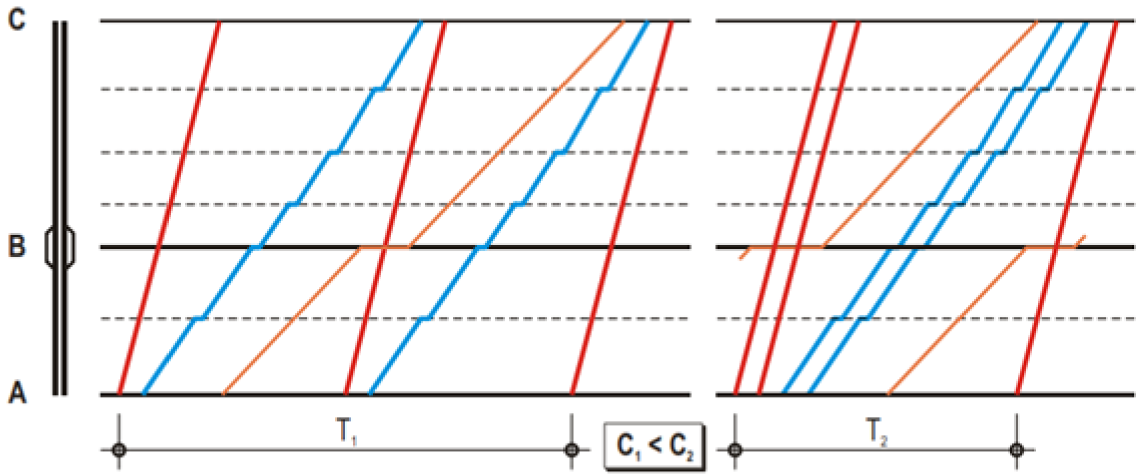


Figure 2.6: Capacity of a Line with Mixed Traffic

Now, extending the stopping time of a slow train, to let a faster train overtake it, increases the line capacity, but at the expense of service quality for the slow one. This is a commonly used solution for freight trains, but that should be applied to local passenger trains with reluctance. Even on top-equipped lines, the slow train stop lasts for at least 5 to 6 minutes, which clearly degrades its service and its commercial appeal.

Gaining Capacity by Speeding up Slowest Trains

On mixed traffic lines, train paths comes the closest to each other on entering or leaving major stations where fast trains overtake slower ones. Maximum capacity is reached when those converging or diverging train paths are separated by time intervals equal to the minimum headway set by the safety installations. Speeding up the slowest train, makes it possible to let it enter earlier or leave later the major stations. All other things being equal, that increases headways in the tightest part of the space time diagram. If time savings reach or exceed the minimum headway set by the signaling, it becomes Possible to offer an extra train path, usable by a fast or a slow train

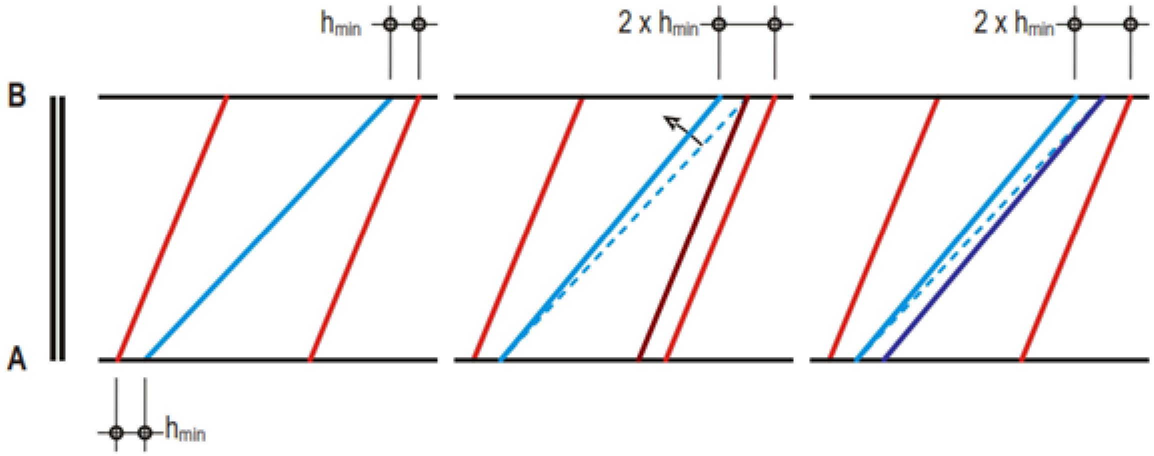


Figure 2.7: Gaining Capacity by Speeding up Slowest Trains

In those cases, it is wiser to value the speeding up of slow trains in terms of minutes and not on commercial speed. One can therefore compare directly time gains to minimum headways 'values and to verify whether the speeding up is sufficient to reach the threshold where capacity gains become possible.

This is obviously not the only possible measure to improve capacity, but it is an important lever to use in overall optimization of the railway system.

2.8. Parameters Related To Speed Restriction

2.8.1. Speed Restrictions in Station Entrance

Ideally, braking to stop in a station should occur as late as possible, as any early braking leads to purposeless time losses. The earlier speed restrictions apply when entering a station, the larger are the time losses. Speed restrictions are due to:

-Technical reasons taking the diverting direction in a switch induces speed restrictions which require previous braking.

-Safety reasons when slip distance is not sufficient, or in dead-end stations, speed restrictions ensure that a train stopping beyond the nominal point bears no consequence.

2.8.2. Driving Sensitivity

The human factor is also a key element in the operation's stability. Manual driving never reproduces accurately the speed-space diagrams that planners compute, due to inherent variations in drivers' behavior. Usually, time differences resulting from drivers' behavior variability do not exceed a couple of seconds, and train scheduling takes them into account by including recovery times in timetable design (travel times in the timetable are slightly increased compared to computed running times, by means of an added percentage increase).

Despite recovery times, some drivers (the most cautious ones) may experience difficulties running on time, especially during peak periods. On heavily loaded or near-saturated lines, this may impact stability. Without driving assistance systems onboard, some companies design drivers' roster so that the most alert drivers are assigned to peak-period services.

2.8.3. Terminals

The location of the turnouts needs to be carefully selected so that the speed limit through the turnout matches, as closely as possible, the braking curve of the train approaching the terminal. This will not always be possible but some degree of integration in this area is most desirable. The terminal itself will also need to be designed so that the train protection system includes a buffer zone for the speed limit of the final block. It is, perhaps, worth noting here that platform capacity at the terminals is another constraint that must not be ignored. A single terminal platform cannot normally handle more than two intercity trains per hour. An allowance of at least 20 minutes has to be made for time to unload passengers and their baggage, clean the interior, replenish water, restock victuals, change the crew and load the passengers and their baggage for the outgoing trip [21]. To this must be added the incoming route setup time, the run in time, the run out time and the route clearance plus a margin.

2.8.4. Stop Duration

Minimum stop duration in a station depends on volume of passengers' movement per vehicle door, width of the doors, step distance (both height difference between the platform and the first step and gap between the platform and the vehicle), etc.

Rail operators set stop duration depending on the type of station and the rolling stock.

Minimal values vary across countries and operators. In Switzerland, for instance, minimum stop duration for a regional train is between 30 and 326 seconds (0.5 to 0.6 min); in France, minimum stop duration in such cases is 1 minute; in AALRT the design stopping duration is 30seconds but practically it will wait up to 3 minutes.

In minor stations, stops frequently require significantly less time; the extra time spend in waiting to exhaust the minimal time of 1 minute is lost. Losses cumulated over several minor stations may become significant. Saving this time, in conjunction with other optimization measures can be helpful in increasing capacity of saturated lines.

2.9. Energy Consumption

Electric trains and railways have until now been the mode of transport generally considered being “the best” from an environmental point of view, in particular regarding energy consumption and its related emissions to the air.

With its large capacity, the total urban rail transit energy consumption is very high; thus, energy saving operations is quite meaningful. Low energy consumption at increased speeds requires a new train concept and design, using the most modern technologies and knowledge available [16].

2.9.1. Increasing Power to Ton Ratio

Adding locomotives to lower priority unit trains reduced the delay on these trains in a similar manner for all train scenarios. However, additional locomotives are a major capital investment and will also increase maintenance and fuel costs. The increased power reduces time lost in meets for the unit trains, thereby reducing run times; however, if delays to following trains are not also reduced there will be no improvement in capacity. If additional locomotives can be combined with increased speed the benefits will be enhanced. The effectiveness of this method of increasing capacity is dependent on reducing the delays experienced by following trains due to the slow acceleration of a preceding train. Urban and other high density scenarios are the most likely situations where this method would be beneficial [15].

2.9.2. Journey time and energy consumption calculation

Based on the theory presented below. The force related to train motion is given as a form of Newton’s second law of motion [6].

$$Ft - Fr - Fg - Fc = Me.a \qquad \text{Equation 5}$$

Where

Ft = tractive force,

Fr = running resistance force,

Fg = resistance force from gradient,

Fc = resistance force from curvature [N],

Me = effective mass [kg],

a = acceleration [m/s^2].

The effective mass is given by

$$Me = M_t\,(1+\lambda) + M_p, \qquad \text{Equation 6}$$

Where

M_t = is train mass,

λ = is the rotary allowance (typically 0.05 to 0.15), and

Mp = is the payload.

Running resistance is given by

$$F_r = A + Bv + Cv^2 \qquad \text{Equation 7}$$

Where

A = is a coefficient related to the rolling resistance,

B = is related to bearing friction coefficient,

C = is related to the aerodynamic drag coefficient, and

v = is velocity [m/s].

At high speeds, the contribution of the aerodynamic drag becomes dominant.

Resistance from a gradient is given by

$$F_g = (M_t + M_p)\, g \sin\alpha \approx (M_t + M_p)\, g \ast n/1000 \qquad \text{Equation 8}$$

Where

g = is the acceleration due to gravity, and

α = is the gradient of the line.

In reality, α is such a small angle that sinα can be approximated by tanα, which is generally measured as n [m] of rise or fall in one thousand meters, that is, %.

Resistance from curvature is given by

$$F_c = (M_t + M_p)\ g * 1/1000 * 700/R \qquad \text{Equation 9}$$

Where

R = is the radius of the curve.

This equation means that the resistance force of curvature with a radius of 700 m has the same magnitude as the gradient force of a 1% gradient [6].

The power of the traction system (P)[W], tractive force (Ft) and velocity (v) have the following relationship:

$$Pt = F_t\, v \qquad \text{Equation 10}$$

Energy consumption at the wheel (EC wheel) is calculated by the integration of Ft with respect to distance (x). Journey time (T) is also calculated by the integration of time (t) for each calculation step,

$$EC_{wheel} = \int Ftdx = \int \frac{Pt}{v} dx \qquad \text{Equation 11}$$

$$T = \int tdx = \int \frac{x}{v} dx \qquad \text{Equation 12}$$

As a first approximation, the energy consumption by auxiliary power needs (Pa) is a function of journey time (T) although it also depends on the comfort level required and the outside temperature:

$$EC_{\ auxiliary} = P_a\ T \qquad \text{Equation 13}$$

Energy consumption of a single train, EC, is given in terms of the efficiency of the traction system, η, $0 = \eta = 1$,

$$EC = \eta\ EC_{\ wheel\ +}\ EC_{\ auxiliary} \qquad \text{Equation 14}$$

Energy consumed by train operation can be reduced using mass reduction, aerodynamic and friction reduction by appropriate design of train and space utilization

Here, according to Equation 12, we can minimize the journey time and energy consumption of the train by using the possible traveling speed of the train.

CHAPTER THREE

3. Light Rail Capacity and overview of AALRT

3.1. Overview of AALRT system

Addis Ababa Light Rail is a light rail transportation system in Addis Ababa, Ethiopia. Opened on 20 September 2015.Service began on 9 November 2015 for the second line (east –west). The line has two direction east –west (EW) and north- south (NS) direction. The total length of both lines is 31.6km, with 39 stations. Trains are expected to be able to reach maximum speeds of 70 km/h.

Figure 3.1: Train of AALRT

The east-west line extends 17.4km, stretching from Ayat Village to Torhailoch, and passing through Megenagna, Meskel Square, Legehar and Mexico Square. The north-south line, which is 16.9km in length, passes through Menelik II Square, Merkato, Lideta, Legehar, Meskel Square, Gotera and Kaliti. However, two lines have a common track of about 2.7 km. The common track is the elevated section which runs east to west across the southern edge of the CBD from Meskel Square to Mexico Square, and onwards to Lideta. Trains on the north south line are blue and white, while on the east west line they are green and white. The Fares cost 2-6 Ethiopian birr. The final cost to build the railway was US$475m, with construction taking three years. The Addis Ababa Light Rail was originally to have a total of 41 stations on its two lines, and each train was planned have a capacity to carry 254 passengers. This will enable the light rail transit to provide a transportation service to 15,000 passengers per hour per direction (PPHPD) and 60,000 in all four directions. The railway lines have their own dedicated power grid.

