Addis Ababa Institute of Technology (AAiT)

School of Graduate Studies

Capacity Analysis on Single and Double-Truck Lines

By

Hewan Getachew

Thesis Submitted to the Addis Ababa Institute of Technology School of Mechanical and Industrial Engineering in Partial Fulfillment of the Requirement for the Degree of

Master of Science

In

Mechanical Engineering

(Under Railway Engineering)

Dr. Gulelat Getaw (advisor)

July 2014

Addis Ababa, Ethiopia

Addis Ababa Institute of Technology (AAiT)

School of Graduate Studies

Capacity Analysis on Single and Double-Truck Lines

Submitted by:

Hewan Getachew	_______________	________________
Student	Signature	Date

Approved by:

1. ________________	________________	_________________
Chairman, Dep.'s Graduate Committee	Signature	Date
2. Dr. Gulelat Getaw	________________	_________________
Thesis Advisor	Signature	Date
3. _________________	_______________	________________
Internal Examiner	Signature	Date
4. __________________	______________	__ _____________
External Examiner	Signature	Date

Dedication

To my beloved mom, for her immeasurable love, encouragement, and patience.

Table of content

Abstract

Railway networks are complex technical systems. Investments in railway infrastructure are expensive and already constructed railway infrastructure is not easily adjusted or changed. Dimensioning and constructing railway lines and networks therefore require extensive knowledge of future operation and demand. However, experience shows that the traffic often develops differently than expected. This means that railway infrastructure has to be designed for flexibility, i.e. for different operational conditions. To achieve such flexibility, a deep knowledge of infrastructure, timetable and perturbation properties, as well as inter-correlations between these, is essential.

This research has been investigate the impact of various operational changes on different level of heterogeneity to specify the potential use of operational changes to reduce delay in different scenarios especially for single- and double-track systems based on graphical calculation from time-space diagram and CN parametric model. The time-space diagram which is a simple but powerful graphical thinking tool has been used to mode the idealized existing operation. CN parametric model was used to investigate the impact of various operational changes on differing levels of heterogeneity on a hypothetical signalized, single-track rail line using delay as capacity metric unit. Changes considered included: adding sidings, increase in train headway, equalizing maximum speeds, increasing uniformity, removing dispatching priorities and the combination of the best ones.

Since the railway transportation can have significant effects on mobility, economic development, environmental quality, government finance and the quality of life, this study did analyze that the change of each parameters would have great improvement for the idealized existing operation, the combination of specified alternatives, specially adding sidings did provide a great capacity increment for the particular subdivisions. Those results from this study has great significance for railway operational capacity problems specifically for single -track lines and provides insight into which aspects of train type heterogeneity have the greatest impact on delay and leads to investigate the potential use of different operational changes that may reduce this delay in Ethiopian, Addis Ababa-Djibouti rail line.

Acknowledgement

When thinking whom to acknowledge at the beginning of my Thesis, I came across a long list of people. Oh...I felt lucky having all those supporting and giving people around me throughout my life.

I would like to express my gratitude to all teachers who ever tough me since my early age to this point of life, to my divisor, to all the supporting friends I have, to my sole, *Doc*, *Selamyea* to the little brother and be loved sister, to the greatest mom and before all, my ultimate gratitude goes to God.

List of Tables

List of Figures

Chapter One

Problem and Its Approach

1.1. Background of the Study

Railway is a very important mode of transportation for passengers and freight, due to its peculiar characteristics. Few other transportation modes combine dedicated infrastructure connecting point to point cities and places of interests, high operational speed, high reliability, cost effective operations, high energy efficiency and very high safety rate. The slower growth of railways and the unfavorable modal split towards railways have been acknowledged by governments and transport authorities which are looking to counterbalance this trend in the long term, to decongest highways and urban roads, foster sustainable development, and decrease pollution levels in cities and globally. Despite providing a good solution for commuting and transfer between cities, railway transport has a limited attractiveness to potential users, mainly due to perceived consequences of delays and unreliability towards the travel time ratio between train and other modes, like cars.

Overall, the increase in traffic and the higher speed differences have resulted in capacity shortages and low punctuality on several lines. The situation calls for more investments, but also for more accurate capacity analyses. Along with increasing environmental awareness and a political desire to reduce emissions, the railway has a good opportunity to increase its market share and contribute to a sustainable society. Such an increase is strongly dependent on competitiveness and so rail services need to be fast, frequent, comfortable, reliable and not too expensive.

These competitive factors, in turn, are dependent on technical properties in the railway system:

- Infrastructure design and operational reliability.
- Vehicle design and operational reliability.
- Timetable.

Regarding speed, frequency and reliability of services, single-track lines exhibit special properties, most of them tightly connected to crossings. On single-track lines, with only ordinary crossing stations, each crossing implies longer running times. The crossings also imply reduced reliability since delays propagate between crossing trains. The limited crossing possibilities also constrain capacity and thereby also the frequency of services on single-track lines. Double-track lines being operated with mixed traffic, i.e. both fast and slow trains, have properties similar to single-tracks. In this case the crossings are replaced by over takings, where the faster trains pass the slower ones. These over takings imply longer running times (scheduled delays) for the slower trains and decreased reliability through delay propagation.

The objective of this work is to show railway capacity and provide insight into which aspects of train type heterogeneity have the greatest impact on delay and investigate the potential use of different operational changes that may reduce this delay. In this research herein, the CN parametric model and time-space diagram is shown to solve the railway operations problems specifically for a case study in Ethiopia.

1.2. Problem Statement

Transportation can have significant effects on mobility, economic development, environmental quality, government finance and the quality of life. Significant railroad transportation projects require a long lead time for their design and construction. Since Investments in railway infrastructure are expensive and already constructed railway infrastructure is not easily adjusted or changed, railway infrastructure has to be designed for flexibility, i.e. for different operational conditions. To achieve such flexibility, a deep knowledge of infrastructure, timetable and perturbation properties, as well as inter-correlations between these, is essential.

Delays in railway networks cause problems in the daily operation and result in reduced reliability of the railway operation. Therefore, attention to transit quality and efficiency in general and reliability in particular is increasingly significant. Since it depends on the average minimum headway time between consecutive trains, the signaling system, train speeds, track age configuration etc, far-reaching operational capacity analysis and evaluations are recommended.

In the case of Ethiopia rail road transportation system is on the way of construction and not yet having experiences on operation which the best opportunity to have pre described capacity analysis for better feature operation for considering beginning, short term, and long term demands. For this objective, the analysis of railway capacity in single and double-track systems based on mathematical calculation, graphical and CN parametric model considering to be powerful graphical thinking tool for transportation and traffic engineers to analyze vehicle motions and solve transportation operations problems.

1.3. Research Questions

1. Determining appropriate key operational capacity concept for railway transportation system.

- What is the approach (or combination of techniques) to be adopted in capacity analysis?
- What are the important conditions that should be considered for capacity analysis?

2. Understanding different phenomenon and technical parameters for operational capacity.

- What technical parameters are essentially significant for capacity improvement?
- How we attain the feature capacity demand?

1.4. Research Objective

1.4.1 Main Objective

The overall objective of this study is to analysis of railway capacity in different scenarios especially for single- and double-track systems to show railway capacity and provide insight into which aspects of train type heterogeneity have the greatest impact on delay and investigate the potential use of different operational changes that may reduce this delay based on mathematical model.

1.4.2. Specific Objectives

1. Assessing an overview of the rail traffic and the most relevant conditions in relation to consequence calculations and project evaluation of railway projects

2. Examine the capacity concept in railway operation and describing it parametrically.

3. Formulating mathematical model for capacity assessment.

4. Analyzing and calculating operation capacities on single and double-truck lines.

5. Investigate the impact of various operational changes on single-truck lines.

6. Making significant decisions and preconditions for improving operation capacity

1.5. Organization

This thesis is consisting of six main chapters as follows:

This chapter provides a brief introduction to operation capacity and rail traffic. It also serves to represent the scope of research in this thesis *and the **second** one which is Literature Review* provides a comprehensive literature review of various railroad network systems and various types of models. The research conducted prior to selection of the proposed model type. The ***third*** chapter introduces the study area in railway operation and describes parametrically and provides a comprehensive review of specific railroad characteristics. And it also describes components, procedures, methods, materials and conditions of the study. Data Collection, Presentation and Analysis are provided hear. This chapter outlines the proposed model including inputs, outputs, and most importantly methodology. The parameters and variables used in the analysis as well as assumptions are described.