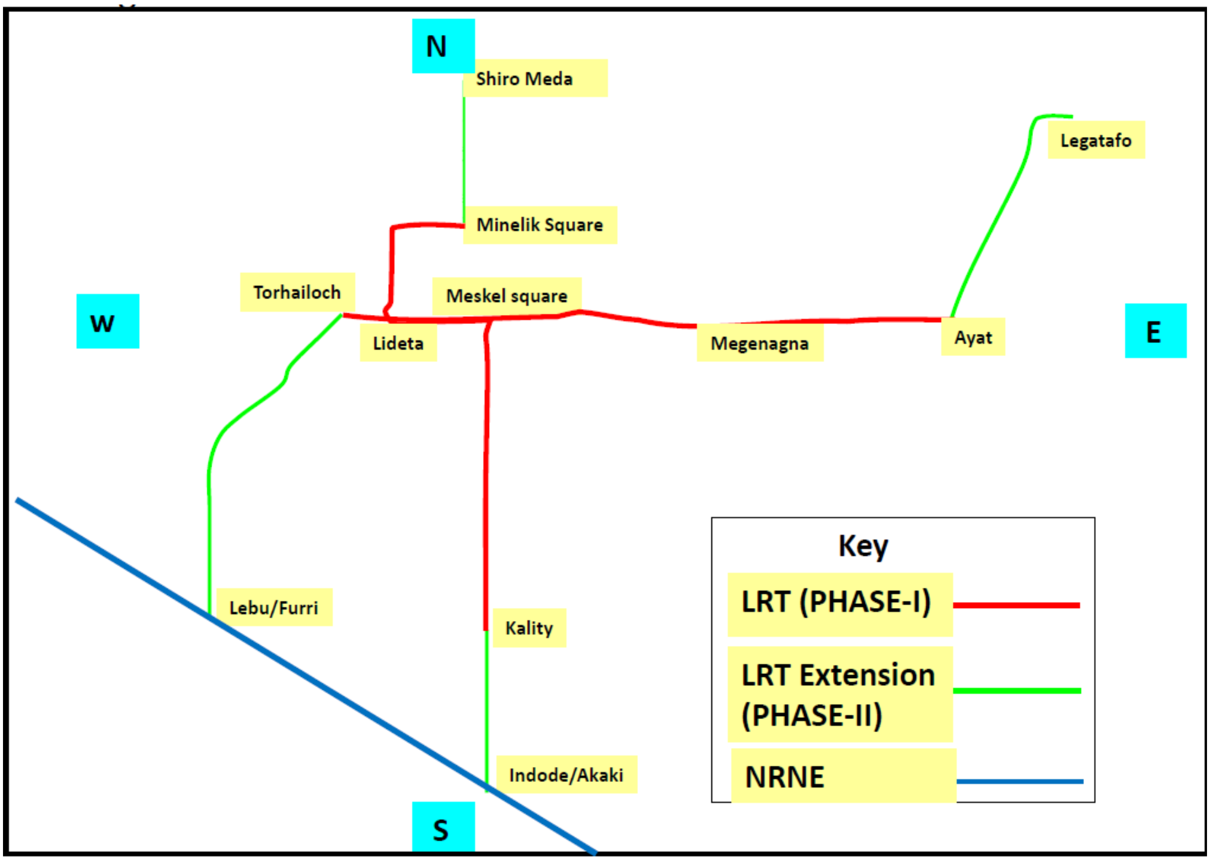


Figure 3.2: AALRT Alignment with Extension

These are some of the important information about the AA-LRT Light Rail Vehicles:

- ✓ Maximum speed of train on level track = 70kph
- ✓ Maximum speed of train on level crossing = 50kph
- ✓ Maximum average deceleration rate = 1 m/s^2
- ✓ Maximum average deceleration at emergency brake = $2m/s^2$
- ✓ Average dwelling time is = 30s
- ✓ Operating margin time = 7s
- ✓ Number of passengers per train = 317 (8 person/m^2) and 254 (6 person/m^2)
- ✓ Length of a train = considering the connecting length in between the two coupled trains, the total length of the coupled trains from tip-to-tail is about 59m. Simply from the station platform a maximum of two trains can only be coupled because of the designed curve radius of the AA-LRT infrastructure.

3.2. Introduction of Light Rail Capacity

This chapter covers methods for determining the capacity of light rail transit lines.

Light rail transit lines often have characteristics such as street running, grade crossings, and single track sections which are of importance in capacity determination. The key to determining the capacity of a light rail transit line is to find the weakest link the location or factor that limits the capacity of the entire line.

3.2.1. Selecting the Weakest Link

Determining the capacity of light rail transit lines is complicated by the variety of rights-of-way that can be employed. However, most light rail transit lines use a combination of right-of-way types which can also include on-street operation and private right-of-way with grade crossings. Other limitations can be imposed by single-track sections and the street block lengths. The line capacity is determined by the weakest link; this could be a traffic signal with a long phase length, but is more commonly the minimum headway possible on a block signaled section. The right-of-way capacity constraints are listed below in the order of their decreasing relative importance for most systems. This order is as follows:

- ✓ single track,
- ✓ signaled sections,
- ✓ on-street operation, and
- ✓ Private right-of-way with grade crossings.

This order is not definitive for all systems, but it is appropriate for most. Systems specific differences, such as short block lengths on signaled sections, will change the relative importance of each item.

3.3. Other Capacity Issues

Car loading levels for light rail transit, should be determined with reference to the passenger loading standards for light rail transit, the standards are discussed in chapter four. Light rail loading levels are generally lighter than those for heavy rail transit but not as generous as the one seat per passenger policy common on commuter rail.

3.3.1. Loading Diversity

Passengers do not load evenly into cars and trains over the peak hour. Three different types of loading diversity have to be considered.

The first level of loading diversity is within a car. In individual cars the highest standing densities occur around doorways, the lowest at the end of the cars. Several European urban rail systems add doors, sometimes only single-stream, at the car ends to reduce this unevenness.

A second level of diversity occurs in uneven loading among cars of a train. Cars that are closer to station exits and entrances will be more heavily loaded than more remote cars. This inefficiency can be minimized by staggering platform entrances and exits between ends, centers and third points of the platforms. This is not always possible or practiced. Even so, relatively even loading often occurs due to the duress factor that encourages passengers to spread themselves along the platform during heavily traveled Times or risk being unable to get on the next arriving train.

Few systems count passengers by individual cars when these are crush loaded. This is difficult to do with any accuracy and the results differ little from assigning a set full load to each car of a fully loaded train [23].

3.3.2. Passenger Loading Levels

Establishing the loading level of rail transit is the final step in determining capacity.

After the maximum train throughput has been calculated capacity is then based only on train length and loading level.

3.3.3. Loading Standards

Most rail transit systems have loading standards for the peak-hour, peak-point location with more relaxed standards away from entry into the city center and for off-peak times.

Care should be taken in comparing and applying the service standards with hourly average loadings.

3.3.4. Space Requirements

The Batelle Institute recommends comfort levels for public transport vehicles and provides details of the projected body space of passengers in various situations. The most useful of these for rail transit capacity [23].

- ✓ Comfortable: 2-3 passengers per m2 (5.4 to 3.6 ft/p),
- ✓ Uncomfortable: 5 passengers per m2 (2.2 ft/p), and

- ✓ Unacceptable: >8 passengers per m (1.3 ft/p)

3.3.5. Vehicle Specification

The residual floor area can now be assigned to standing passengers. Light rail vehicles with step wells should have half the step well area deducted. Although prohibited by many systems, passengers will routinely stand on the middle step, squeezing into the car at stops if the doors are treadle operated.

Articulated light rail vehicles should have half the space within the articulation deducted as unavailable for standing passengers, even if the articulation is wider. Many passengers choose not to stand in this space.

Standing passengers can be assigned as follows:

- ✓ 2.5 passengers per square meter, or 0.4 m^2 (4.3 ft^2) per passenger, comfortable level without body contact, reasonably easy circulation, and similar space allocation as seated passengers
- ✓ Passengers per square meter, or 0.3 m^2 (3.2 ft2) per passenger, a reasonable service load with occasional body contact. Moving to and from doorways requires some effort.
- ✓ 5 passengers per square meter, or 0.2 m^2 (2.15 ft2) per passenger, an uncomfortable near crush load for North Americans with frequent body contact and inconvenience with packages and brief cases. Moving to and from doorways is extremely difficult [23].

In case of AALRT the standing passengers are assigned 6 passengers per square meter. According to the above standards our LRT vehicle specification is uncomfortable.

Light rail train lengths are more restricted than for heavy rail transit or commuter rail because of lower car and coupler strengths, and street block and station platform lengths.

These issues are considered under Train Length and Station Limitations later in this chapter.

One additional issue that is of particular importance to light rail operations and capacity is the method of access for passengers with mobility limitations. While the speed of each access method varies, all can have an effect where close headways and tight scheduling prevail.

3.4. Single Track

Single track is the greatest capacity constraint on light rail lines where it is used extensively. Single-track sections are used primarily to reduce construction costs. Some lines have been built with single track as a cost-saving measure where the right-of-way would permit double track. In other areas single track has been built because widening the right-of-way and structures is impossible. Single-track sections can be very short in order to bypass a particular obstacle; for example, an overpass of a highway.

While determining the potential extent of single-track construction is possible, the exact layout is highly system specific. Estimates can be made of the number of track kilometers or miles required for a certain number of route kilometers or miles once the intended headway is known. While this does not tell the user where the single-track sections can be used, it can provide assistance in determining the possible extent of single track for use in cost estimates.

3.4.1. Calculating Single-Track Headway Restrictions

Single-track sections greater than 400-500 meters (0.25-0.30 miles) are potentially the most restrictive capacity constraint for light rail [23]. The headway limitation is very simply twice the time taken to traverse the single-track section, plus an allowance footswitch throw and lock unnecessary for spring switches or gauntlet track plus an operating margin to minimize the potential wait of a train in the opposite direction.

The time to cover a single-track section is:

$$T_{st} = SM\left(\frac{(N_s+1)}{2}\left(\frac{3v_{\max}}{d_s}+t_{jl}+t_{br}\right)+\frac{L_{st}+L}{v_{\max}}\right)+N_s t_d+t_{on} \qquad \text{Equation 15}$$

Where

T_{st} = time to cover single track section

L_{st} = length of single track section

L = train length

N_s = number of stations on single track section

T_d = average station dwell time on section

V_{max} = maximum speed reached

Ds = deceleration rate

t_{jl} = jerk limited time

t_{br} = operator and breaking system reaction time

SM = speed margin

t_{om} = operating margin

Trains should be scheduled from their termini such that passing locations are not close to the single-track sections. Where there is more than one single-track section this can become difficult but not impossible.

Lengthy single-track sections can severely limit headways and capacity and may require one or more double track passing sections in the single-track section. These should, wherever possible, be of sufficient length to allow opposing trains to pass on-the fly and to allow some margin for off-schedule trains. Obviously trains should be scheduled to pass at this location.

3.5. Train Length and Station Limitations

3.5.1. Street Block Length

The length of street blocks can be a major limitation for at-grade systems which operate on-street. Most jurisdictions are unwilling to allow stopped trains to block intersections and so require that trains not be longer than the shortest street block where a stop is likely.

Street block length is also an issue if another vehicle occupies the same lane used by light rail trains in a block. If this would cause the rear of the train to protrude into an intersection then the train must wait for the block to clear before advancing. This fact provides a strong argument for the provision of an exclusive light rail transit lane where street running with long trains occurs. Indeed, as a result of this concern, operation with mixed traffic is very rare on new light rail transit systems. Where buses and light rail transit trains operate alongside each other on transit malls. The rail stations, bus stops, and lanes are laid out to cause a minimum of interference between the modes.

3.5.2. Station Limitations

An obvious limitation to train length is the length of station platforms. For most light rail transit routes this is not a problem as stations have been built with current ridership and service levels in mind.

The high volumes of transit vehicles and passengers can cause delays to following streetcars while passengers board and alight from the preceding car. Scheduled recovery time for the streetcar operator is hard to accommodate in these conditions as the volume of following cars precludes layover time.

3.6. Capacity Determination Summary

Calculating the capacity of light rail transit lines is a complex process because of the varieties of rights-of-way which can be employed for the mode. The basic approach is to find the limiting factor or weakest link on the line and base the capacity on this point. The limiting factor for each line could be street-running with long traffic signal phases, a section of single track, or the length of signal blocks where block signaling is used.

The key factors to be considered are:

- ✓ Single track.
- ✓ Signaled sections. Of particular importance where, for cost reasons, the signaling is not designed to allow minimum possible headway operation.
- ✓ On-street operation. Capacity effects are strongly related to the degree of priority given to light rail vehicles relative to other traffic.
- ✓ Private right-of-way with grade crossings.

3.7. Grade-Separated Systems Capacity

Grade-separated rail transit is operated by electrically propelled multiple-unit trains on fully segregated, signaled, double track right-of-way.

Light rail operates in a variety of rights-of-way, each of which has specific achievable capacities. However these are rare and achievable capacity is usually controlled by the signaling throughput of grade-separated sections.

This is due to two reasons. Several light rail systems converge surface routes into a signaled grade-separated section operating close to capacity. Other, less busy systems have the signaled grade-separated sections designed economically not for minimum headways down to two minutes. Typically this signaling is designed for three to four-minute headways more restrictive than the headway limitations of on-street operation, with or without varying forms of traffic signal pre-emption. However, signaled grade-separated sections may not always be the prime headway limitation.

3.8. Rail Capacity Basics

Many rail transit capacity calculations add constants, multipliers, reductive factors, or other methods to correlate theory with practice. In this section emphasis has been placed on reducing the number of qualifications and quantifying, describing and explaining adjustments between theory and practice in determining rail transit capacity.

3.8.1. Design Capacity

The maximum number of passengers past a single point in an hour, in one direction on a single track.

Design capacity is similar to, or the same as, maximum capacity, theoretical capacity, or theoretical maximum capacity expressions used in other work. It makes no allowance for whether those spaces going by each hour will be use they would be fully used only if passengers uniformly filled the trains throughout the peak hour. This does not occur and a more practical definition is required. Achievable capacity 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.

Design capacity has two factors, **line capacity** and **train capacity**, and can be expressed as:

$$C_D = C_L * C_T \qquad \text{Equation 16}$$

Where:

C_D = design capacity (p/h);

C_L = line capacity (trains/h); and

C_T = train capacity (p/train).

In expanded form, design capacity is given by Equation 16:

$$C_D = \frac{3600}{(ts + td)} \text{ x } P_c \text{ x } N_c \qquad \text{Equation 17}$$

Where:

C_D = design capacity (p/h);

t_s = minimum train separation (s);

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

P_C = total passengers per car; and

N_C = number of cars per train

3.8.2. Achievable Capacity

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 (sometimes called practical capacity) refers to capacity in one direction on a single track. The capacity of four track lines is not a simple multiple of two single tracks and varies widely with operating practices such as the merging and dividing of local and express services and trains holding at stations for local express transfers. The result is that four tracks rarely increase capacity by more than 50% over a double track line and often less. A third express track does not necessarily increase capacity at all when restricted to the same station close-in limitations at stations with two platform faces [23].

The achievable capacity can be expressed as:

$$C_A = C_D * PHF \qquad \text{Equation 18}$$

Where:

CA = achievable capacity (p/h);

CD = design capacity (p/h);

PHF = peak hour factor.

The expression in Equation 16 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. In rare cases speed restrictions or heavy mixed passenger flows may dictate that other than the maximum load point station controls train throughput. 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. This is referred to as the “close-in” time and is based on non-interference with the following train, i.e., no speed restrictions or stops. In a small number of cases the critical governor of headway is a junction or a terminal maneuver.

Controlling dwell is based on actual station dwell time adjusted to a controlling value over the peak hour. The controlling dwell may contain an operating margin or a margin can be added separately to the denominator of the expression.

3.8.3. Design versus Achievable Capacity

The difference between design and achievable capacity is an important consideration.

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 standee density),
- ✓ number of cars per train, and
- ✓ Train headway (minimum headway determined by a combination of the signaling system, station dwell, and terminus constraints).

This approach does not incorporate factors that reduce the actual number of regular riders that the system can sustain.

Standing densities vary; people will crowd in more tightly in some situations than in others.

- ✓ In a multi-car train; some cars carry more passengers on average than others.
- ✓ Many factors reduce train performance (propulsion faults or differences, door problems, operator variation), which may not only increase the sustainable average headway, but will increase the variation in headway, and consequently the passenger load waiting for that train.
- ✓ Minimum headway, by definition, leaves no margin for schedule recovery from even minor delays, leaving the system susceptible to more variation in service.
- ✓ Passenger demand is unevenly distributed within the peak period; there may be predictable “waves” of demand, corresponding to specific work start and finish times.
- ✓ There is day-to-day fluctuation in demand. Some may be associated with the day of the week (peaks have become lighter on Mondays and Fridays as more people move into shorter or flexible work weeks), seasonally (lighter in the summer and at Christmas time), weather and special events.
- ✓ Passengers are resilient to a degree, and will tolerate overcrowding or delay on occasion. This permits systems at capacity to accommodate special events or recover from service delays.

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).

3.9. Operating Margin Time and Dwell Time

To accommodate these routine irregularities, two allowances are made in rail transit operations planning and scheduling. An operating margin is added to the minimum train separation time and maximum load point station dwell time to create a minimum headway. This operating margin is, in effect, the amount of time a train can run behind schedule without interfering with the following trains. The operating margin is an important component in determining the maximum achievable capacity.

The second allowance is schedule recovery, an amount of time added to the terminal turn-around time to allow for recovery from accumulated delays on the preceding trip.

Schedule recovery time has some effect on achievable capacity and has economic implications as it can increase the number of trains and staff required to transport a given volume of passengers [23].

Service Headway

Design (minimum) train operating headway is a function of:

- ✓ signaling system type and characteristics, including block lengths and separation;
- ✓ operating speed at station approaches and exits or other bottlenecks such as junctions; and
- ✓ Train length and station dwells.

Achievable headway, must account for additional factors that can affect the separation of individual trains. These include differences in operator and rolling stock performance, external factors, such as grade crossings, that can impose delays, and the need for schedule recovery time.

Station dwells combine with minimum operating headway to create a constraining headway bottleneck in the system. Typically this is a concern on fully segregated systems that are operating long trains on close headways. Busy stations, especially major passenger interchanges, can produce block occupancy times that limit the entire system.

3.10. Impact of Operations on Railroad Capacity

Railroad operations encompass all aspects of the movement of passengers and goods over the rail infrastructure between many origin and destination pairs. This includes how railroads create, operate and dispatch trains, and is influenced by a complex interaction of traffic, infrastructure, and geographical characteristics. Efficient railroad operation may require intensive planning and analysis. Decisions to improve one aspect may have unintended consequences on other aspects of railroad operations. Operations affect the use of the available rail network capacity and inefficient operations can result in lost capacity. Consequently, in order to more effectively use the available resources, a railroad must understand how their operations influence capacity.

3.10.1. Operational Factors That Influence Capacity

Railroad operating factors that influence capacity can be separated into two broad groups: train characteristics, and scheduling and dispatching. The key train characteristics include the length, tonnage and power and are determined when a train is made up in a yard. Scheduling and dispatching determine when and how trains are moved from origin to destination. Scheduling is the planning of traffic before leaving the terminal, while dispatching is the control of the trains while in transit. The two groups are closely linked, as train speed is influenced by the power of the train, and train length affects which sidings the dispatcher can direct a train into during meets and passes. In the following sections discuss operational factors and their effect on railroad capacity.

3.10.2. Train Characteristics

Train length affects the required number and handling of trains. Longer train lengths reduce the number of trains required to move the same amount of cargo. Fewer, longer trains free up additional train slots for new traffic. However, longer train lengths cause longer train braking distances, resulting in longer blocks and slower speeds. Train length is often limited by yard constraints or the length of sidings on a route. Operating longer trains may also result in longer intervals between trains, with the consequent potential to reduce service quality.

Train weight, much like train length, affects the required number and handling of trains.

Heavier railcars reduce the required number of trains, but increase the distance it takes for a train to stop. Depending on the traffic control system, this may require increased train spacing.

Train power affects the ability of a train to accelerate and reach its desired operating speed. A train with a higher power-to-ton ratio or tons-per-equivalent-axle can accelerate more rapidly from a stop and reach a higher maximum speed. Additional power can increase speeds, reduce time lost when a train stops due to a conflict and reduce additional delays to following trains if they must slow to wait for a train to accelerate.

3.10.3. Dispatching and Scheduling Parameters

Such as **Train mix, Train priorities, Traffic patterns, Stability, Train speed** and all this are discussed in chapter 2 parameters of capacity.

3.11. Use of Delay to Measure Railroad Operations

The most frequently used metric for analyzing railroad operations is train delay. Train delay is the additional travel time resulting from various events in route. Delay is not a direct measure of capacity but rather a measure of the level of service. Delay has direct costs to the railroads due to penalties from shippers but also results in car and locomotive ownership costs, fuel costs, crew costs and lost opportunity costs due to longer cycle times.

Trains can be delayed for a number of reasons. In general these delay types can be categorized as either scheduled or unscheduled delays [15]. Scheduled delay is the delay incorporated into the timetable as buffer time to allow for conflicts with other traffic. These delays are related to the volume of traffic on a route. With more traffic, the number of meets and passes increases, and headways are reduced, increasing the probability that a faster train will be delayed by a slower preceding train. It is generally agreed that delays increase exponentially with train volume, with the specific relationship being dependent on the infrastructure and train mix unlike scheduled delays; unscheduled delays are random and independent and vary from train to train. For this reason, they are a leading factor in unreliability and instability of a network. Unscheduled delays can be caused by: mechanical failures, malfunctioning infrastructure, weather conditions, excessive boarding times of passengers, and accidents at road-railroad crossings and so on .Large unscheduled delays can cause crew shortages and disrupt operations on the entire network.

While unscheduled delays have a low probability they can cause substantial amounts of delay. Consequently, adjustments to a train’s schedule to account for potential unscheduled delays are difficult.

Unscheduled delays to one train sometimes referred to as primary or exogenous delay, can lead to secondary or “knock-on” delays to other trains. Secondary delays are a result of the shared usage of infrastructure, rolling stock and crews. Delay of one train may cause a following train to stop or reduce its speed and may potentially affect subsequent trains as well. The amount of secondary delay depends not only on the frequency and duration of primary delays, but also on the amount of available capacity. As a route nears its theoretical capacity the probability that primary delays will lead to secondary delays increases, while the ability to recover from these delays decreases .The relationship between delay and capacity is not simple. The maximum capacity for a route in terms of volume is dependent on operational decisions by the railroad. Each railroad determines the maximum allowable delay based on the traffic mix, route geography and service requirements. Different types of traffic have different requirements; for instance, due to competition from trucks intermodal traffic requires higher velocities and fewer delays, than shipments of coal that are less time sensitive. If a railroad requires a more reliable schedule with fewer delays, the capacity utilization on a route will be less than if a railroad is willing to accept higher delays.

Additionally, different traffic patterns will result in different delay-volume relationships; therefore the maximum volume will be different at the same amount of acceptable delay.

The difference between the minimum, or unopposed, run time and the actual run time required to traverse the route. This includes both scheduled and unscheduled delays. Delays using this definition are directly related to the run time or average speed of the traffic. The other definition of delay only calculates the unscheduled delays. This is calculated as the difference between the scheduled and actual run time. Delays using this definition are directly related to the reliability or on-time performance of the traffic.

Delay is often used as the output in simulations and can provide a basis for decisions on infrastructure projects or operational changes. Each railroad has calculated the costs of train delay to their operations. Using this value they are able to calculate the economic value of a project or operational change.

Although delay is a useful and widely used metric, it is not without its limitations. Delay, volume and capacity are not always related. Delay can change independently of capacity depending on the train speeds and the arrangement of the sidings. Additionally, it is possible for increased traffic to cause increased delays without a negative effect on existing traffic. For example, assume that an increase in train speeds reduces travel time by twenty minutes but new traffic is added that increases delay by ten minutes. The result is an increase in volume and a ten minute reduction in total travel time, but, this improvement is not reflected in the delay measurement.

3.12. Demand-Capability Gaps

Demand-capability gaps arise from a number of factors but fundamentally it refers to the complex relationship between passenger and freight demand and the railway network capability to satisfy and carry it. Actual passenger demand is a response to the train service offered and rail's competitive position in the market for travel.

Many factors influence that response including cost, quality and ease of access. The capability gap is often referred to as a capacity gap.

For the purposes of this analysis a 'capacity gap' has been defined as follows:

'A capacity gap occurs where the current capacity of the network is exhausted. A capacity gap can manifest itself in a number of ways. One manifestation of this gap occurs when sufficient capacity cannot be provided between two places so that all passengers who wish to travel can do so in appropriate comfort. Another manifestation of a capacity gap can be seen when markets between origin and destination pairs cannot be served with an appropriate level of rail service.'[24].

3.13. Quality of Service

Quality of Service proposed as an improved definition of railway system capacity. Quality of service is an indication of the comprehensive performance of the railway system. It covers Transport Volume, Journey Time, Connectivity, Punctuality, Resilience, Passenger Comfort, Energy and Resource Usage. The railway systems are expected to be optimal in terms of all the indicators; however, trade-off needs to be made in practice due to the various constraints in real life railway operations. On the engineering side, the factors affecting Quality of Service can be broken down into Capability and Dependability. Capability covers all the "static" elements which are relatively hard to change, such as Rolling Stocks, Infrastructure, Timetable and Operational Rules. Dependability includes all the dynamic components of the system, such as Traffic Management, Operational Management, Human Factors, System Maintenance and Environmental Factors. These components can be modified in short term practice.

Capability: Rolling stock

Rolling stock comprises all the vehicles running on the railway network. The main features of rolling stocks that can affect Quality of Service are as follows:

- ✓ Dynamic Performance: braking, acceleration, resistance, traction force, etc.
- ✓ Static Performance: length, mass, adhesion, maximum speed, etc.
- ✓ Configuration: the way rolling stocks are formed is also very important. This may affect the length, mass, traction, etc. and thus affect the running dynamics.

Capability: Infrastructure

Infrastructure is a vital component of the railway system. It has great influence on the train run, energy utilization and potentially passenger comfort. Infrastructure is mainly made up of the following elements:

- ✓ Station: The number, positions and architecture of stations on the network have great impact on the throughput. They may also influence the service pattern and the robustness of the timetable.
- ✓ Track section: The length, gradient, adhesion and curvature of track sections will affect the braking, acceleration and maximum speed of trains. Moreover, the number of available track sections is an influencing factor of throughput.
- ✓ Signaling: The signaling system determines the headway time and thus the throughput of the network.
- ✓ Power network: A good power network can ensure the safety and energy efficiency of the train run.
- ✓ Communication network: The communication network transfers the traffic information to and from trains. Faults of the communication network can lead to delays, conflicts or even accidents in the system.
- ✓ Passenger Information System (PIS): This system provides information to the passengers, helping them make travel decisions and reduce stress.

Capability: Timetable

A railway timetable is a detailed plan of trains departing and arriving at stations.

- ✓ Pattern: the time slots arrangement pattern for all the trains in the nominal timetable, e.g. the mixture patterns for fast trains and slow trains. This would affect the resilience of the nominal timetables.
- ✓ Allowance time: the time added into the nominal timetable to compensate the additional train sectional running times, dwell times and other scheduled process times due to the unavoidable variability of physical characteristics, driver behaviors, passengers boarding and alighting variations and other potential influencing factors to train operations in real life conditions.
- ✓ Buffer time: the time added into the nominal timetable (between train slots) to reduce or avoid propagation of knock-on delays among running trains due to initial and/or primary train delays.

- ✓ Recovery time: the time added into the nominal timetable to be reserved for the trains to be recovered from initial and/or primary delays by using effective train operation strategies.

Capability: Operational rules

Operational Rules are the short-term requirements in practice. The main aspects are:

- ✓ Train operational rules: Long term regulations for train operations.
- ✓ Infrastructure operational rules: Long term regulations for infrastructure operations.
- ✓ Traffic operational rules: Conflict/ Delay management plan, Priority, Train Mix etc.
- ✓ Crew operational rules: The allocation plan of crew.

Dependability: Traffic management

Traffic Management controls the movement of rolling stocks in short term practice. The content of traffic management includes:

- ✓ Priority/ Objectives: This is the importance level of trains and target of service level.
- ✓ Conflict detection: The system should be able to detect conflicts in time.
- ✓ Conflict resolution: When a conflict occurs, effective measures should be taken to resolve the conflict.
- ✓ Delay management: If there is lateness, there should be plans to reduce the delay or to recover from a major disruption.

Dependability: Operational management

- ✓ Resource allocation: Rolling stock, crew and other resource planning.
- ✓ Incident management: This deals with faults and break-downs in the operation.

Dependability: Human factors

There are a number of human factors in the system. They introduce uncertainties into the practice.

- ✓ Planners: These are the people creating long term and ad-hoc timetables.
- ✓ Dispatchers: These people monitor the system running and make decisions when incidents and delay occur.
- ✓ Drivers: These are the people driving the trains. Their driving style and behavior has an influence on the trains' actual journey time.

Dependability: System maintenance

The equipment and facilities are essential foundations of the railway system. The condition of them should be observed and maintained regularly. The practices are:

- ✓ Condition Monitoring: It monitors and reports on the state and quality of the railway hardware.
- ✓ Maintenance Plan: A regular maintenance plan is also vital in keeping the “health” of the system.

Dependability: Environmental factors

Environmental factors such as wind, rain, snow and lightning are the source of many railway accidents. The measures taken to protect against environmental factors are listed below:

- ✓ Technical Protection Facilities: These are the facilities equipped to the vulnerable parts, including wind shields, rain shields, lighting conductors, etc.
- ✓ Environmental Incident Handling: Plans are made to deal with emergencies caused by environmental factors.

CHAPTER FOUR

4. Capacity Design Model for AA-LRT

4.1. Introduction

This section describes how to calculate and achieve better capacity for AALRT by considering crucial parameters. As we know line capacities depends on train performance, particularly braking and acceleration, length and how trains are controlled. How many train can be run will also depend on the infrastructure, the power available, the maximum line speed, the station spacing, the terminal design, gradients and the railway control (signaling) system. On top of that, the operating conditions dwell times at stations, terminal operations, allowances for speed restrictions and recovery margins will also affect throughput [27].

Here is, the braking distance is a crucial parameter to calculate the possible travel speed for a train on a certain railway line. After knowing the braking distance and the possible travel speed it is possible to determine the most suitable travel speed and utilized capacity using the method described in this section.

Furthermore, this section will describe the consequences of deviations from the most suitable travel speed.

4.2. Braking

Like acceleration, a train's deceleration curve forms a parabolic shape but one that steepens at the lower end of the range. Again, a straight line approach is necessary to obtain a simple view of the effect on capacity Figure 4.1.

In considering train braking, it should be remembered that it is the most difficult part of a train's operation. At any speed over 100km/h and often at lower speeds, the driver must commence braking for a stop at a point from where the final stopping location is not visible. If line side or cab indications of the braking commencement points are not provided, the driver has to learn them during training. The braking commencement points will usually be conservative, with allowances for variations in weather and visibility conditions, individual train performance and individual driver performance. Many railways in the UK, nowadays insist on a "defensive" driving approach to reduce the risk of signal overruns and some operators advise a platform entry speed of under 32 km/h (20 mi/h). This is not conducive to efficient capacity but is does reduce the overrun risk during poor adhesion conditions.

Another point to consider for train braking is the need to reduce the rate at the lower end of the speed range, in order to allow for accurate positioning and to create a comfortable station stop for passengers, many of whom could be on their feet preparing to alight.