Then chapter ***forth*** will show the model development approaches for analytical and empirical results from time-space diagram analysis and results of various operational changes from train dispatch simulation in different scenarios. Then after chapter ***five*** also discusses briefly about the model results and presents the calculation and analysis in different scenarios. Results of model formulations and comparisons of capacities in different scenarios are shown. And summary, conclusions and recommendations based on the research in this thesis provides in ***Chapter Six***. The recommendations proposed future study in this field applies to possible extensions of the model.

Chapter Two

Literature Review

2.1. Introduction

Railway traffic offers a number of characteristics which are very different from both road traffic and other kinds of public transport (in this case bus traffic). An important difference between a road and a railway infrastructure project lies in the consequences of the projects.

Primarily, because the characteristics of road traffic differ considerably to those of railway traffic. Road traffic is (essentially) individual traffic, whereas railway traffic is exclusively public transportation. With respect to the travelers, the infrastructure therefore only appears indirectly in the lines/routes available to the traveler. Furthermore, the use of the lines/routes is paid directly to the transport company in the form of fares.

At first sight, planning of railway traffic has a number of features in common with bus traffic (lines, connections, regular frequency, regular interval timetables, etc.). However, this does not mean that the consequence calculation models used for bus traffic can be used directly. This is partly because busses are considered road traffic, partly because bus traffic has a relatively high frequency and that the traveler often has alternative routes 1. That is seldom the case of railway traffic, and part of the approximations that are used for calculations of bus traffic will be too rough for calculation of railway traffic. Railway systems have much more bindings in the form of safety systems, overtaking possibilities, etc. Railway traffic (and modeling hereof) has also considerably more discreet phenomena than road and bus traffic, i.e. it is difficult to assume linear correlations *[4, 6]*.

Effective capacity management is the key to a railroad company's success but this is a non-trivial task. One the one hand, capacity planners work on multiyear capacity planning projects aiming to provide enough network capacity to accommodate customers' future demand at a desired service level; on the other hand, they must try and maximize the use of assets (track age and related infrastructure) because overcapacity may be as harmful as insufficient capacity to company performance. The first step in capacity management is usually measuring and monitoring capacity and congestion; however, railway capacity is a loosely defined term that has numerous meanings. In general, it can be stated as a measure of the ability to move a specific amount of traffic over a defined rail line with a given set of resources under a specific service plan (Level of Service (LOS)). This capacity is highly dependent on a number of infrastructure and operational factors, such as:

- Length of subdivision
- Siding length, spacing, and uniformity
- Intermediate signal spacing
- Percentage of single, double, or multiple track
- Peak train counts
- Average and variability in operating speed
- Heterogeneity in train types (train length, power to weight ratios)
- Dispatching priorities
- Schedule

Numerous approaches and tools have been developed to determine rail line capacity; however, unlike the highway capacity analysis domain, there is no commonly accepted standard for railway capacity measurement in Ethiopia. Each model has its strengths and weaknesses and is generally designed for a specific type of analysis. Railway capacity tools can be categorized into three groups: (i) theoretical (ii) simulation, and (iii) parametric. In general, simulation is best suited to analysis of local-level problems, as it becomes computationally intensive when applied at the network level. Theoretical models can often be computed manually but are sometimes too simple to be valid for anything more than high-level comparisons. Parametric capacity models fill the gap between detailed simulation and simple formulae; they focus on key elements of line capacity to quickly highlight “bottlenecks” in the system. Parametric models are suitable for strategic capacity planning because they can account for the dynamic nature of line capacity, and provide system-wide capacity measurement of subdivisions in a rail network *[7, 10]*.

Railways are complex technical systems. They are often considered to be static, stiff and inflexible. As long as only constant, non-dynamic parts, such as the infrastructure, are considered, the system is quite easy to understand. Reality is different. The variance in different parameters makes the system difficult. Some examples *[12, 16]:*

- The *infrastructure* is adjusted and complemented all the time. Most of the adjustments are minor, but these changes nonetheless imply that important factors for operation vary over time.
- The *timetable* creates a well defined structure. However, the capacity is utilized differently every day since the actual timetable varies from one day to another due to delays, extra trains and cancelled trains. The planned timetable is also modified once or twice a year. The principles for this capacity allocation also change over time.
- The *available capacity*, which is an important condition for the timetable, varies over time. Failures, construction works, accidents and delays all make the available capacity vary over time.
- *Vehicle properties*, relative to those assumed during timetable construction, vary. Important examples are freight trains whose train mass often differs from the timetabled train mass, change of vehicle types without corresponding changes in the timetable, partial vehicle failures, weather conditions that affect adhesion, etc.
- The railway system is used and operated by humans. *Human behavior* varies naturally from one time to another. Train crews, dispatchers and passengers all contribute to this variance.

All these variances make the railway system complex and interesting to analyses. Modeling the railway system means modeling all these variables. To find general relations in this noise of superposed variances is not easy. Moreover, strong interactions between factors can be expected that make the task of analysis even more difficult.

2.2. Transportation in Ethiopia

In our country, the dominant mode of transport is road transport, having a share of 90% in transporting passenger and cargo transports across the country. And, that has been the focal point of the government for the last two decades and continues to be so. The activities undertaken over the last 16 years in the sector enabled the country to raise the road coverage to 70 per cent. The total length of road in the country has reached over 86,000-kms due to the enormous investment and commitment of the EPRDF led government *[2, 5]*.

In the past years Ethiopia invested more than 142 billion birr in the road sector. However, despite what the detractors routinely claim, the main source was not foreign donation. Of the entire total amount spent, 77 percent was by the government. One of the major works in that regard is the two roads linking the Addis Ababa-Adama Expressway with Addis Ababa City into two directions.

The 28.1-km roads Addis Ababa-Adama Expressway is being constructed at a cost of more than 4.2 billion birr allocated by the government of Ethiopia and loan obtained from Chinese EXIM bank. Another major example is the construction and renovation of 1,700-kms roads carried out in the Benshangul -Gumuz State with over 172 million birr in the last twelve months. Now, as result of the works, the once marginalized regions now have 3,000-kms roads.

Similarly, the capital city Addis Ababa, which has long been horrible in its roads network, has seen a major leap unprecedented in her recent history. Addis Ababa has constructed more than 1,219- kms road in the last five years with more than 10 billion birr budget. Now, Addis Ababa's road coverage has reached 15.64 per cent raising the network to 4,148-kms of which 2002- kms is asphalt, 727-kms cobblestone and the remaining 1,419- kms is gravel. In the processes, the city created jobs for more than 50,000 youths and women in cobblestone road construction. The same can be said with regard to other sectors of the transport industry.

2.3. Ethiopian Railway Corporation

The new Ethiopian railroad network will connect about 49 urban centers. The new railroad network is planned to have at least 8 main routes that extends to all compass points. The rail line will link no less than 49 urban centers, where railway stations are to be established. The proposed rail line crosses the borders of all regions, except Gambella. The network connects, among others, the Chartered Cities Addis Ababa & Dire Dawa, 7 of the 9 State capitals, and towns bordering Sudan, Kenya and Djibouti *[2, 5, and 6]*.

Fig.1 The new Ethiopian railroad network

2.4. Related Literatures

In order to minimize delays in delivering freight goods, each train has to travel on a route that minimizes travel time, meet/pass interferences and expected delays. To accomplish this, it is imperative to have a robust delay estimation technique that is capable of accurately predicting travel time delay as a function of the operating parameters. There exists a considerable amount of rail transport literature that aims to better comprehend the nature of knock-on delays.

Since the definition of railway capacity could be different, in this paper herein, railway capacity is defined as the maximum number of trains that can traverse the entire railway in a given period of time, subject to management constraints (such as junction capacity, track capacity, line capacity and interference between trains. This definition is correspondent with Abril *et al* (2008), Ambre et al. (2005), Mussone and Calvo et al. (2013), etc. Generally, there are two approaches to determine the railway capacity.