Consideration of capacity values therefore, must include variable train braking skills, conditions of reduced adhesion and the adoption of a "defensive" driving policy [27].

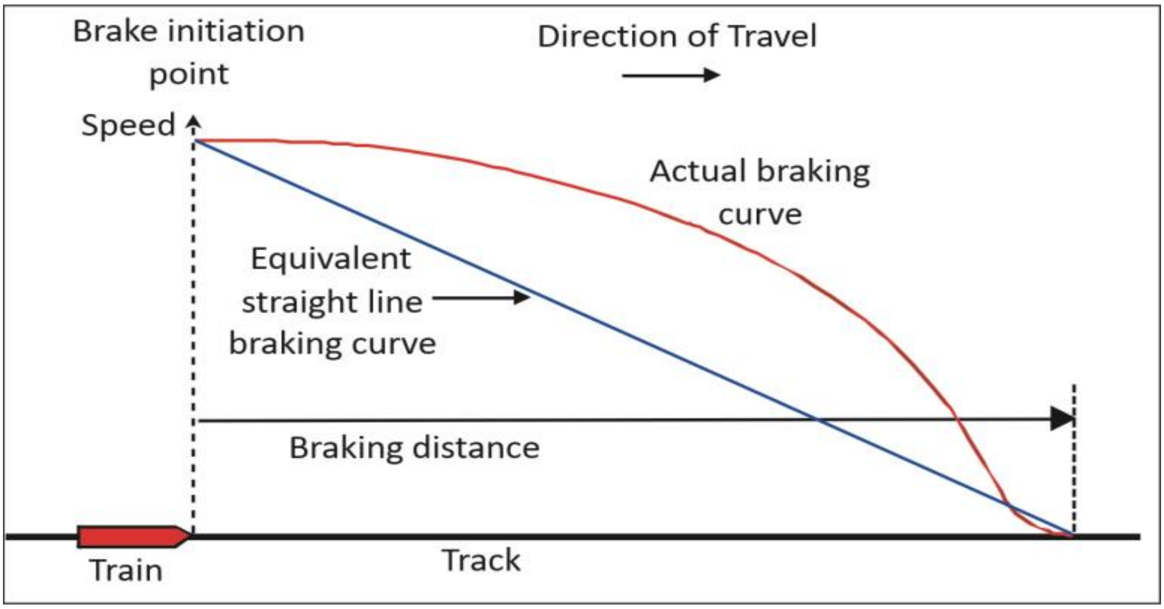


Figure 4.1: Straight Line Braking Curve [27]

Simple diagram demonstrating the principle of the Straight line braking curve. The approach to the stopping point is characterized by a reduction of brake effort for positioning and comfort purposes.

4.3. Calculation of Braking Distance

To be able to calculate the most suitable speed to minimize the block occupation time, it is necessary to know the possible braking distance at the current line section. In simple mechanics, it is possible to calculate the braking distance (S_b) as a function of the speed (v) when the breaking starts and the braking retardation (ar) of the train,

$$S_b = v^2/2.a_r \qquad \text{Equation 19}$$

The breaking retardation (a_r) in AALRT standard is $1m/s^{2.}$

The reaction time can be divided into the reaction time of the engine driver (t_r) and the reaction time of the brakes (t_s). The reaction time of the brakes can be further divided into the reaction time from the brakes are applied to the brakes start braking the train (t_s), and the time it takes from the train starts braking, until the brakes of the whole train are working with full braking force (t_b) [21]. Depending on the type of brakes, the reaction times of the brakes can have a large variation.

The reaction time of the engine driver (t_r), and the time from the brakes are applied to the brakes start braking the train (t_s) extends the braking distance proportionally with the speed. The time it takes from the brakes start working before all brakes work with full braking force (t_b) depends on the type of braking system.

This gives the braking distance as,

$$S_b = v^2/2.a_r + (t_r + t_s + ½.t_b)\ V \qquad \text{Equation 20}$$

The braking distance has been seen calculated in various ways however, chosen to use the expression in Equation 20 while it is a commonly used empiric formula, and no better formulations are known used internationally. And t_R is equal to summation of $(t_r + t_s + ½.t_b)$ called total reaction time of brakes for calculation of braking distance (i.e. operating margin time in AA-LRT case). And its value is 7second.

So we can rewrite Equation 20 like this,

$$S_b = v^2/2.a_r + t_{R.V} \qquad \text{Equation 21}$$

For this project, some stations are select from both directions that have no speed restriction and common stations with their own speeds to show the effect of braking distance and speed of the train over line capacity. There is a restricted speed when the track involves a curve, level crossing or due to any other special case.

EW direction: EW1-EW2, EW3- EW4, EW5- EW6, EW6- EW7 and the speed of each station is 20km/hr, 35km/hr, 55km/hr and 65km/hr. respectively.

NS direction: NS8- NS9, NS9- NS10, NS10- NS11, and NS25- NS26.With the speed of 30km/hr, 40km/hr, 45km/hr, and 60km/hr. respectively.

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

For EW line

According to Equation 21 the braking distance of the above station is calculated as follows:

S_b of EW1- EW2 = $(5.56\text{m/s})^2/2*1\text{m/s}^2$ + (7s*5.56m/s) = **54.37m**

S_b of EW3- EW4 = $(9.72\text{m/s})^2/2*1\text{m/s}^2$+ (7s*9.72m/s) = **115.28m**

S_b of EW5- EW6 = $(15.27\text{m/s})^2/2*1\text{m/s}^2$+ (7s*15.27m/s) = **223.48m**

S_b of EW6- EW7 = $(18.05\text{m/s})^2/2*1\text{m/s}^2$+ (7s*18.05m/s) = **289.25m**

For NS line

S_b of NS8- NS9 = $(8.33\text{m/s})^2/2*1\text{m/s}^2$+ (7s*8.33m/s) = **93.M**

S_b of NS9- NS10 = $(11.11\text{m/s})^2/2*1\text{m/s}^2$+ (7s*11.11m/s) = **139.49m**

S_b of NS10- NS11 = $(12.5\text{m/s})^2/2*1\text{m/s}^2$ + (7s*12.5m/s) = **165.63m**

S_b of NS25- NS26 = $(16.67\text{m/s})^2/2*1\text{m/s}^2$+ (7s*16.67m/s) = **255.63m**

For Common stations

S_bo f EW16- EW17 = $(15.27\text{m/s})^2/2*1\text{m/s}^2$+ (7s*15.27m/s) = **223.48m**

S_b of EW17- EW18 = $(12.5\text{m/s})^2/2*1\text{m/s}^2$ + (7s*12.5m/s) = **165.63m**

S_b of EW18- EW19 = $(12.5\text{m/s})^2/2*1\text{m/s}^2$ + (7s*12.5m/s) = **165.63m**

S_b of EW19- EW20 = $(12.5\text{m/s})^2/2*1\text{m/s}^2 + (7\text{s}*12.5\text{m/s})$ = **165.63m**

For Common stations

S_b of EW16- EW17 = $(15.27\text{m/s})^2/2*1\text{m/s}^2 + (7\text{s}*15.27\text{m/s})$ = **223.48m**

S_b of EW17- EW18 = $(12.5\text{m/s})^2/2*1\text{m/s}^2 + (7\text{s}*12.5\text{m/s})$ = **165.63m**

S_b of EW18- EW19 = $(12.5\text{m/s})^2/2*1\text{m/s}^2 + (7\text{s}*12.5\text{m/s})$ = **165.63m**

S_b of EW19- EW20 = $(12.5\text{m/s})^2/2*1\text{m/s}^2 + (7\text{s}*12.5\text{m/s})$ = **165.63m**

4.4. Speed of Train

According to the relation between capacity and speed of the train discussed in chapter two, it has a lot of effects in most of the other parameters to be considered.

In the AA-LRT the designed speed ranges is from 20-70km/h [3].

4.4.1. Calculating the possible Travel Speed

To be able to calculate possible travel speeds for trains, it is necessary to know the allowed braking distance of the train. The possible travel speed (v) according to Equation 20 become,

$$v \le a_r \cdot \left(-t_R \pm \sqrt{t_R^{\,2} + \frac{2 \cdot S_b}{a_r}} \right)$$

Equation 22

When calculating the possible travel speeds for trains using Equation 22, only the positive value of the term in the square root is used.

The allowed braking distance is determined by the signal system of the railway line. If there is a moving block system on the line, the maximum allowed braking distance is the actual braking distance of the train plus a safety distance. Moving block systems are still not common and not existing in AALRT. Instead discrete block systems or discrete ATC are used.

4.4.2. Discrete ATC

Based on discrete blocks where the ATC information is only updated at the balises placed close to the signals is so called discrete ATC system. The headway distance (Sh) for the discrete ATC system can be measured as the sum of block sections within the braking distance (Sb) of a train and an extra block section, a safety distance (Ss) after the red signal and the length of the train in front (L), as shown in Figure 4.2.

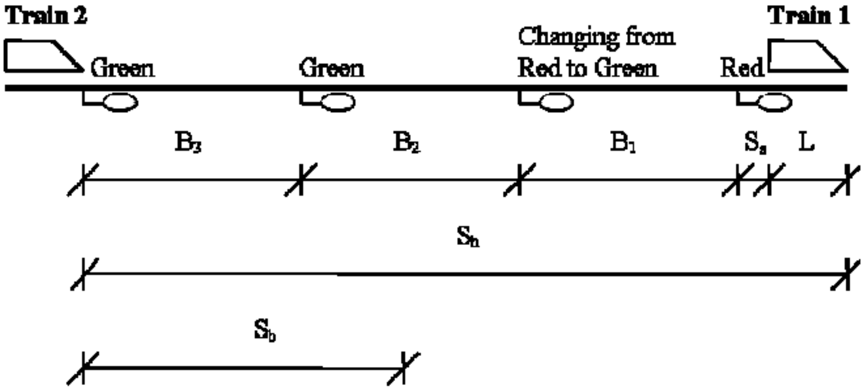


Figure 4.2: Discrete Blocks and Discrete ATC

The headway distance can then be expressed as,

$$S_h \geq \sum_{j=1}^{n} B_j + S_s + L .$$

Equation 23

The sum of Bj’s describes the number of block sections plus an extra block section. The braking distance can be expressed as,

$$S_b \leq \sum_{j=2}^{n} B_j .$$

Equation 24

Besides the expression in Equation 24, the braking distance depends on the ATC system. At present, which limits the travel speed, hence the speed depends on the allowed braking distance.

For railway lines with a discrete ATC system or without any ATC system, the travel speed has a greater impact on the minimum headway distance than when having a continuous ATC system. Even a slight increase in the travel speed can cause a much longer minimum headway time, hence the braking distance occupies an extra block section. When the braking distance is inside the span of a block section, the minimum headway time will decrease with increased travel speed. The optimal travel speed then occurs, when the minimum headway time for the discrete ATC system is close to the minimum headway time achieved with the continuous ATC system.

Here to calculate the most Suitable Travel Speed of the train using Equation 22 the extra block section must be considered,

Then by considering the extra block section with the length of 30m and by adding it with the above calculated braking distance, we can get new breaking distance as follows:

For EW line

S_b of EW1- EW2**; 54.37m +30m = 84.37m**

S_b of EW3- EW4**; 115.24m +30m = 145.24m**

S_b of EW5- EW6**; 223.48m +30m = 253.48m**

S_b of EW6- EW7**; 289.25m +30m = 319.25m**

For NS line

S_b of NS8- NS9**; 93 m +30m = 123 m**

S_b of NS9- NS10**; 139.49m+30m = 169.49m**

S_b of NS10- NS11**; 165.63m+30m = 195.63m**

S_b of NS25- NS26**; 255.63m+30m = 285.63m**

For Common stations

The same calculation performs like the above stations.

Here we can calculate the suitable traveling speed using this formula:

$$v \leq a_r \cdot \left(-t_R \pm \sqrt{t_R^{\ 2} + \frac{2 \cdot S_b}{a_r}} \right)$$

Table 4.1: calculated Speed value

Stations	calculated speed value (m/s)
EW1- EW2	7.76m/s
EW3- EW4	11.42m/s
EW5- EW6 and EW16- EW17	16.58m/s
EW6- EW7	19.22m/s
NS8- NS9	10.18m/s
NS9- NS10	12.7m/s
NS10-NS11, EW17-EW18, EW18- EW19 and EW19- EW20	13.99m/s
NS25- NS26	17.90m/s

Table 4.2: Speed Comparison

Stations	New designed speed value (m/s)	Existing speed value (m/s)	Average speed For designed (m/s)	Average speed For Existing(m/s)
EW1- EW2	7.76m/s	5.56m/s	13.74	12.15
EW3- EW4	11.42m/s	9.72m/s		
EW5- EW6	16.58m/s	15.27m/s		
EW6- EW7	19.22m/s	18.05m/s		

NS8- NS9	10.18m/s	8.33m/s	13.69	12.15
NS9- NS10	12.7m/s	11.11m/s		
NS10- NS11	13.99m/s	12.5m/s		
NS25- NS26	17.90m/s	16.67m/s		
EW16- EW17	16.58m/s	15.27m/s	14.64	13.19
EW17- EW18	13.99m/s	12.5m/s		
EW18- EW19	13.99m/s	12.5m/s		
EW19- EW20	13.99m/s	12.5m/s		

4.4.3. The most Suitable Travel Speed

The most suitable travel speed can be defined in different ways. For the passengers, the most suitable travel speed is achieved when the total travel time including waiting times etc. is as short as possible. For a congested railway line, the most suitable travel speed is when the headway time is as short as possible because it results in the highest possible capacity. For the railway company, the most suitable travel speed will be a mix of the most suitable travel speed for the passengers and the shortest headway time on the railway line/lines [20].

The headway time (t_h) depends on the headway distance and the block occupation time, which is equivalent to the travel speed of the train, is

$$t_h = \frac{S_h}{V} .$$

Equation 25

The difference in the minimum headway distance between the discrete and the continuous ATC system can be seen in figure.

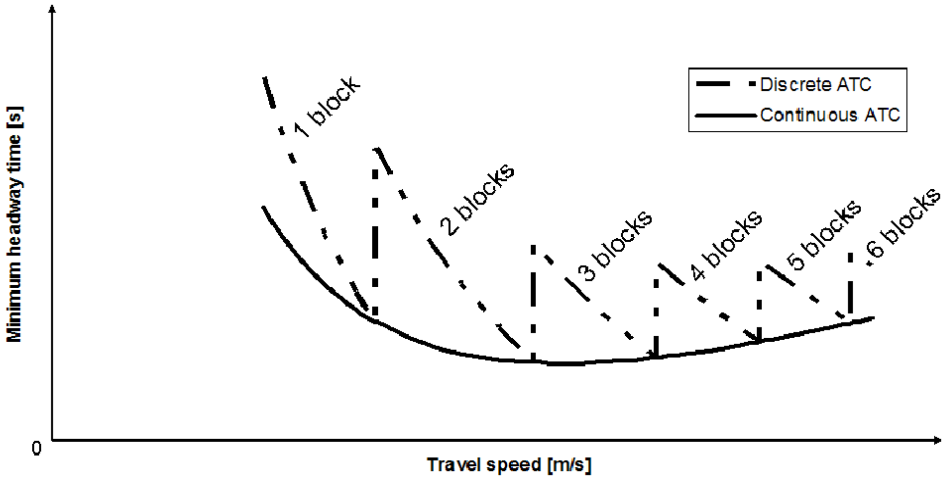


Figure 4.3: Minimum Headway Time as a Function of the Travel Speed and the Block Sections in the Minimum Headway Distance

Figure 4.3 is a conceptual figure showing that the minimum headway time in the discrete ATC system in the best case is equal to the headway time for the continuous ATC system. The optimal travel speed is when the minimum headway time is as short as possible.

When the travel speed is below the optimal travel speed the minimum headway time can be reduced by speeding up since the block occupation time is too long. At travel speeds above the optimal travel speed, the braking distance has become too long, so that the block sections are reserved for too long time. It is not possible to have travel speeds which require looking more block sections ahead than the ATC system allows.

4.4.4. Deviation from the Most Suitable Travel Speed.

The method for calculating the most suitable travel speed also provides the possibility of calculating the consequences of deviations from the most suitable travel speed. Knowing the planned headway time between two subsequent trains and the realized headway time at different travel speeds, also the buffer times are known for different travel speeds, hence the headway time can be divided into minimum headway time and buffer time,

$$t_h = t_{h,min} + t_{bt} .$$

Equation 26

Information about the minimum headway time and the planned headway time for a congested or high frequency railway line can be seen on Figure 4.4.

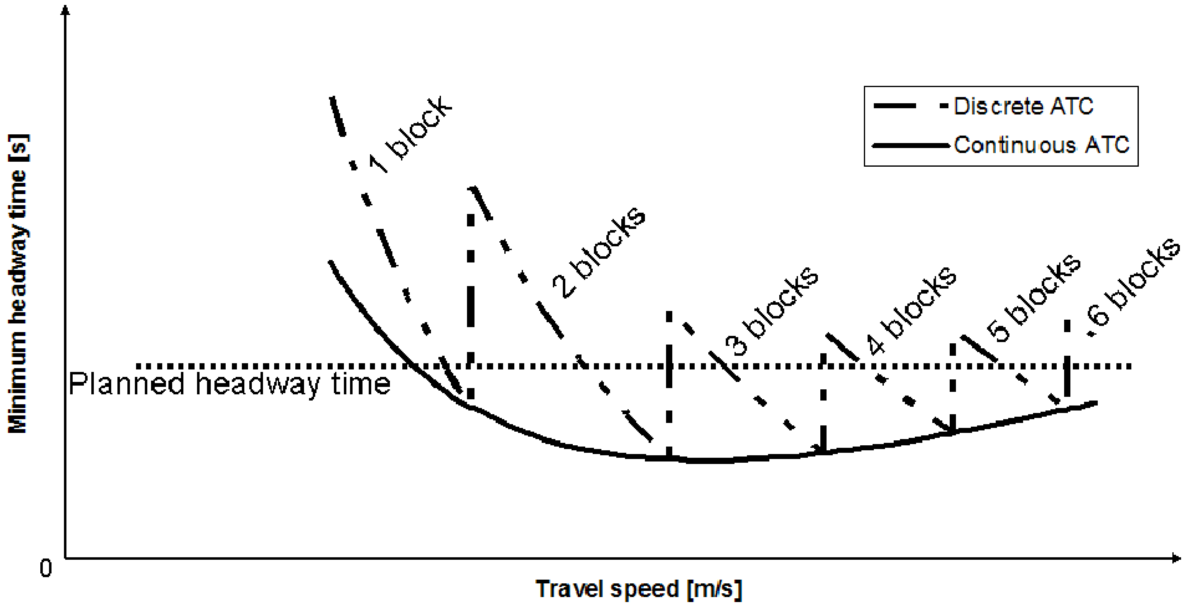


Figure 4.4: Minimum Headway Time as Function of the Speed and the Planned Headway Time.

The information in Figure 4.4 shows that it is possible to run the train at (almost) all speeds if the railway line is equipped with continuous ATC. If the railway line is only equipped with a discrete ATC system it is not possible to run the train at certain travel speeds, hence the minimum headway time is longer than the planned headway time.

4.5. Headway Calculation

In AA-LRT case, the headway between all consecutive pair of stations is calculated as follows [3].

Ht =Tt +Bt +Rt +Dt +Omt Equation 27

Where:-

Ht = Headway Time

Tt = Travel Time between two consecutive stations

Bt = Braking Time

Rt = Release Time

Dt = Dwell Time

Omt = Operating Margin Time

After calculating the headway time for each selected section we will take the maximum headway time from those individual headways.

NB: during headway calculation we use the new speed of the train that are calculated above

Tt $= {}^{Distance}/_{average\ speed}$

Bt $= {}^{braking\ distance}/_{speed}$

Rt $= {}^{length\ of\ the\ train}/_{speed}$

Dt = in AALRT case average dwell time is taken as 30 seconds but in this project we take average dwell time 20 seconds in order to show the effect of variation of dwell time on line capacity.

Omt = this time is the constant time in which the train spends for the reaction time to give commands (e.g. to apply the brake). The constant time is set by the infrastructure managers and most of the time it is a small number. For AA-LRT it has about duration of 7 seconds.

Table 4.3: value of Travel Time, Braking Time and Release Time

Stations	Travel Time (Tt) in sec	Braking Time (Bt) in sec	Release Time (Rt) in sec
EW1- EW2	162.37	10.87	7.6
EW3- EW4	75.57	12.72	5.17
EW5- EW6	43.72	15.29	3.56
EW6- EW7	50.47	16.61	3.07
NS8- NS9	52.55	12.08	5.80
NS9- NS10	78.35	13.35	4.65
NS10- NS11	61.54	13.98	4.22
NS25- NS26	52.79	15.96	3.30
EW16- EW17	26.84	15.29	3.56
EW17- EW18	40.03	13.98	4.22

EW18- EW19	49.18	13.98	4.22
EW19- EW20	52.54	13.98	4.22

Now we calculate the headway time of EW line for each selected stations

Ht for EW1- EW2 = **162.37 +10.89 + 7.6 +20 + 7 = 207.86sec or 3.46min**

Ht for EW3- EW4 **= 75.57 + 12.72 + 5.17 +20 + 7 = 120.46sec or 2min**

Ht for EW5- EW6 **= 43.72 + 15.29 + 3.56 +20 +7 = 89.57sec or 1.49min**

Ht for EW6- EW7 **= 50.47 + 16.61 + 3.07 +20 +7 = 97.15sec or 1.62min**

- ✓ Here the average minimum headway time for EW direction become: **2.14min**

For the NS line the headway time is calculated as follows**:**

Ht for NS8- NS9 = **52.55 +12.08 + 5.80 +20 +7 = 97.43sec or 1.62min**

Ht for NS9- NS10 = **78.35 +13.35 + 4.65 +20 +7 = 123.35sec or 2.06min**

Ht for NS10- NS11 = **61.54+13.98+ 4.22 +20 +7= 106.74sec or 1.78min**

Ht for NS25- NS26 = **52.79+15.96+ 3.30 +20 +7= 99.05sec or 1.65min**

- ✓ Also the average minimum headway time for NS direction become: **1.78min**

For the common lines the headway time becomes**:**

Ht for EW16- EW17 **= 26.84 + 15.29 + 3.56 +20 +7 = 72.69sec or 1.21min**

Ht for EW17- EW18 = **40.03 +13.98+ 4.22 +20 +7= 85.23sec or 1.42min**

Ht for EW18- EW19 = **49.18 +13.98+ 4.22 +20 +7= 94.38sec or 1.57min**

Ht for EW19- EW20 = **52.54 +13.98+ 4.22 +20 +7= 97.74sec or 1.63min**

Average minimum headway time the common lines become: **1.45min**

Therefore the overall minimum headway time become **2min**

Then, capacity of a line for each selected stations becomes 60/Ht. the results of capacity of a line for each selected station are listed in the following table.

Here we can see the effects of breaking distance, speed and dwell time over capacity of a line and the headway time for each stations by comparing the newly design and the current AALT headway time.

Table 4.4: Comparison between New Designed and Existing Headway and Line Capacity

Stations	New designed headway time (min)	Existing headway time (min)	New designed line capacity (train/hr)	Existing line capacity (train/hr)
EW1- EW2	3.44	4.73	17	13
EW3- EW4	2	2.4	30	25
EW5- EW6	1.49	1.72	40	35
EW6- EW7	1.62	1.83	37	33
NS8- NS9	1.62	2.05	37	29
NS9- NS10	2.06	2.41	29	25
NS10- NS11	1.78	2.06	34	29
NS25- NS26	1.66	1.88	36	32
EW16- EW17	1.21	1.41	49	42
EW17- EW18	1.42	1.66	42	36
EW18- EW19	1.57	1.83	38	32
EW19- EW20	1.63	1.9	36	31

Different from the designed headway time (6 minute), practically the current timetable has headway time of 15 minute and hence the line capacity is 4 trains per hour for a single line and direction.

Now we can find the practical headway for the new designed headway time (2min) according to the following formula:

$$L = \frac{T}{t_{fm} + t_r + t_{zu}}$$

Equation 28

Where

L= Capacity of the line

T = period

t_{fm}= occupation time of a train compared to next train

t_r = recovery margin

t_{zu} = additional time

The estimation of the capacity can be based only on the number of trains of each type, with a random approach for scheduling, using:

$$t_{fm}=\frac{\sum n_i * n_j * t_{fij}}{\sum n_i * n_j}$$

Equation 29

Where

$t_{fi\ j}$= is the minimum headway between a train of type j following a train of type i. in AALRT case we have one type of train.

t_r =The running time margin is a breathing space added to train headways to reduce knock-on delays and to achieve an acceptable quality of service.

The UIC proposed two expressions for this extra time margin:

$t_r = 0.67 \times t_{fm}$, when the desired utilization is 0.6;

$t_r = 0.33 \times t_{fm}$, when the desired utilization is 0.75. We take this one because our peak hour factor is 0.7.

The additional time t_{zu} is added to take in account the fact that the capacity decreases when the number of sections increases:

$t_{zu} = 0.25 \times a$, where a is the number of sections. For this project 12 sections are selected.

Therefore, according to Equation- the practical headway (Hp) become

$Hp=t_{fm}+ t_r + t_{zu}$, 2min + (0.33*2) + (0.25*12) = **5.66min**

So, based on the new designed headway time 2 minute, practically we can have a timetable having 5.66 minute headway time and line capacity become 10.6 ≈10 trains per hour for a single line and direction.

As we discussed in chapter 3 **Design Capacity** is:

$C_D = C_L * C_T$

For the existing design $C_D = 4 * 317 = 1268$ passenger/h

For the new design $C_D = 10 * 317 = 3170$passenger/h

Therefore the new design capacity is **40%** better than the existing.

The **achievable capacity (practical capacity)** can be expressed as:

$C_A = C_D * PHF$

Based on AA-LRT operational condition we take 0.7 for PHF.

For the existing design $C_A = 1268 * 0.7 = 887$passenger/h

For the new design $C_A = 3170 * 0.7 = 2219$passenger/h

Here **70%** of practical capacity can achieve from the new design.

Used capacity = CA*PHF

For the existing design, 887 * 0.7 = 621passenger/h

For the new design, 2219 * 0.7 = 1553passenger/h

49% of used capacity can achieve from the new design.

Available capacity = Used capacity - practical capacity

For the existing design, 621 – 887 = -266passenger/h

For the new design, 1553 – 2219 = -666passenger/h

NB: In the **a**vailable capacity the negative (-) sign is an indication of the additional traffic volume that could be handled in the route. If it allows new trains to be added, it is a useful capacity; otherwise, it is lost capacity.

CHAPTER FIVE

5. Results and Discussions

5.1 Anylogic Simulation Software

5.1.1 Introduction to Anylogic software

AnyLogic is a multi-method simulation modeling tool developed by The AnyLogic Company (former XJ Technologies). It supports agent-based, discrete event, and system dynamics simulation methodologies. AnyLogic is a cross-platform simulation software as far as it works on Windows, macOS and Linux.

It is used to simulate: markets and competition , healthcare, manufacturing, supply chains and logistics, retail, business processes, social and ecosystem dynamics, defense, project and asset management, pedestrian dynamics and road traffic , IT , aerospace .