The first method is a rough estimation by using traditional Scott's formula. This formula's interpretation is that the maximum trains that can be scheduled depends on the total time required by the train to cross the critical block section plus block working time. A scheduling factor is a constant number ranged between 0.7 to 0.9, depending whether the section is busy or free. The second method of capacity estimation is to use the chart called Train Dispatch Simulator (TDS), which depicts the movement of trains on the distance-time plot, or the time-space diagram, the classical diagram for traffic and transportation engineers. Daganzo et al. (1997) describes the time-space diagram as a powerful graphical thinking tool for transportation and traffic engineers to analyze vehicle motions and solve transportation operations problems. The uses of time-space diagram in railway operations were found since mid-nineteenth century, the era of railroad development in Europe. This TDS can be used together with stochastic models to give more realistic railway capacity results.

Recent research developments in railway capacity analysis are found in numerous literatures. In the past, researchers have used either analytical methods or simulation-based methods to study delay and/or capacity assessment in railroads.

2.4.1. Analytical Based Researches

One of the earliest analytical models on capacity and delay assessment was developed by Frank et al. (1966). He studied delay on a single track with unidirectional and bidirectional track. By restricting only one train on each link between sidings and using single train speeds and deterministic travel times, he estimated the number of trains that could travel on the network. Petersen et al. (1974) extended this work to accommodate for two different train speeds. He assumed independent and uniformly distributed departure times, equally spaced sidings and a constant delay for each encounter between two trains. Chen et al. (1990) extended Petersen's model to present a technique to calculate delay for different types of trains over a specified single track section as a function of the schedules of the trains and the dispatching policies. They assumed sidings to be equally distributed, that faster trains can overtake slower trains, meets and overtakes occur only between 2 trains at a time, and there exists a fixed probability P_{ij} of a train i getting delayed by a train j. This modeling technique was extended by Parker et al. (1990) to a partially double-track rail network which consisted of a single-track section with sidings and double-track sections. Similar to the previous work, trains depart according to their scheduled departure times. The train to be delayed during a meet (or overtake) is determined by a trade-off between the lateness of the train with respect to its schedule and the overall priority of the train. Carey et al. (1994) studied the effects of knock-on delays between two trains on a single-track. They used non-linear regression to develop stochastic approximations of the relation between scheduled headways and knock-on delays, and tested these approximations by conducting detailed stochastic simulation of the interactions between trains as they traverse sections of the network. Ä Ozekici et al. (1994) used Markov chain techniques to study the effects of various dispatching patterns and arrival patterns of passengers on knock-on delays and passenger waiting times. Given a travel time probability density function for a train on a track link, a departure time transition matrix was constructed for the calculation of the expected departure delay. Higgins et al. (1998) presented an analytical model to quantify the positive delay for individual passenger trains, track links and schedule as a whole in an urban rail network. The network they considered has multiple unidirectional and bidirectional tracks, crossings and sidings. Yuan et al. (2006, 2008) proposed probability models that provide a realistic estimate of knock-on delays and the use of track capacity. The proposed model reflects speed fluctuation due to signals, dependencies of dwell times at stations and stochastic interdependencies due to train movements. D'Ariano

(2008) studied delay propagation by decomposing a long time horizon into tractable intervals to be solved in cascade, and using advanced Conflict Detection and Resolution with Fixed Routes (CDRFR) algorithms. These algorithms are used to detect and globally solve train conflicts on each time interval.

Queuing theory is another methodology that has been used for estimating delay in railroads. Greenberg et al. (1988) presented queuing models for predicting dispatching delays on a low speed, single track rail network supplemented with sidings and/or alternate routes. Train departures are modeled as a Poisson process, and the slow transit speed and deterministic travel times enable them to travel with close headways. This work assumes sidings to have infinite capacity. Huisman et al. (2001) investigated delays to a fast train caught behind slower ones by capturing both scheduled and unscheduled movements. This is modeled as an infinite server G/G/*1* re-sequencing queue, where the running time distributions for each train service are obtained by solving a system of linear differential equations. Wendler et al. (2007) presented an approach for predicting waiting times using an M/SM/1/*1* queuing system with a semi-Markovian kernel. The arrival process is determined by the requested train paths. The description of the service process is based on an application of the theory of blocking times and minimum headway times.

A bottleneck approach is one way to determine the absolute capacity of a network, by identifying the maximum number of trains that can travel through the track segments constituting a bottleneck in a given time period. De Kort et al. (2003) considered the problem of determining the capacity of a planned railway infrastructure layout under uncertainties for an unknown demand of service. The capacity assessment problem for this generic model is translated into an optimization problem. Burdett and Kozan et al. (2006) developed capacity analysis techniques and methodologies for estimating the absolute (theoretical) track carrying ability of facilities over a wide range of defined operational conditions. Specifically, they address the factors on which the capacity of a network depends on, namely, proportional mix of trains, direction of travel, length of trains, planned dwell times of trains, the presence of crossing loops and intermediate signals in corridors and networks. Gibson et al. (2002) also developed a regression model to define a correlation between capacity utilization and reactionary delay. Landex et al.

(2006) and Kaas (1998) discussed techniques to calculate capacity utilization for railway lines with single and multiple tracks, as per the UIC (International Union of Railways) 406 method. Research on single-track systems generally focuses on either infrastructure or timetable. This is a simplification since infrastructure and timetable are closely interconnected. Analyses concerning just one of them therefore imply considerable assumptions as regards the other.

Petersen et al. (1987) presents a method to find the best locations of crossing stations for a given timetable and line alignment. The method focuses on frequent small delays that can be managed by longer crossing stations (i.e. partial double-tracks) and time supplements. Longer delays are handled by secondary crossing stations. The study concludes that single-tracks work quite well, as long as infrastructure and timetable are coherent and delays limited.

Higgins et al (1997) describe a decomposition procedure that for a given cyclic timetable (day or week) for high-speed trains finds the numbers and positions of crossing stations that minimize both the risk of delays and the delays caused by train conflicts. The timetable is specified only by information about earliest possible departure times. The output from the model is both an optimal infrastructure and an optimal timetable. This combination gives a useful technical solution to the single-track problem.

There are several examples of studies where the infrastructure design is fixed and the timetable is somehow constructed according to infrastructure constraints (and market demand). An early example of this is the mathematical treatment of two-way traffic on a single-track presented by Frank et al. (1966). Using simplified models for train movements he calculates the capacity of a single-track line both for one-way traffic and for certain (fleet) systems of two-way traffic. The results are most applicable on freight or military transport systems but may also serve as a starting point for further studies.

Petersen et al. (1974) presents a simple model that can be used to describe the scheduled delay as a function of the traffic intensity. The main timetable assumption, that makes the study general, is that trains' departure times are independent random variables that are uniformly distributed over the defined time period. Given this randomized timetable, the time costs (delays) for crossings and overtaking are calculated. One conflict at a time is identified and resolved and so the trains are treated pair-wise.

Higgins et al (1996) present a model for scheduling of single-track lines. Their model can be used as a decision support tool in dispatching situations as well as a planning tool to evaluate the impact of timetable changes. It is also possible to use the model to evaluate infrastructure changes. The model minimizes scheduled (end) delays and operational costs.

Brännlund et al (1998) present a similar optimization approach for scheduling of single track lines. They model a profit function as sum of the profits of the trains in the schedule and use Lagrangian relaxation to obtain optimality. So far only scheduled delays are taken into account, but a possible development could include also operational delays.

Medanic and Dorfman et al. (2002) also address the problem of scheduling trains on single-track lines. Their idea is to use a local, state-dependent, travel-advance strategy instead of non-linear programming. The advance of a train only depends on the position and speed of trains in its vicinity. This strategy results in suboptimal, but time-efficient schedules and has some similarities to the single-track model, SAMFOST, presented in this thesis.

Chen and Harker et al. (1990) present a sophisticated model for estimation of mean delays and delay variance for trains that operate on a single-track. In this model, the inter-station distances are assumed to be even and the actual departure time of each train is randomized around a specified timetable time. The conflict resolution is handled through calculation of probabilities of conflict between every pair of trains. The study shows that shorter inter-station distances lead to lower mean delays and delay variances. The number of trains also influences the delays significantly.