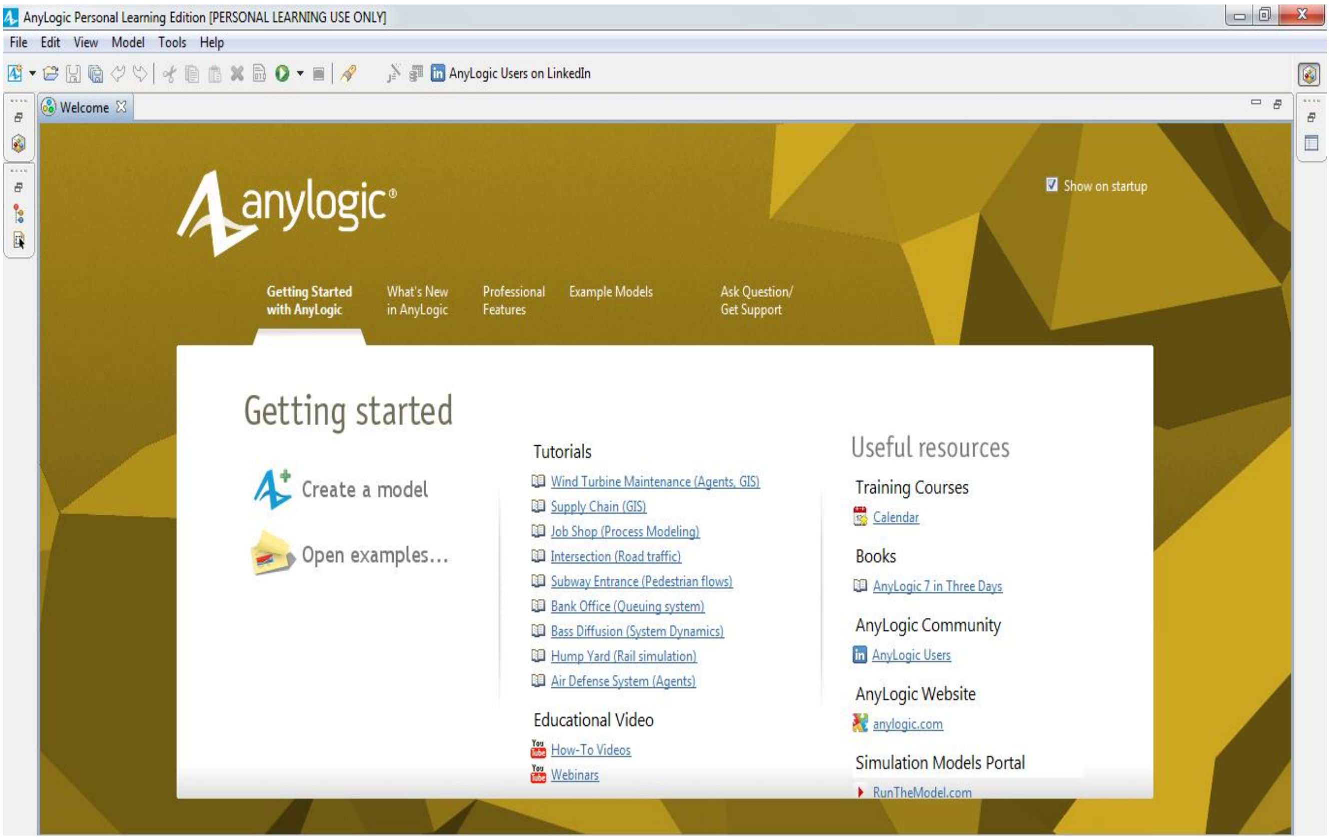
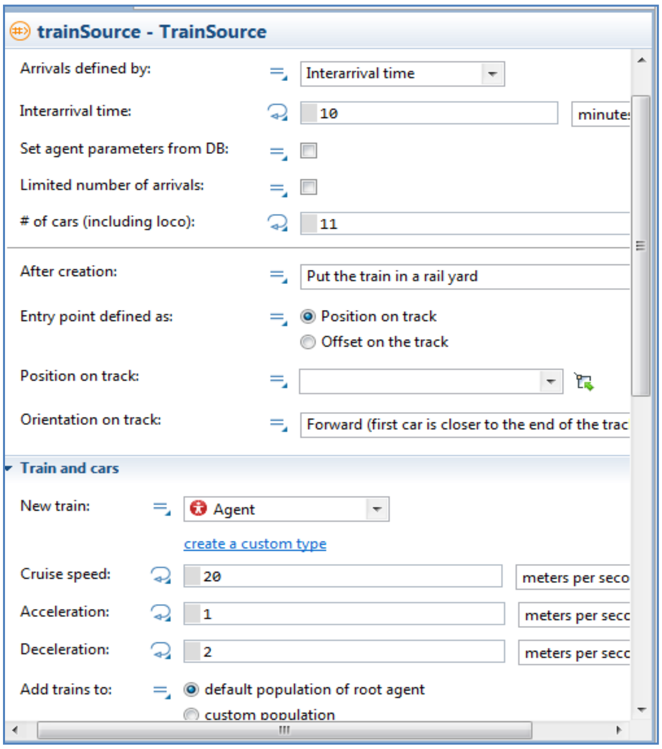


Figure 5.1: Welcome Page of Anylogic Software

5.2 Design methodology

As we discussed above anylogic simulation software have a wide range of application, railway is one of the area that highly use, this software to analyze the movement of the train in a given tack by configuring different parameters inside palette views, these are some palettes that are widely used for the simulation of this project:

- ✓ **AnyLogic Rail Library**
- ✓ **TrainSource**: is the object that starts any railway process flow.



trainSource - TrainSource

Arrivals defined by: Interarrival time

Interarrival time: 10 minute

Set agent parameters from DB: ☐

Limited number of arrivals: ☐

# of cars (including loco): 11

After creation: Put the train in a rail yard

Entry point defined as: ● Position on track ○ Offset on the track

Position on track:

Orientation on track: Forward (first car is closer to the end of the trac

Train and cars

New train: Agent

create a custom type

Cruise speed: 20 meters per seco

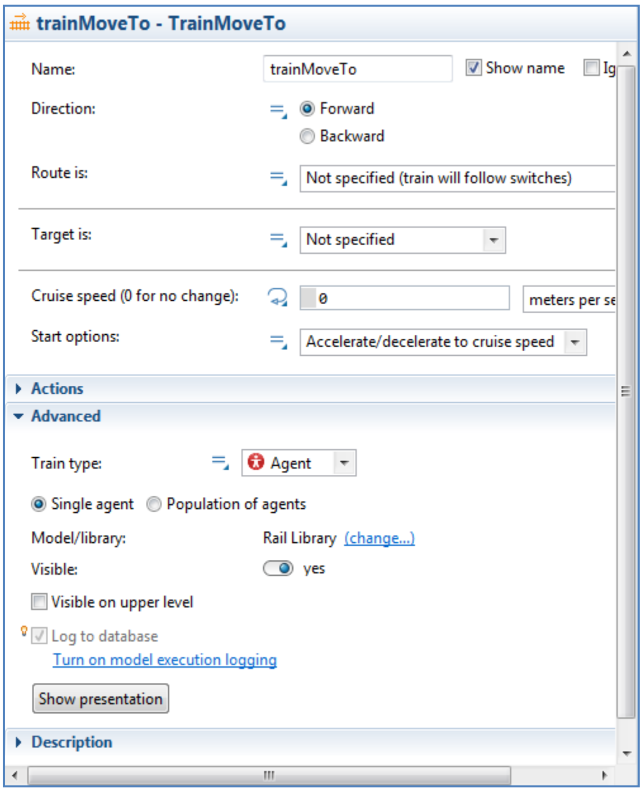
Acceleration: 1 meters per secc

Deceleration: 2 meters per secc

Add trains to: ● default population of root agent ○ custom population

Figure 5.2: TrainSource Window

- ✓ **TrainMoveTo:** The one and only block that controls the train movement.



trainMoveTo - TrainMoveTo

Name: trainMoveTo ☑ Show name ☐ Ig

Direction: ● Forward ○ Backward

Route is: Not specified (train will follow switches)

Target is: Not specified

Cruise speed (0 for no change): 0 meters per se

Start options: Accelerate/decelerate to cruise speed

▸ Actions

▾ Advanced

Train type: Agent

● Single agent ○ Population of agents

Model/library: Rail Library (change...)

Visible: yes

☐ Visible on upper level

☑ Log to database

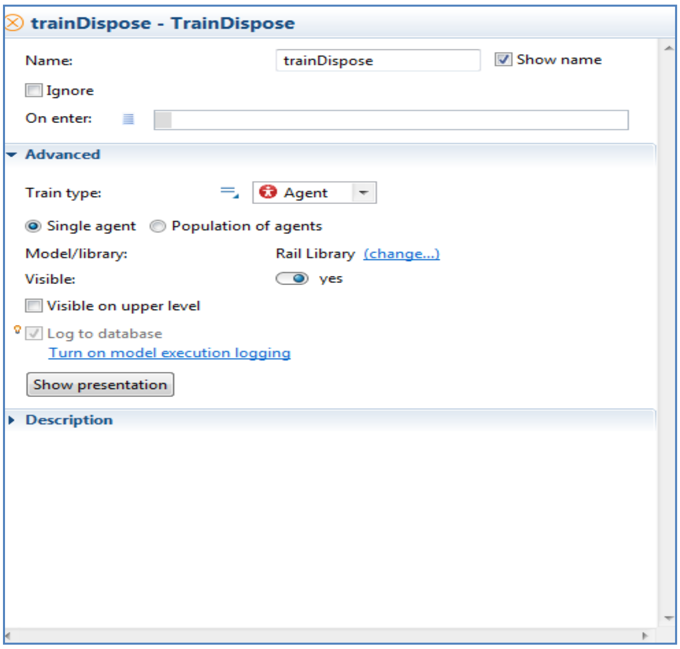
Turn on model execution logging

Show presentation

▸ Description

Figure 5.3: TrainMoveTo Window

- ✓ **TrainDispose:** Remove a train from the model.



trainDispose - TrainDispose

Name: trainDispose ☑ Show name

☐ Ignore

On enter:

▾ Advanced

Train type: Agent

● Single agent ○ Population of agents

Model/library: Rail Library (change...)

Visible: yes

☐ Visible on upper level

☑ Log to database

Turn on model execution logging

Show presentation

▸ Description

Figure 5.4: TrainDispose window

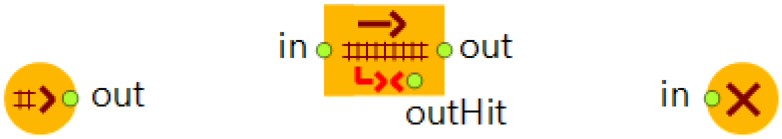


Figure 5.5: Objects of TrainSource, TrainMoveTo and TrainDispose Respectively

5.3 Simulation parameters for the designed model

Now the parameters that are calculated in chapter four are used as an input data to get desirable output from the simulation.

NB: The track assigned by naming TR1 up to TR7 represents the selected stations

For EW direction

TR1 represent (EW1-EW2), TR2 (EW3-EW4), TR3 (EW5-EW6), TR4 (EW6-EW7)

For NS direction

TR1 represent (NS8-NS9) TR2 (NS-NS10), TR3 (NS10-NS11), TR4 (NS25-NS26)

For common line

TR1 represent (EW16-EW17), TR2 (EW17-EW18), TR3 (EW18-EW19), TR4 (EW19-EW20)

Here are some consideration that are taken to simulate the designed model

- ✓ For the Cruise speed, average speed is taken
- ✓ For existing EW and NS line, Headway time (interval time) is 15min, based on AA-LRT standard
- ✓ For the new designed model, Headway time (interval time) for both directions and common line is average headway time.

FOR THE NEW NS, EW AND COMMON LINE

Table 5.1: Simulation parameter for the new NS, EW and common line

Parameters	values
Rail yard object:	railYard
Track (polyline)	TR1, TR2, TR3, TR4, TR5, TR6, TR7
Number of cars(including Loco)	2
Switches	SW1, SW2
Offset of 1st car, meters	59
Cruise speed, meters/sec	14.02
Headway time (interval time) (min)	5.66
Arrivals defined by	Arrival schedule
Schedule time	12.00AM-1.00AM
Acceleration (m/s^2)	1
deceleration (m/s^2)	1
movement	forward

depending on the above parameter that are calculated analytically (in chapter four), the simulation result shows 10 trains are moving on each track within one hour by 5.66min approximately 6min interval times and average speed of 14.02 m/s without any delay and collusion. And also the simulation results validate the analytical result for each parameters of speed, headway and line capacity of the stations realistically.

FOR EXISTING NS, EW AND COMMON LINE

Table 5.2: Simulation Parameter for Existing NS, EW and common line

Parameters	values
Rail yard object:	railYard
Track (polyline)	TR1, TR2, TR3, TR4, TR5, TR6, TR7

Number of cars(including Loco)	2
Switches	SW1, SW2
Offset of 1st car, meters	59
Cruise speed, meters/sec	12.49
Headway time (interval time) (min)	15
Arrivals defined by	Arrival schedule
Schedule time	12.00AM-1.00AM
Acceleration (m/s^2)	1
deceleration (m/s^2)	1
movement	forward

Here also, According to the above existing parameters, for both directions and common lines the output shows 4 trains are moving on each track within one hour by 15min interval times and 12.49 m/s average speed. Therefore from the above two different cases we can understand how headway time, breaking distance, dwell time and speed of the train affects the capacity of the line.

CHAPTER SIX

6. Conclusion and Recommendation

6.1 Conclusion

The thesis has shown that even slight changes in the travel speed can have an impact on the capacity at railway lines with intermittent ATP system like AALRT. The large impact on the capacity is due to large changes in the minimum headway time; hence, by carefully study the way of operation better capacity can be obtained by updating few parameters while for the remaining parameters keeping unchanged. For instance by maximize the operational speed and by considering extra block section (30m) for the selected stations we can operate better headway time and breaking distance respectively, According to the calculated values in chapter 4, the large headway time of AALRT (15min) can be minimized up to 5.66 min. Consequently, more trains can give service with headway of 5.66 min than the number of trains with 15 minutes of headway hence the line capacity can be increased by 40%.

This thesis also described how to calculate the braking distance, headway time, speed of the train and capacity of a line using the standard formula compatible with AALRT standard. Having knowledge about different parameter affecting the capacity of the given railway line, signaling systems and methods to evaluate railway capacity and also the possibility of using the developed method to calculate the most suitable travel speed leads to achieve better capacity for the selected stations.

In addition, journey times of the train, waiting time at the station and energy consumption, are highly influenced by increasing of line capacity.

Finally, anylogic simulation software is used to analyze and validate the capacity a railway line by using different value for different parameter.

6.2 Recommendation

The method that we used to optimize the travel speed to the block lengths has through simulations shown to be a powerful tool to gain as much capacity as possible on an existing railway line. And the presence of extra block section has a great impact for safe breaking of a train.

So, I recommend ERC consider the above parameters to achieve better capacity than the existing.

The simulations have furthermore shown that it is possible to run more trains with a better punctuality when the travel speed is adjusted to the block lengths.

Also this anylogic Simulation models can be animated in 2D/3D, allowing concepts and ideas to be more easily verified, communicated, and understood. Engineers gain trust in a model by seeing it in action and can clearly demonstrate findings to management.

With a further development and implementation of the method it will be possible to use the method in the planning of timetables.

In the future its better ERC uses anylogic software especially for the second and third phase of its project in order to maximize the capacity of the railway line including for effective usage of infrastructure and energy consumption.