Higgins and Kozan et al. (1995) address the overall timetable reliability in terms of schedule adherence. They present a model that can be used to prioritize investments designed to improve timetable reliability. Using their model it is possible to compare effects of track, station and rolling stock projects. The study is interesting since it focuses on the entire railway system and not only on one single part. The literature shows alternative approaches to handle and model the timetable on single-tracks. In some cases a timetable structure is given while in others trains are assigned randomly. A third approach concerns scheduling as an optimization problem. The single-track model presented in papers I, II and III in this thesis endeavors to show the effect of different timetables, i.e. scheduled delays and knock-on delays, and infrastructure designs in a transparent way. This approach is useful since the timetable on most Swedish railways lines is changed and adjusted every now and then.

Queuing theory and other types of statistical methods, where delay distributions are combined, are used to model interactions between delayed trains analytically. This type of model was first introduced for railway capacity analysis by Schwanhäusser et al. (2009). He makes a general analysis of buffer times based on queuing theory and includes a number of factors such as initial delays, supplements, mix of priority classes, punctuality, headways and overtaking possibilities. The buffer times are either constant or exponentially distributed.

Wendler et al. (2008) provides a general introduction to capacity analysis based on queuing theory. He considers both scheduled delays and knock-on delays and emphasizes the usefulness of queuing theory for long and medium term studies, where the requested train paths are not known in detail.

Huisman et al (2005) use queuing theory to analyze the dependencies and interactions between the individual components in a railway system. Operation is here defined by frequencies of service and no specific timetable is defined. Stations, junctions and line sections are modeled according to their special properties. The model seems to be a good alternative to simulation and the result is, in some sense, mean values of all possible timetables that can be constructed from the frequencies given as input data. In the model, both occupation times and minimal headway times are assumed to follow negative exponential distributions.

Huisman and Boucherie et al. (2001) provide a model to forecast knock-on delays due to differences in speed of trains on double-track line sections. These speed differences may be caused by different train services, or by primary delays. Train arrivals are modeled as a stochastic process, requiring train frequencies of each service only. Running time distributions for each train service is then obtained solving a system of linear differential equations. The model seems to be useful for analysis of isolated track sections between overtaking stations and the approach is well suited for long term planning where no detailed timetable data is available.

Vromans et al (2006) introduce two heuristic measures that can be used to evaluate the homogeneity of a timetable. Through simulation experiments they show that traffic reliability increases considerably with homogeneity, due to reduced delay propagation. Carey (1999) takes up different measures of reliability. He discusses the advantages and disadvantages of measures based on probabilities (i.e. observed delays) and measures not using probabilities. Almost all measures for prediction of reliability involve headways (time space between two consecutive trains) since longer headways generally reduce knock-on delays. It is clear that there are several advantages to using simple measures that are not based on probabilities, although mathematical methods for more exact calculations are available.

Goverde et al. (2007) uses max-plus algebra to analyze the Dutch railway network. This type of heterogeneous traffic that is operated according to an integrated periodic timetable, with high degree of synchronization, is feasible for linear algebra methods. Several kinds of train interdependencies resulting from the timetable, logistics and infrastructure are taken into account. Goverde analyses stability as well as delay propagation through higher-order max-plus linear systems.

The timetable is also crucial for analysis of double-track lines. Some literature proposes randomized timetables through exponential, distributed buffer times, whereas other analyses propose the use of existing timetables. The contribution of this thesis is a combinatorial approach for analysis of periodic timetables, paper IV. The systematic evaluation of different timetables gives insights in the effect of infrastructure and timetable factors on capacity, scheduled delays etc. While the research on knock-on delays concerns small delays that occur with high frequency, the focus in rescheduling is on large delays and disturbances. In a rescheduling problem the aim is to restore the traffic to the timetable in such a way that knock-on delays are minimized. The infrastructure is then a given constant as is the planned timetable. The literature on rescheduling is extensive and only a few examples are mentioned here.

Törnquist et al. (2007) and Törnquist and Persson et al. (2007) present an optimization approach to the rescheduling problem. A mathematical formulation which allows an n-tracked network to be modeled is constructed. Alternative objective functions, such as total final delay and total cost associated with delays are used and four rescheduling strategies are tested. The study shows that it is possible to find rescheduling solutions that limit the knock-on delays and/or costs associated with these delays. The most complete rescheduling strategy is sometimes too time-consuming for practical use. However, a more limited optimization strategy is often good enough.

A special field in rescheduling research concerns connections between trains (most often passenger trains). One example is Schutter et al (2002) who examine the possibilities to recover from delays by breaking connections. In the presented model the connections are represented by different kinds of synchronization constraints. In case of delay the so-called soft constraints may be broken, but at a cost that represents compensation activities and dissatisfaction for passengers. The model is feasible for real-time dispatching since the system uses a moving horizon in which the model is continuously updated.

Hellström et al. (1998) examines a decision support tool for train dispatchers. He concludes that this type of tool is especially useful on single-track lines where on-time performance is sensitive to the choice of decision. Algorithms for rescheduling and dispatching are crucial in detailed models of railway operation, e.g. simulation models. This is also a major concern in paper V in this thesis, which deals with calibration of a simulation model.

2.4.2. Simulation Based Researches

A major challenge in analytical models is to capture the effect of primary delays, dispatching and interactions between trains, run time variations, etc. Several of these effects are typically disregarded, or handled in a simplified way, in the analytical models. In a simulation model it is, however, possible to capture these effects with high accuracy.

Simulation techniques can be used to study direct, knock-on and compound delays and ripple effects from conflicts at complex junctions, terminals, railroad crossings, network topology, and train and track parameters. The compound interaction effects of these factors cannot be effectively captured in an analytical delay estimation model. Petersen et al. (1982) present a structured model for rail line simulation. They divide the rail line into track segments representing the stretches of track between adjacent switches and develop algebraic relationships to represent the model logic. Dessouky et al. (1995) use a simulation modeling methodology to analyze the capacity of tracks and delay to trains in a complex rail network. Their methodology considers both single and double-track lines and is insensitive to the size of the rail network. Their model has a distinctive advantage of accounting for track speed- limits, headways, and actual train lengths, speed-limits acceleration and deceleration rates in order to determine the track configuration that minimizes congestion delay to trains. This work is extended by Lu et al. (2004). Hallowell et al. (1998) improve upon the work by Parker et al. (1990) by incorporating dynamic meet/pass priorities in order to approximate an optimal meet/pass planning process.

Extensive Monte Carlo simulations are conducted to examine the application of an analytical line model for adjusting real-world schedules to improve on-time performance and reduce delay. Krueger et al. (1999) uses simulation to develop a regression model to define the relationship between train delay and track volume. The parameters involved are network parameters, track parameters and operating parameters.

Siefer et al. (2008) describes the state-of-the-art as regards railway operation simulation, emphasizing the main advantages, i.e. to make and evaluate changes in infrastructure, timetable, rolling stock, delays and/or dispatching strategies, along with discussions of important areas of use, such as planning, timetable construction, robustness analysis, operation etc.

Ho et al (2002) discuss the difficulties and requirements of effective simulation models for railways. They include several subsystems such as the signaling, power and traction systems and emphasize the advantages of modeling these together in the same simulation tool.

Koutsopoulos and Wang et al. (2007) present a framework for the application of rail simulation, including calibration, validation, evaluation methodology and interpretation of results. Their calibration methodology uses track occupation and release data to estimate important model parameters and inputs. Weits et al. (1998) focuses on modeling of traffic control in railway simulation models. He describes the dispatching in detail and five functional levels for planning and operation of railway traffic. He states that most dispatching actions are performed as “short-term reconstruction of the traffic plan without violation of transport and logistics constraints”. Sometimes, however, actions have to be taken at a higher level, i.e. decisions violate actual transport and/or logistic constraints. These kinds of dispatching decision are difficult to replicate in simulation models.

Mattsson et al. (2007) proposes a combination of micro-simulation experiments and statistical analyses. By considering the results generated by a simulation model as the actual situation, one can carry out quasi-experiments that can be subjected to statistical analysis. In this way it is easy to control different influencing factors and determine the importance of each one individually. This type of response surface methodology and use of metamodels is an efficient way of evaluating simulation experiments. Myers and Montgomery et al. (2201) describe the method in detail. One advantage of simulation is that the operator can control many factors. Using simulation for multifactor analysis, however, calls for careful planning. Barton et al. (2004) and Sanchez (2007) provide ideas for how simulation experiments are performed efficiently. Several examples of designs are described and the importance of interaction effects between factors is underlined.

Kleijnen et al (2005) point out that simulations are well suited for experiments, but that the experimental designs have to be adjusted for multi-factor analysis. They also discuss the importance of orthogonality, which simplifies computations and makes it easier to determine whether to include a factor in the metamodel or not.

Rudolph et al. (2004) develops strategies for an optimized allocation and dimensioning of time supplements in railway timetables. This is an important field since time supplements directly affect operational reliability (delays) as well as travel times. Rudolph makes use of synchronous micro simulation to evaluate different strategies for allocation of supplements. She finds that supplements should be allocated before scheduled arrival time and concentrated at stations with a high demand for punctuality. In some cases this strategy implies shorter overall running times due to better utilization of allocated supplements.

Lindahl et al. (2002) performs simulation experiments to evaluate how capacity can be increased on a double-track railway line with mixed traffic. He tests different speed ratios, overtaking patterns and train lengths.

A majority of the prior work on delay estimation and capacity assessment for railway net- works does not explicitly consider the vital and complex interactions between track, operating and network parameters. In the case of the analytical models, heavy assumptions are made in order to maintain the complexity of the problem within solvable bounds, thereby rendering the problem to be far of from real-life rail operations. Furthermore, these models may be incapable of recognizing the dynamic nature of capacity and knock-on delays involving more than two trains. More often than not, delay or capacity estimation is unlikely to be the final step in railway operations planning. Instead, a dispatcher might use these estimated values in railway routing and scheduling, that is, to route a set of trains over tracks with the minimum expected delay so as to minimize the overall system delay. For such purposes, it would be beneficial to design simple delay estimation models that could be easily integrated with or incorporated into a routing, scheduling or dispatching model. Analytical models requiring algorithms to solve a system of equations might not be the best option for this purpose. Simulation models, on the other hand, would enable us to develop simple, yet accurate, algebraic relationships that better capture the stochastic nature of the interactions between the track, operating and network parameters, and their impact on travel time delays.

2.4.3. Combinatorial Based Researches

Combinatorial methods are well-suited for analysis of railway systems that are operated with a periodic timetable. Most of the literature on combinatorial methods focuses on synchronization and optimization within networks. The main goal is often to minimize resources (rolling stock, staff etc) and waiting times for passengers who need to change trains.

Liebchen and Möhring et al. (2002) and Liebchen et al. (2004) use PESP (Periodic Event Scheduling Problem) to show that optimization models can be used to find periodic timetables that need a minimum number of vehicles and give short waiting times for changing passengers. Nachtigall et al. (1996) provides an improved branch and bound approach to find a timetable such that the arising changing time is minimal for selected stations.

2.4.4. Conclusion

As we have seen from the related literature numerous approaches and tools have been developed to determine rail line capacity; however unlike other countries experience in our country there is no actual operation for analytical bases. So first, an idealized existing operation should be modeled by using time-space diagram which is analytical model.

Then after, based on the alternatives, simulation models are the most powerful capacity analysis method; however, since simulation software are not available in our company, using parametric modeling for further analysis was the only option in this study.

2.5. Introductions to Time-space diagram

2.5.1. Homogeneous System

I. Double-track scenario

The analysis of homogenous double-track scenario is considered to be the easiest case. Trains on both sides can travel independently as shown in Fig. 2. The intersecting points outside the stations A and B mean that opposing trains can travel without any conflict.

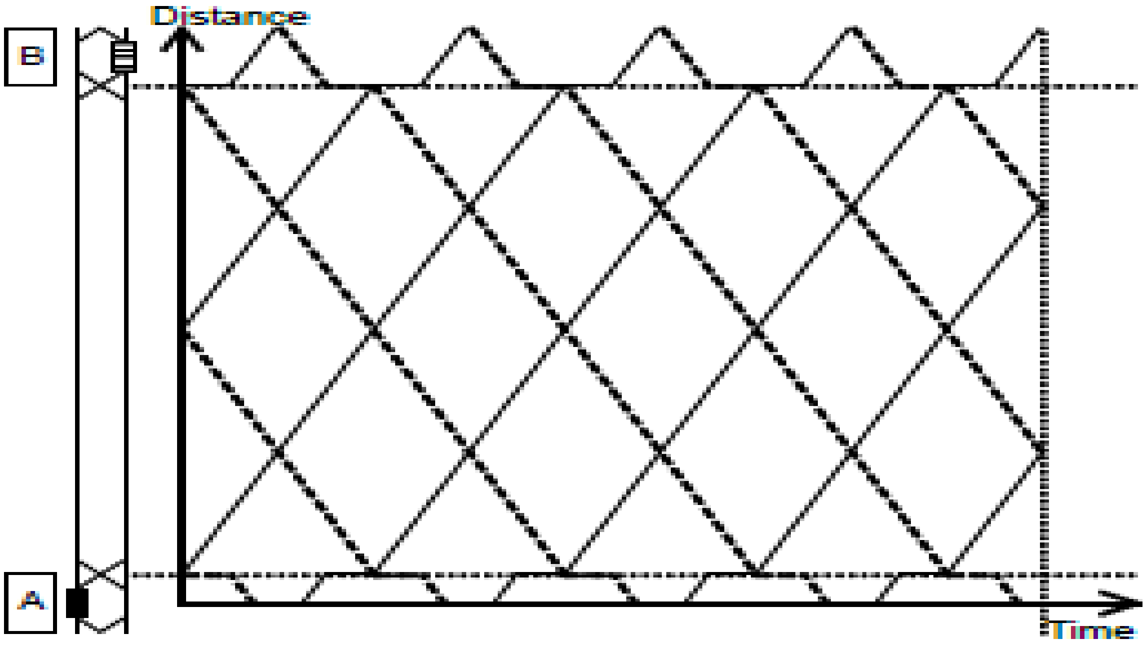
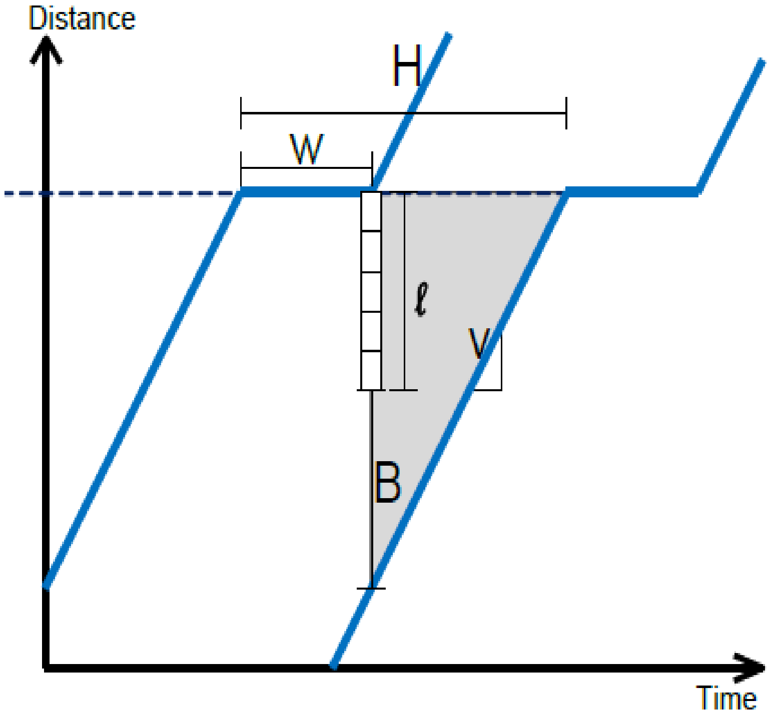


Figure 2 Time-space diagram for double-track homogeneous system *[11, 20]*



$$\text{Capacity} = \frac{1}{H} = \frac{1}{w + \frac{B + l}{V}}$$

Figure 3 Calculation of one-way railroad capacity by time-space diagram *[11]*

II. Single-track scenario

When both directions of train have to travel on a single track, they can traverse each other at a station (with separated track) or at side tracks only. The analysis in the case without a side track is shown in Fig. 4. In this scenario, only one train can be between two stations at a time. The other trains must wait until the track is available. If the trains on both directions use the track alternately in 1:1 ratio, the railway capacity is significantly reduced. Therefore, it might be preferable to group trains in each direction as a platoon and let each group go alternately instead of an individual one, i.e., let N1 trains in A to B direction go first and alternate with N2 trains in B to A direction go (N1:N2 ratio) as shown in Fig. 5 *[20]*.