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Appendix

The appendix part includes:

I. Simulation design with configuration and output of the simulation robotically for both existing and new designed model.
II. Details of the software
III. Platform station type and distance between stations of NS and EW line

Appendix I

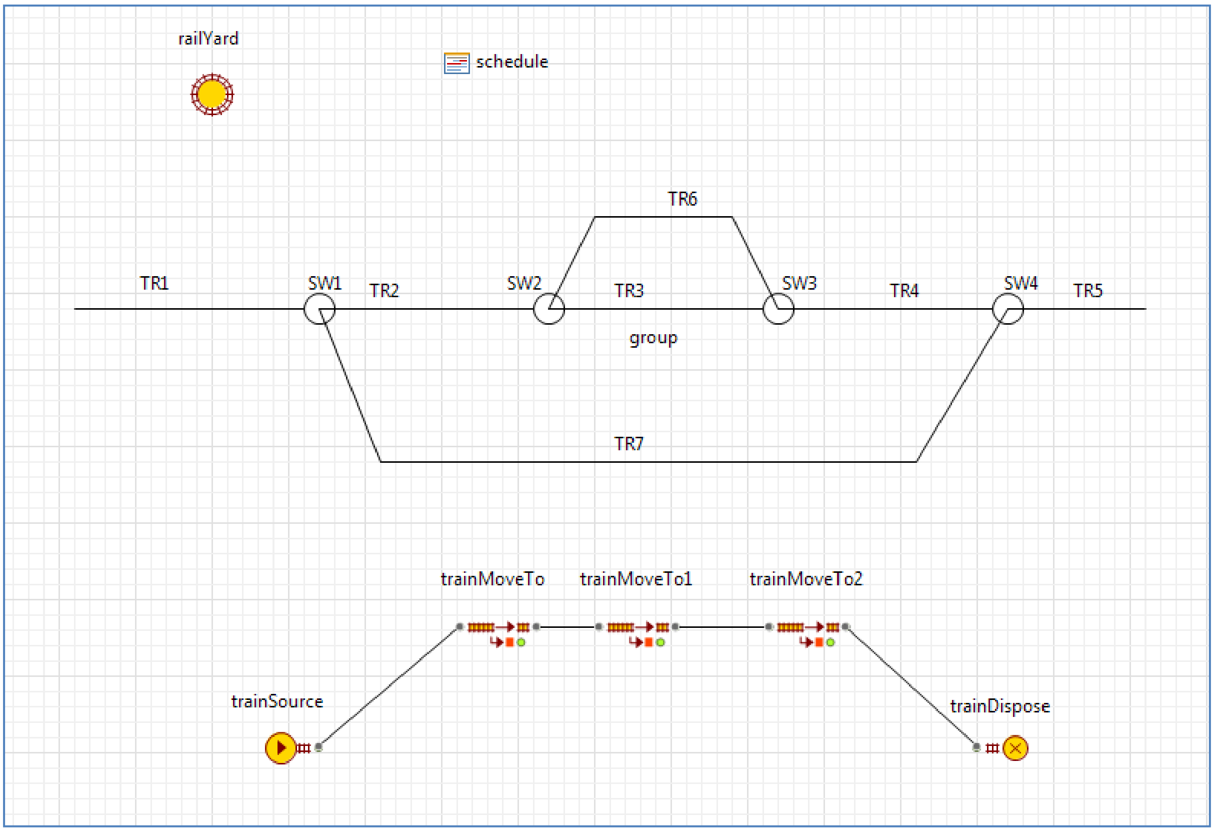
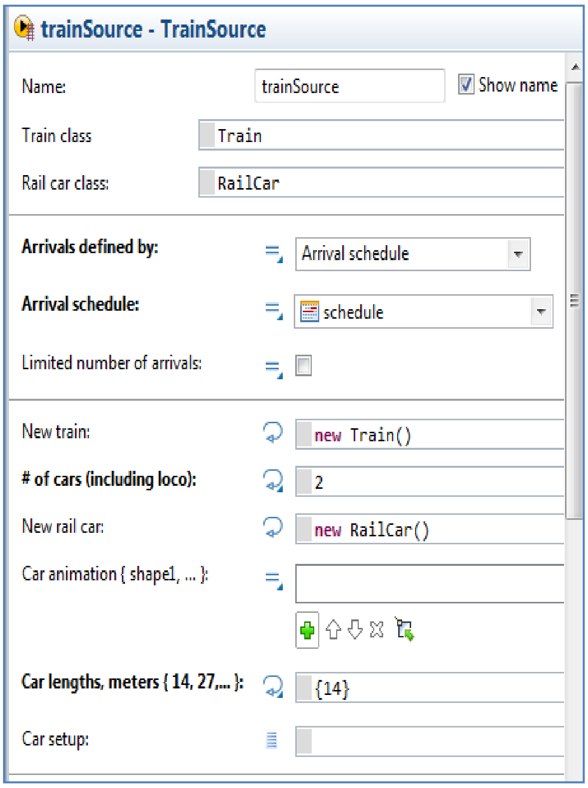


Figure I.1: Simulation Railyard and Object



trainSource - TrainSource

Name: trainSource ☑ Show name

Train class: Train

Rail car class: RailCar

Arrivals defined by: Arrival schedule

Arrival schedule: schedule

Limited number of arrivals: ☐

New train: new Train()

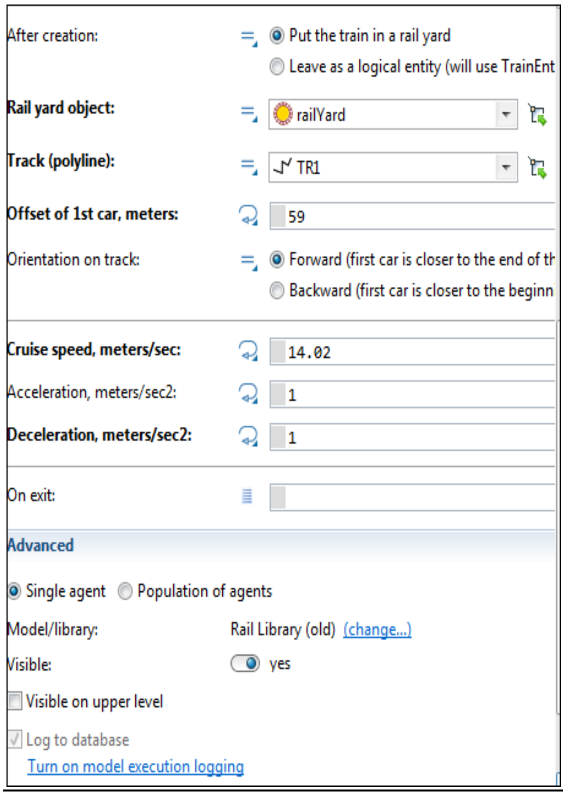
# of cars (including loco): 2

New rail car: new RailCar()

Car animation { shape1, ... }:

Car lengths, meters { 14, 27,... }: {14}

Car setup:



After creation: ● Put the train in a rail yard
○ Leave as a logical entity (will use TrainEnt

Rail yard object: railYard

Track (polyline): TR1

Offset of 1st car, meters: 59

Orientation on track: ● Forward (first car is closer to the end of th
○ Backward (first car is closer to the beginn

Cruise speed, meters/sec: 14.02

Acceleration, meters/sec2: 1

Deceleration, meters/sec2: 1

On exit:

Advanced

● Single agent ○ Population of agents

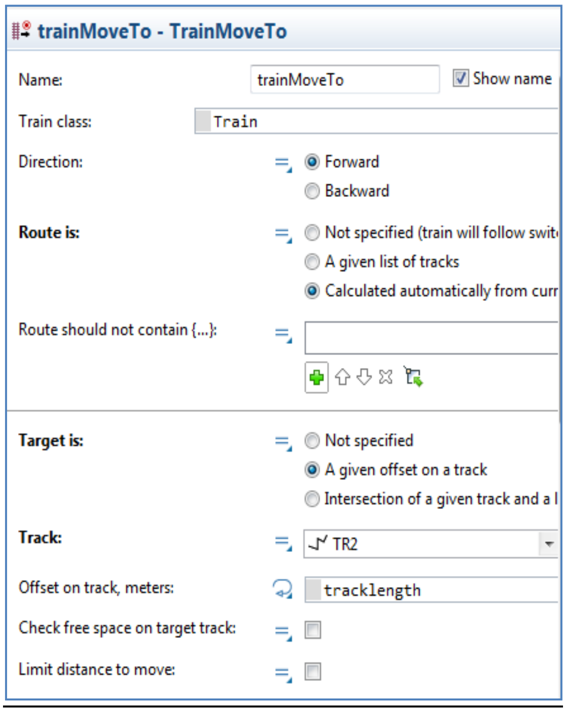
Model/library: Rail Library (old) (change...)

Visible: yes

☐ Visible on upper level

☑ Log to database

Turn on model execution logging



trainMoveTo - TrainMoveTo

Name: trainMoveTo ☑ Show name

Train class: Train

Direction: ● Forward
○ Backward

Route is: ○ Not specified (train will follow swit
○ A given list of tracks
● Calculated automatically from curr

Route should not contain {...}:

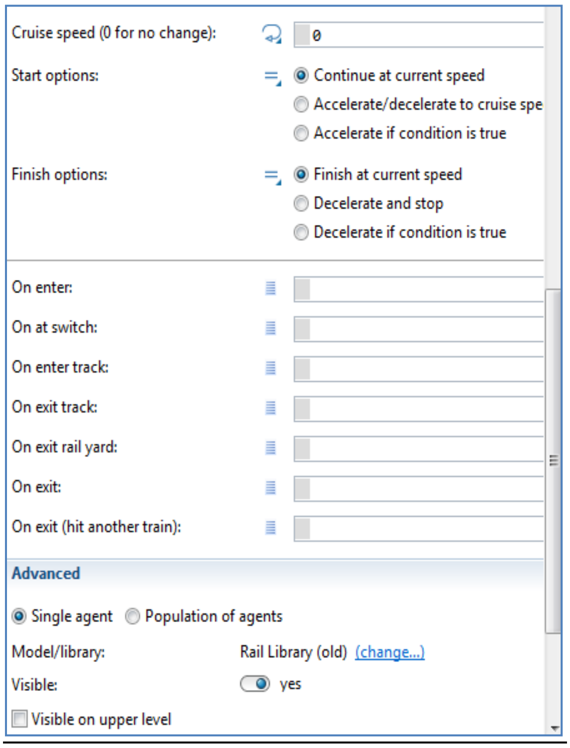
Target is: ○ Not specified
● A given offset on a track
○ Intersection of a given track and a l

Track: TR2

Offset on track, meters: tracklength

Check free space on target track: ☐

Limit distance to move: ☐



Cruise speed (0 for no change): 0

Start options: ● Continue at current speed
○ Accelerate/decelerate to cruise spe
○ Accelerate if condition is true

Finish options: ● Finish at current speed
○ Decelerate and stop
○ Decelerate if condition is true

On enter:

On at switch:

On enter track:

On exit track:

On exit rail yard:

On exit:

On exit (hit another train):

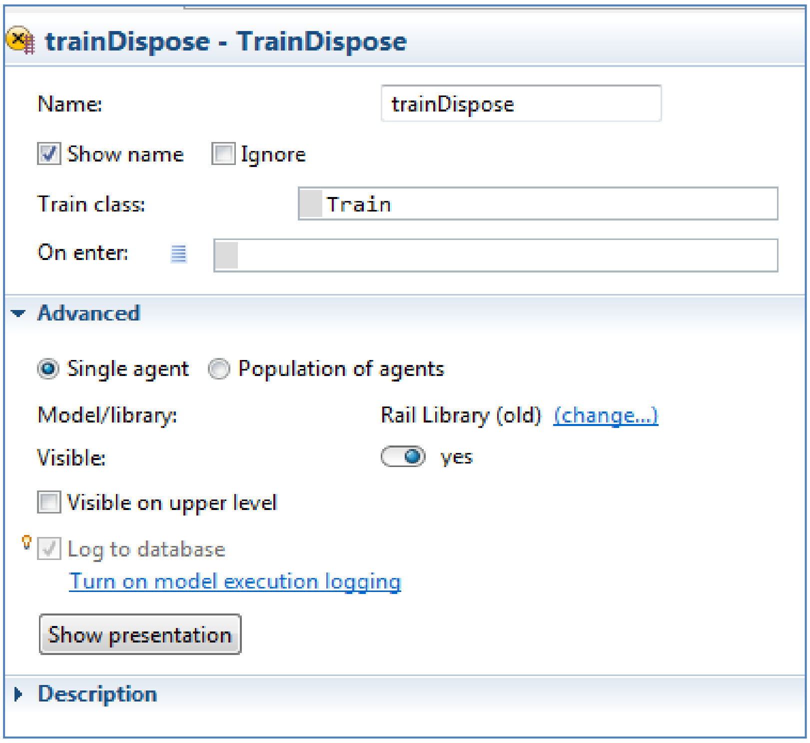
Advanced

● Single agent ○ Population of agents

Model/library: Rail Library (old) (change...)

Visible: yes

☐ Visible on upper level



trainDispose - TrainDispose

Name: trainDispose

☑ Show name ☐ Ignore

Train class: Train

On enter:

Advanced

● Single agent ○ Population of agents

Model/library: Rail Library (old) (change...)

Visible: yes

☐ Visible on upper level

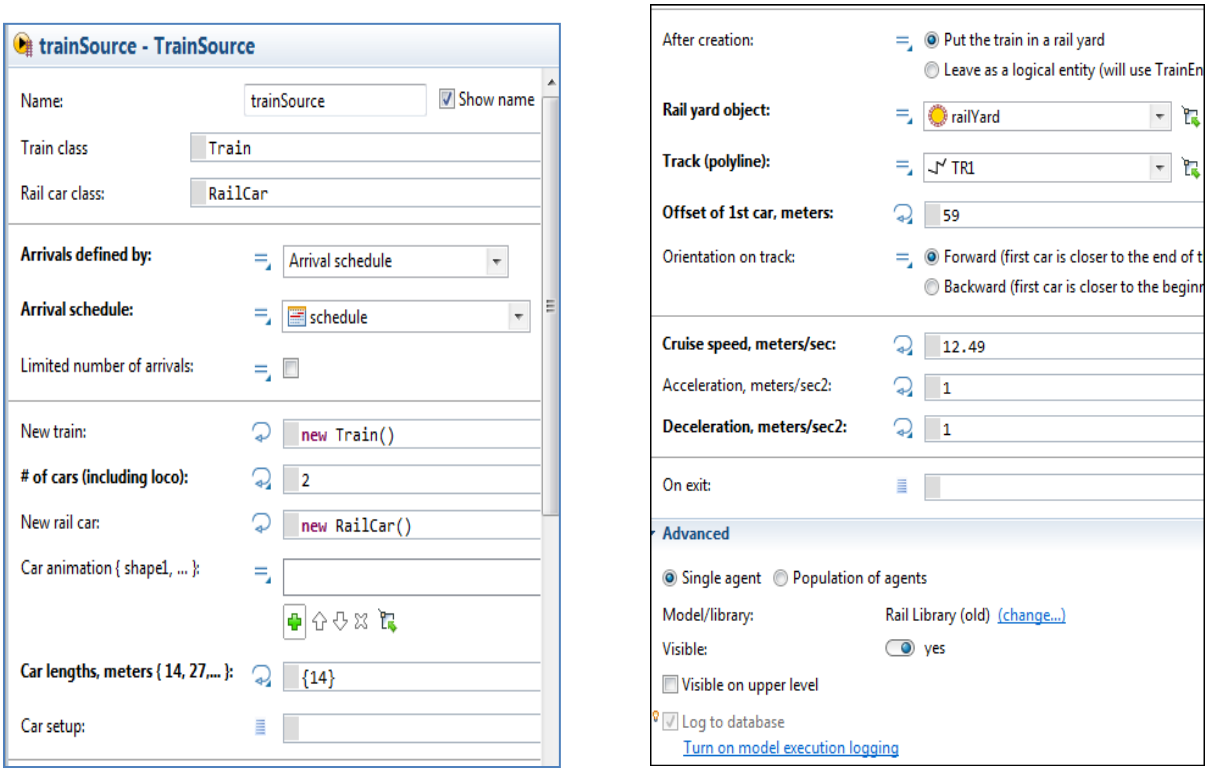
☑ Log to database

Figure I.2: TrainSource, TrainMoveTo and TrainDespose Configuration for the new designed line

NB: Configuration of trainMoveTo1 and trainMoveTo2 are the same with configuration of trainMoveTo except tack name. For trainMoveTo1we use TR3, for trainMoveTo2 is TR4.