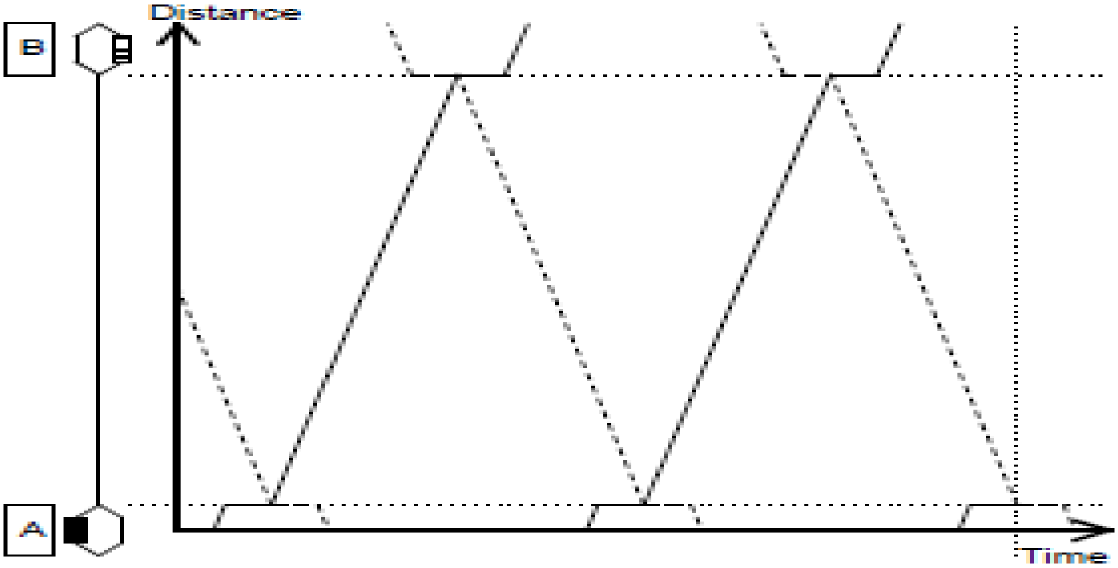


Figure 4 Time-space diagram for single-track system without a side track (1:1 ratio) *[11, 20]*

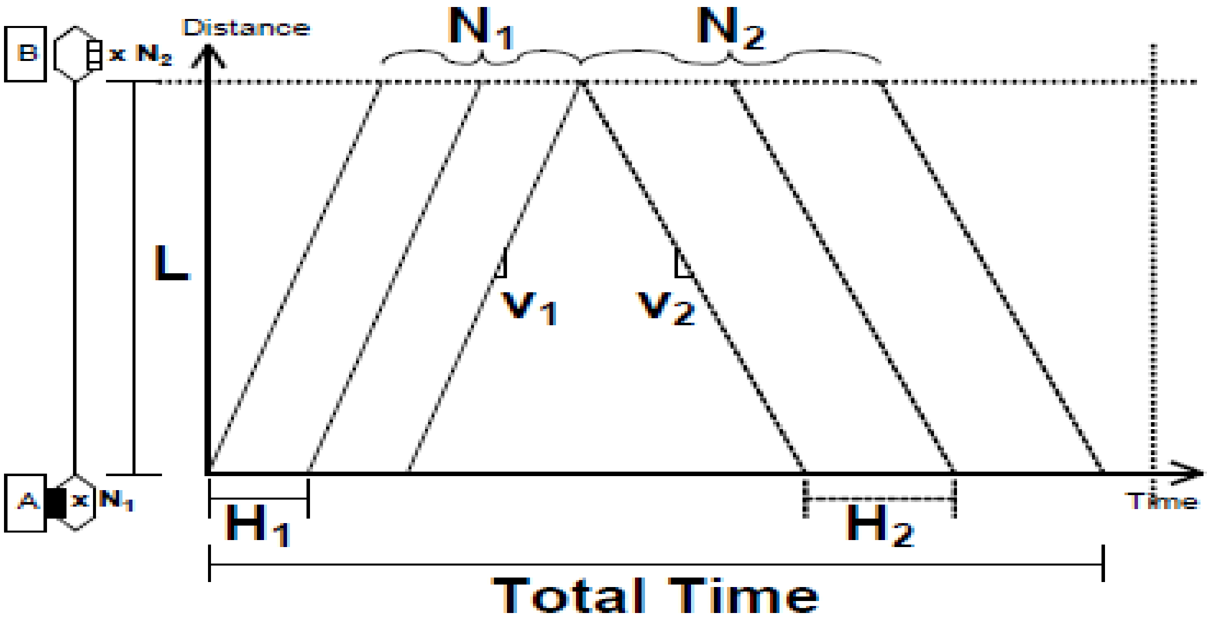


Figure 5 Time-space diagram for single-track system without a side track (N1:N2 ratio) *[11, 20]*

Side track system is a way to reduce the headway between trains and increase railway capacity. Fig. 6 shows that a side track in the middle between two train stations could double railway capacity, and could increase the capacity up to the double-track capacity. However, this case is not always true if the positions of side tracks are not equally located in strategic manners.

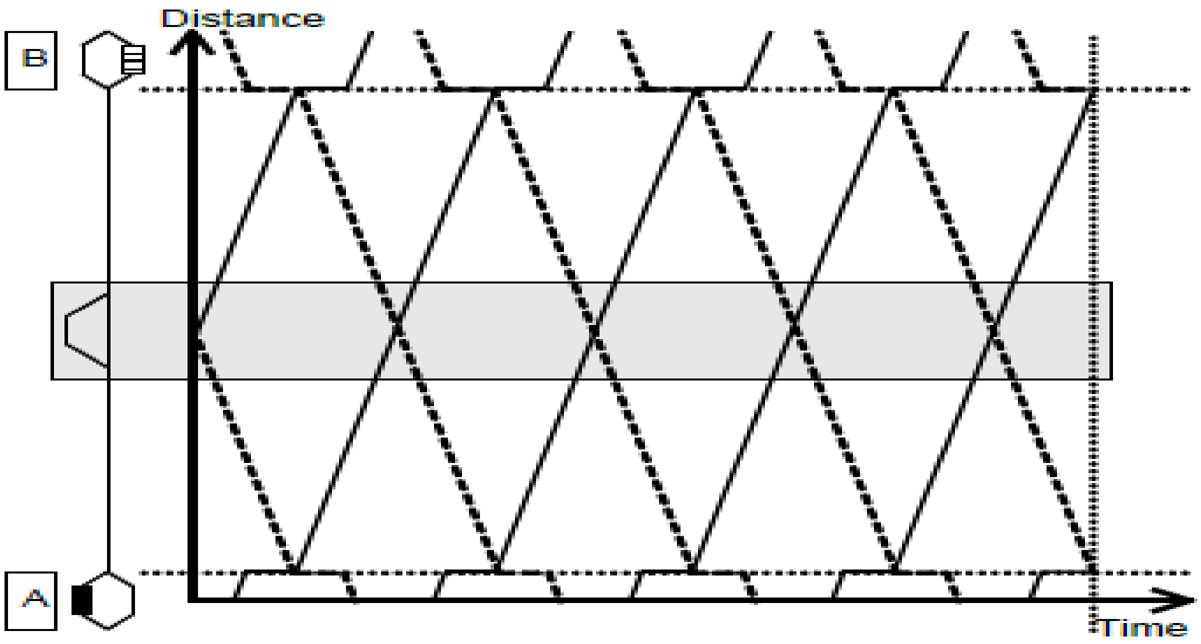


Figure 6 Effect of a side track to railway capacity *[11, 20]*

2.5.2. Non-Homogeneous System

The non-homogenous system is a boarder and more complex case when trains on the same direction travel in different speeds and need to overtake one another to increase higher capacity. To simplify this system, we assume that there are only two types of trains, i.e., freight or "slow" trains and passenger or "fast" trains. Each track scenario is shown below *[15, 20]*.

I. Double-track scenario

When a fast train is followed by a slow one, it can overtake a slow one through three strategies as follows.

(1) Use an opposing track for overtaking this strategy is to use the opposing track when no train is coming. It is similar to traffic operations on a two-lane highway. Fig. 7 shows this strategy on a time-space diagram. The benefit of this strategy is the increase in railway capacity without building more tracks. However, it requires high automated precision in track alteration; otherwise, it could lead to a major train accident *[11]*.

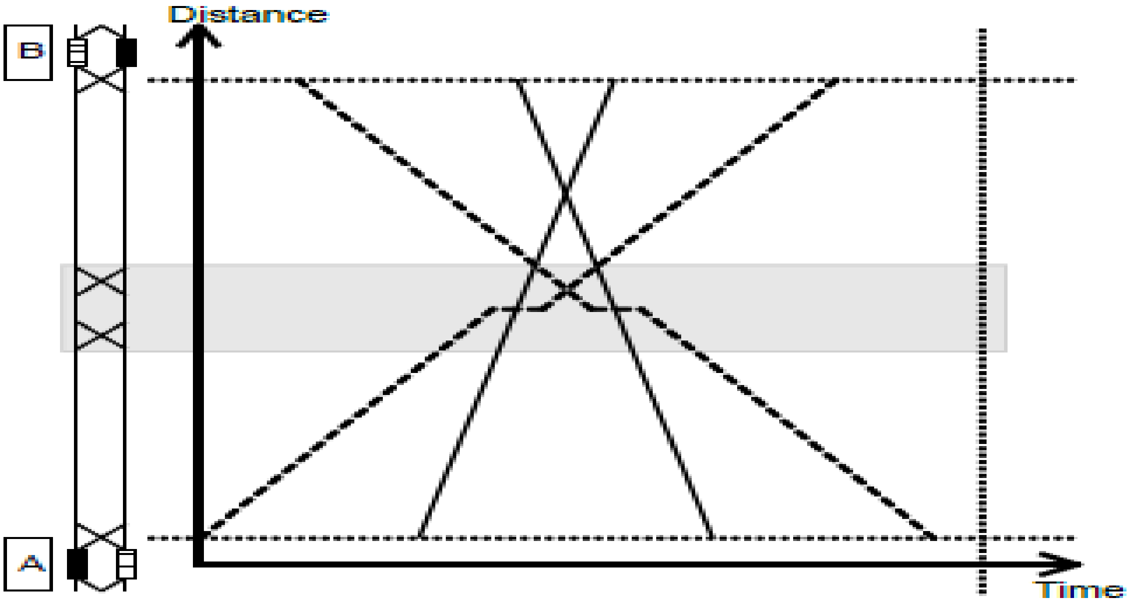


Figure 7 Time-space diagram for using an opposing track for overtaking *[11, 20]*

(2) Overtake at stations only in this strategy, fast trains are allowed to overtake slow ones at stations only.

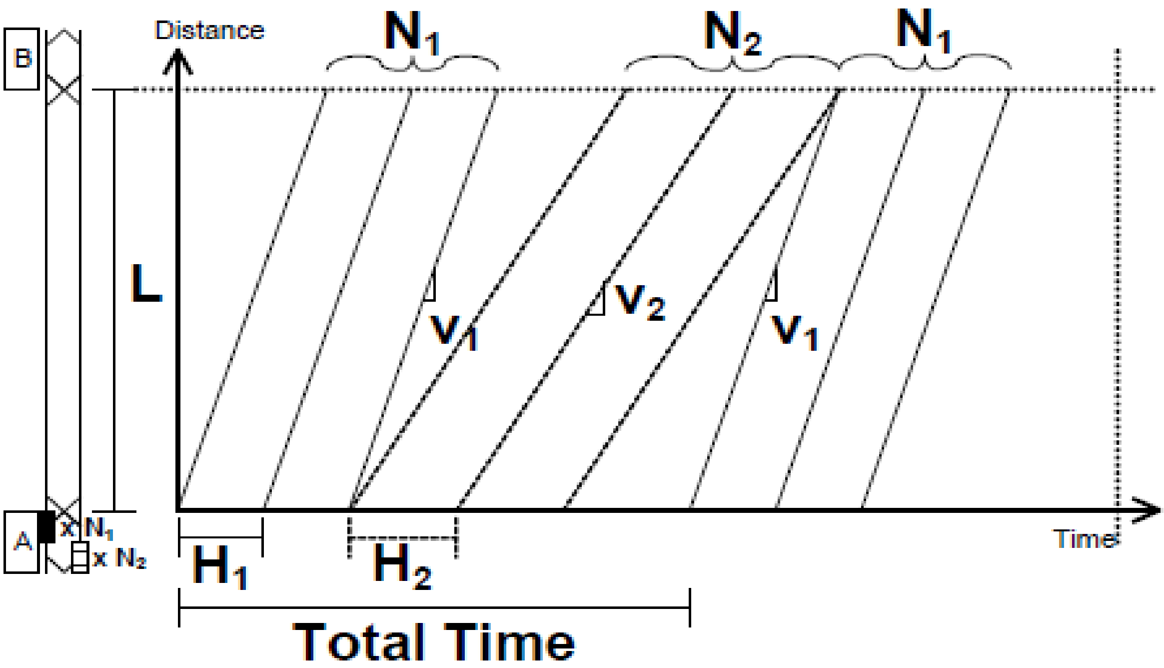


Figure 8 Time-space diagram for double-track system without a side track *[11, 20]*

(3) Use side tracks: this strategy applies side tracks for passing opportunities in the same direction as shown in Fig. 9. The concept is similar to the adding of a passing lane on a two-lane highway. It reduces headways between trains and increase capacity. Similarly, side tracks must be purposefully located evenly in appropriate numbers to maximize the capacity *[15]*.

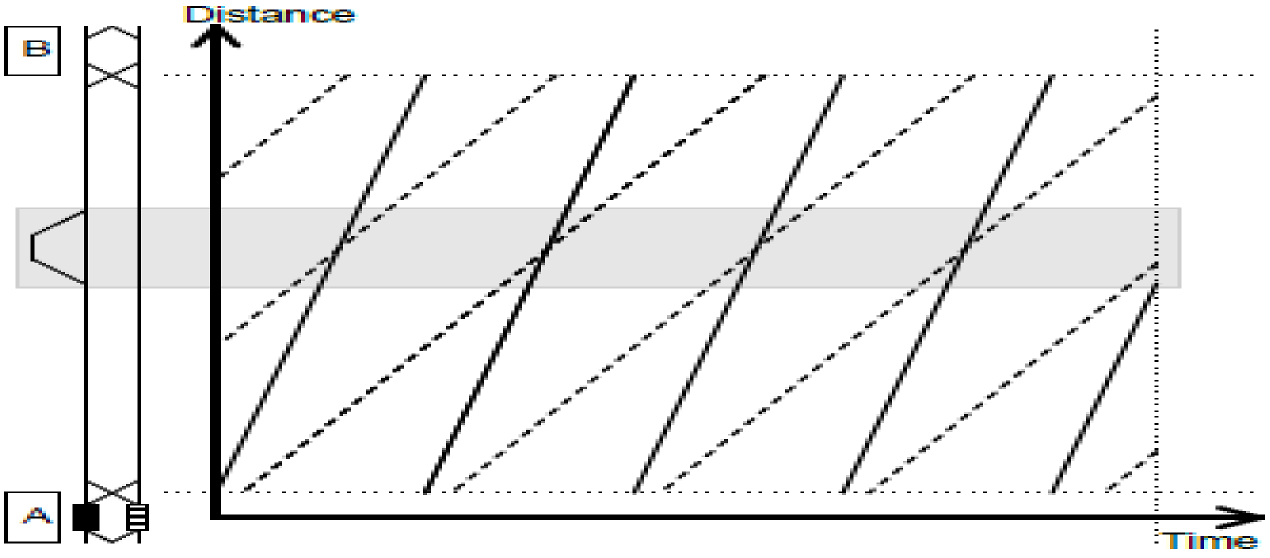


Figure 9 Time-space diagram for one-way double-track system with a side track

II. Single-track scenario

This scenario is the general case on Thai single-track railway system. Without a side track, the operation is similar to the homogenous single-track without a side track in Fig. 11 since all fast trains must follow a slow one until they reach a station. However, if side tracks are built as shown in Fig10, the problem is much more complex since passenger trains can overtake a freight train at a side track or a station only and other trains could not use the track until it is available. This strategy is quite difficult to manage since one side track must be used for both train directions and required automated control to avoid train accidents *[15, 20]*.