And for the existing lines, the configuration of trainMoveTo, trainMoveTo1, trainMoveTo2 and TrainDispose are the same as configuration of the new designed line.

Figure I.3: Trainsource Configuration for Existing NS, EW and common Line



trainSource - TrainSource

Name: trainSource ☑ Show name

Train class: Train

Rail car class: RailCar

Arrivals defined by: Arrival schedule

Arrival schedule: schedule

Limited number of arrivals: ☐

New train: `new Train()`

# of cars (including loco): 2

New rail car: `new RailCar()`

Car animation { shape1, ... }:

Car lengths, meters { 14, 27,... }: {14}

Car setup:

After creation: ● Put the train in a rail yard ○ Leave as a logical entity (will use TrainEn

Rail yard object: railYard

Track (polyline): TR1

Offset of 1st car, meters: 59

Orientation on track: ● Forward (first car is closer to the end of t ○ Backward (first car is closer to the beginn

Cruise speed, meters/sec: 12.49

Acceleration, meters/sec2: 1

Deceleration, meters/sec2: 1

On exit:

Advanced

● Single agent ○ Population of agents

Model/library: Rail Library (old) (change...)

Visible: yes

☐ Visible on upper level

☑ Log to database

Turn on model execution logging

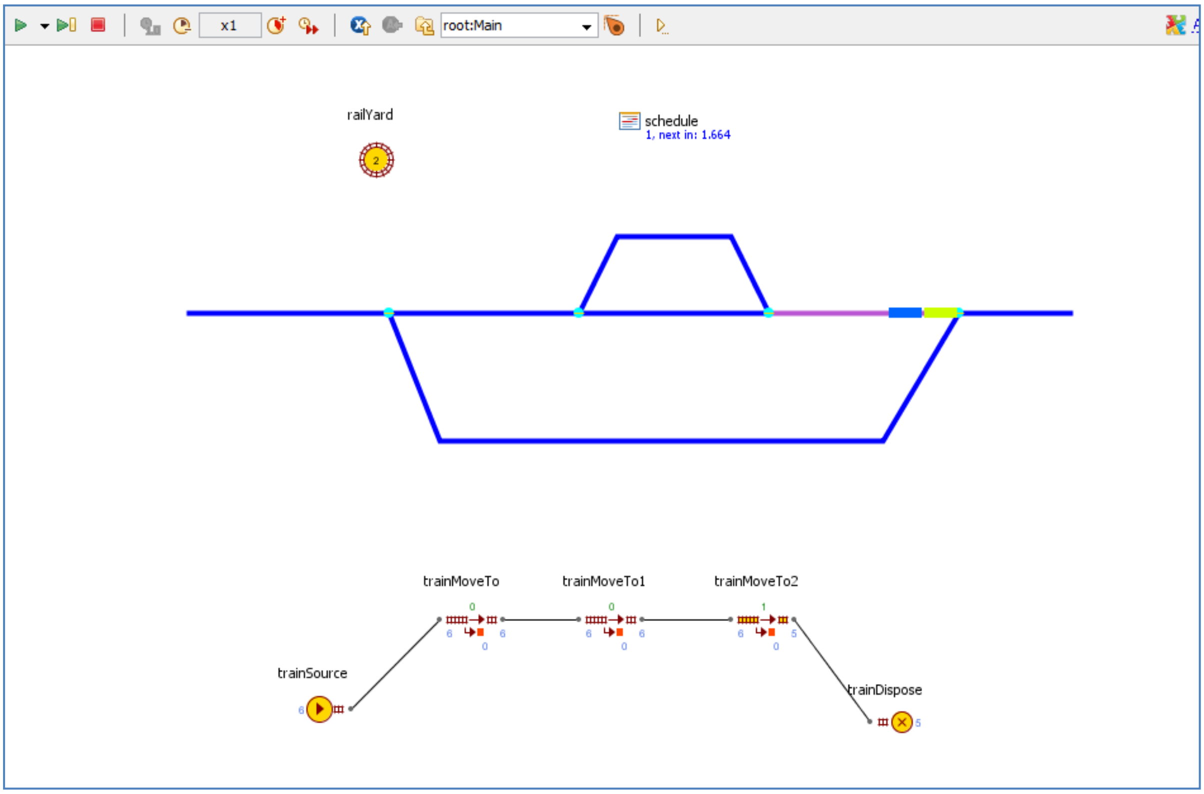


Figure I.4: 3D Image of Simulated Output for both Existing and New Designed Model

Appendix II

Feature of the software

AnyLogic have the following features to make it user friendly:

- ✓ **Graphical editor** - The place to edit graphical diagrams of agents and experiments.
- ✓ **Projects view** - Provides access to AnyLogic models currently opened in the workspace. The workspace tree provides easy navigation throughout the models.
- ✓ **Palette view** - Provides the list of model elements grouped by categories in a number of stencils (palettes).
- ✓ **Properties view** - Allows viewing and modifying the properties of currently selected model items.
- ✓ **Problems view** - Displays errors found during model development and compilation.

The palette views are the place where you can find AnyLogic graphical element and add it onto a graphical diagram of some agent class or experiment.

It consists of different stencils:

Agent: the palette contains elements for defining dynamics of the model, its structure and data.

The Rail Library supports modeling, simulating, and visualizing operations of a rail yard of any complexity and scale. It blocks and shapes related to the library.

The Pedestrian Library is dedicated to simulating pedestrian flows in a physical environment. It allows you to create models of pedestrian-intensive buildings like subway stations, security checks etc.

The Fluid Library allows the user to model storage and transfer of fluids, bulk goods, or large amounts of discrete items, which are not desirable to model as separate objects. The library includes blocks such as tank, pipeline, valve, and objects for routing, merging, and diverging the flow.

The Road Traffic Library allows users to simulate vehicle traffic on roads. The library supports detailed, physical level modeling of vehicle movement. Each vehicle represents an agent that can have its own behavioral patterns inside.

The Process Modeling Library is designed to support DE simulation in Manufacturing, Supply Chain, Logistics and Healthcare areas. Using the Process Modeling Library objects you can model real-world systems in terms of entities, processes and resources.

Presentation allows the user to draw track and switches of the given railway line using the poly line and oval shapes.

Road traffic library, fluid library, control, analysis, space markup, connectivity, action chart, 3d objects are also stencils of the palette view.

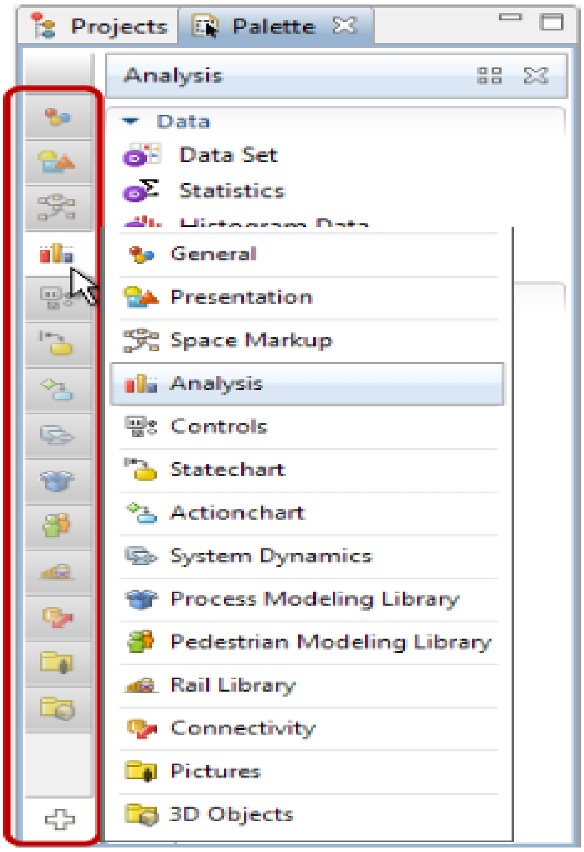


Figure II.1: Palette View

These are some palettes that are widely used for the simulation of this project:

AnyLogic Rail Library allows you to efficiently model, simulate and visualize operation of rail yards and rail transportation of any complexity and scale.

While the library supports detailed and accurate modeling dimensions of individual cars, exact topology of tracks and switches, accelerations and decelerations of trains are supported, the simulation it produces have very high performance, which is important when you use the optimizer to find the best management policies [30].

The two main inputs to a rail model are the rail yard topology and the operational logic of the rail yard.

The rail yard topology is specified by specific space markup shapes designed for rail models: railway tracks, switches and elements defining offsets on the track or Position on track. Those shapes can either be drawn manually using AnyLogic graphical editor or created programmatically by e.g. reading the layout from a database or a file.

Rail Library supports a very easy to use higher-level flowchart interface to define the rail yard operation. There are objects for defining the rail process logic in the library: TrainSource, TrainDispose, TrainMoveTo, TrainCouple, TrainDecouple and TrainExist. This section describes the following objects in detail because almost all part of the simulation is configured on the following stencils:

TrainSource

TrainSource is the object that starts any railway process flow. It generates trains, places them on one of the tracks in the rail yard and injects the train into the train process flowchart.

You can set the object not to place created trains on a track of the rail yard this behavior is controlled with the **after creation** parameter. It is commonly used when you need to pass the train agent to the regular process flowchart where it can go through delays, queues, decisions, etc.

Train "arrival times", i.e. the times when new trains appear in the model can be set up similarly to the **Source** object in the Process Modeling Library. Arrivals can define by inter arrival times or by arrival schedule. Just like in **Source**, you can limit the number of arrivals.

A new train should contain at least one rail car. You can tell **TrainSource** to use your own rail car type. The same applies for the train.

You can assign custom 2D or 3D animation shapes to the cars and perform any additional setup for each car, for example, set up a custom length, in the ***Car setup*** field. Please note that the size of rail car custom animation will not be automatically adjusted to the length of the rail car, so you need to choose the proper scale of the animation shape so that there are no spaces between cars in the train and cars are not drawn one above the other.

A new train is placed on a track, and you should make sure there is a free space on that track for all cars (at the creation time a train should be fully located on a single track). You need to specify the offset of the first car on the track and orientation of the train relative to the track.

The train cruise speed and acceleration/deceleration are also defined in the **TrainSource** object but can be modified later via the train API. The speed of the train is at this time set to its cruise speed, so that, if needed, the train can start immediately at the cruise speed.

TrainMoveTo

The only block that controls the train movement. A train can only move while inside a TrainMoveToblock.The train can move forward (first car in front) or backward. The train can have a target position where it should get, or just move without a target. In the latter case the train agent will exit TrainMoveTo either when it leaves the rail yard via an open-ended track, or if it hits another train. You cannot manually stop the train while it is moving. The train can move without a pre-defined route, i.e. just follow the current states of switches, or you can specify the route explicitly, or you can ask TrainMoveTo to calculate the route automatically from the current location to target. You can optionally ask the train to accelerate to a given speed at the beginning of movement and to decelerate to stop at the target.

If the train hits another train when moving, it stops and exits TrainMoveTo via outHitport. In all other cases namely, when it reaches the specified target or leaves the yard it exits via the out port.

A target is a point on a given track specified as either an offset from the track start in meters or graphically, with Position on Track element intersecting the track. You can additionally tell TrainMoveTo to check if there are other rail cars on the target track and to adjust the target point respectively so that the train stops exactly at the first car on its way (available only if the route is specified). This is useful when the train is going to be coupled with another train. Please note that the check is done only for the target track and only at the time when the train enters the TrainMoveTo block, so if the situation on the target track changes while it is moving it will not notice it.

Route can be specified explicitly as a sequence of tracks or calculated automatically. If you choose to specify the route explicitly you should enter the track where the head of the train is located as the first track, and then all other tracks the train should go by in the correct order. If the target is specified, the target track must be the last track in the sequence. To let **TrainMoveTo** calculate the route automatically you need to specify the target track. **TrainMoveTo** will only find straight routes, i.e. the ones without the need for changing of movement direction. When moving with a route, the train will control the switches on its way, namely, it will change a switch state as needed when it approaches the switch.

Keep in mind that while the Rail Library will detect the train collisions, it does not take care of managing the train traffic, like making one train to wait until another train passes a certain switch or track. The higher-level traffic management may differ from one rail yard to another and is something to be defined by the modeler.

To enable the train to make decisions about acceleration or route while it is moving, a continuous movement can be modeled by a sequence of multiple **TrainMoveTo** blocks, possibly with **SelectOutput** blocks in between. You can let the train keep its current speed between the two **TrainMoveTo** blocks by setting the **Finish option** of the first block to finish at current speed and not to Decelerate and stop. The second **TrainMoveTo** can then either Continue at current speed or Accelerate/decelerate to the cruise speed.

You can specify the cruise speed specific for the movement defined by a particular instance of **TrainMoveTo**; otherwise the current cruise speed of the train will be used. Depending on the length of the route and acceleration/deceleration values, the train may not be able to achieve the cruise speed.

While the train is moving under the control of **TrainMoveTo**, you still can modify its speed or let it accelerate or decelerate by using the train API. **TrainMoveTo** offers a number of callback extension points where you can define the actions to be executed while the train is moving.

TrainDispose

Remove a train from the model. There are two ways a train can be removed: it can move out of the rail yard via an open-ended track, in which case **TrainDispose** should follow the last **TrainMoveTo**block that was controlling the train, or it can "disappear" from any location in the rail yard, provided it is not moving. **TrainDispose** must be used to remove any trains. Using those objects you can perform any operations with trains and rail cars without coding. Moreover, the rail yard process flowcharts can include the objects from the Process Modeling Library, such as **Delay**, **SelectOutput**, **Hold**, **Seize**, **Release**, **Queue**, etc. This means that the operational logic of rail yards can now be fully defined graphically in drag-and-drop way.

Model animation

AnyLogic supports interactive 2D and 3D animation. AnyLogic allows users to import CAD drawings as DXF files, and then visualize models on top of them. This feature can be used for animating processes inside objects like factories, warehouses, hospitals, etc. This functionality is mostly used in Discrete Event (process-based) models in manufacturing, healthcare, civil engineering, and construction. AnyLogic software also supports 3D animation and includes a collection of ready-to-use 3D objects for animation related to different industries, including buildings, road, rail, maritime, transport, energy, warehouse, hospital, equipment, airport-related items, supermarket-related items, cranes, and other objects. Models can include custom UI for users to configure experiments and change input data.

Model integration with other IT-infrastructure

An AnyLogic model can be exported as a Java application, which can be run separately, or integrated with other software. As an option, an exported AnyLogic model can be built into other pieces of software and work as an additional module to ERP, MRP, and TMS systems.

Another typical use is integration of an AnyLogic model with TXT, MS Excel, or MS Access files and databases (MS SQL, My SQL, Oracle, etc.). Also, Anylogic models include their own databases based on HSQLDB.

Appendix III

Table III.1: Platform station type and distance between stations of EW line [3].

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

Table III.2: Platform station type and distance between stations of NS line

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