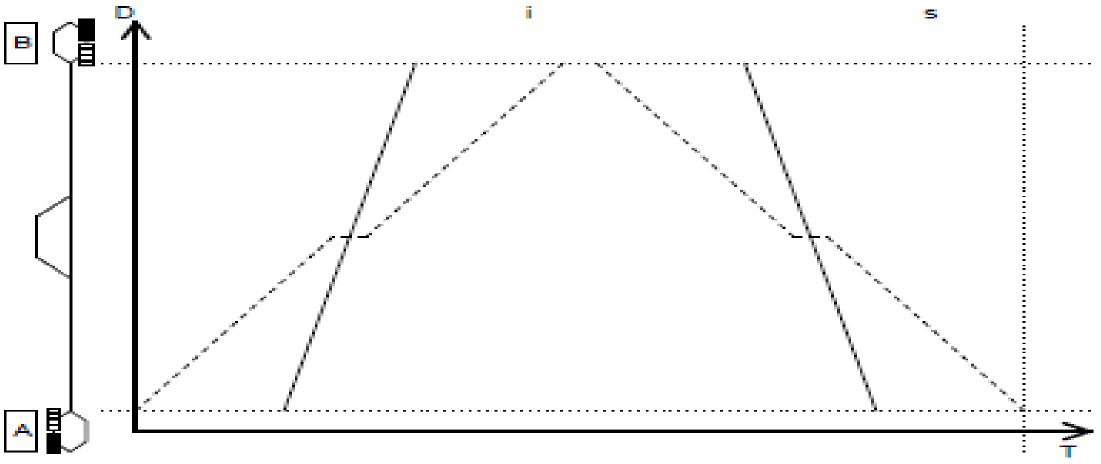


Figure10 Time-space diagram for non-homogeneous single-track system with a side track *[15]*

2.6. Introduction to CN Parameters

The CN parametric model provides a system-wide measure of subdivision capacity in a rail network and enables evaluation of the effect of improvements for various alternatives. The model measures the capacity of a subdivision by predicting its relationship between train delay (hours per trip) and traffic volume (trains per day). In general, the more trains that run on a subdivision in a given time period, the more delay each train experiences *[8, 22]*. The CN model calculates this relationship using several key parameters that affect the traffic handling capability of a subdivision. These parameters are categorized into plant, traffic, and operating parameters as follows:

2.6.1. Plant Parameters

1. Length of Subdivision (SL)
2. Meet and Pass Planning Point Spacing (MPPPS): MPPPS is the mean spacing of locations used to meet or overtake trains, namely siding spacing. Sidings are crucial for operating bi-directional, mixed priority and different speed trains. MPPPS for a subdivision is computed as:

$$\text{MPPPS} = \frac{length\ of\ subdivision}{(number\ of\ MPPP+1)} \tag{1}$$

3. Meet and Pass Planning Point Uniformity (MPPPU): MPPPU is the measure of uniformity in siding spacing (MPPPS). It is a ratio of the standard deviation versus average siding spacing:

$$\text{MPPPU} = \frac{\text{Standard Deviation Of MPPP Spacing}}{\text{MPPPS}} \tag{2}$$

   In general, the higher the uniformity of siding spacing the more the line capacity. Uniformity value of zero represents a subdivision with equally distributed sidings.

4. Intermediate Signal Spacing Ratio (ISSR): Intermediate signals reduce the required headway between adjacent trains thereby increasing line capacity. This parameter

accounts for the ratio of signal spacing to siding spacing. Te parametric expression for ISSR is:

$$ISSR = \frac{(\frac{length\ of\ subdivision}{MPPP+1+of\ signals})}{\mathrm{MPPPS}} \times 100 \tag{3}$$

5. Percent Double Track (%DT): Adding a second track has a significant impact on line capacity (more than double the capacity of a single track mainline). %DT is calculated as the ratio of double track versus the length of the subdivision:

$$\%DT = \frac{miles\ of\ double\ truck}{length\ of\ subdivision} \times 100 \tag{4}$$

Note that the CN parametric model can handle %DT up to 75%; this limit was found to retain the exponential characteristics and fall within the parametric range of most of CN's subdivisions *[9]*.

2.6.2. Traffic Parameters

1. Traffic Peaking Factor (TPF): TPF represents the concentration of traffic within a short time frame (4 hours), often called bunching or peaking. It has a significant impact on capacity, because when the traffic level is greater than the sustainable capacity, it causes lengthy system recovery time *[21, 23]*. TPF is calculated as the ratio between the maximum numbers of trains dispatched in a 4-hour period versus the average number of trains within the same time duration.

$$\mathrm{TPF} = \frac{\text{Maximum trains in 4 hours}}{\text{Average trains in 4 hours}} \tag{5}$$

2. Dispatching Priority Factor (DPF): Dispatching priorities for different types of trains dictate which trains will experience delay. Higher priority reduces transit time for higher priority trains by penalizing trains of lower priority. Generally the greater the number of priority classes, the less capacity is available. DPF is quantified using a

probability function that calculates the chances of a train meeting another train of a higher priority, which is calculated as:

$$\mathrm{DPF} = \frac{1}{T\sum_{j-2}^{N}}\{\frac{C_i}{(T-1)}\sum_{j=1}^{j-1} C_j \tag{6}$$

Where:

N = Number of priority classes (passenger, express, freight, and unit)
T = Daily number of trains
C_i = Number of j^{th} priority class trains
C_j = Number of j^{th} priority class trains

3. Speed Ratio (SR): Besides DPF, speed ratio is another parameter reflecting the traffic mix over the subdivision. The difference in speed among trains can significantly increase delay because of overtakes and/or holding trains in yard. SR is calculated as the ratio of the fastest train speed to the slowest train speed:

$$\mathrm{SR} = \frac{\text{Fast train speed}}{\text{Slower train speed}} \tag{7}$$

4. Average Speed (AS): Average train speed plays a vital role in line capacity because the higher the train speed the lower the delay and transit time. AS is measured as the average minimum run time of all trains in each direction, as obtained from a Train Performance Calculator (TPC).

$$\mathrm{AS} = \frac{\sum_{j-1}^{N} niVi}{\sum_{j-1}^{N} ni} \tag{8}$$

Where:

Vi = Speed of i^{th} class
ni = Number of trains in i^{th} class
N = Total number of classes

2.6.3. Operating Parameters

1. Track Outage (TO): Track outage accounts for the planned and unplanned events that take a track out of service. TO directly reduces the available service time of a subdivision as well as line capacity *[8, 10]*. Capacity is sensitive to the occurrence and duration of TO. This parameter is defined as the number of hours the subdivision is out of service:

$$TO's = \frac{Total\,duration\,of\,Outages}{\sum_{j-1}^{N} \frac{1}{n_T d_i}} \tag{9}$$

Where:

n_T = Total number of outages per day

d_i = Duration of each outage (hrs)

2. Temporary Slow Order (TSO): TSO has a negative impact on line capacity due to: (i) the time loss due to operating at slower than normal speed; and (ii) acceleration and deceleration time (V time). It is often maintenance related and can be applied to a distance or at a single point on the line. TSO is computed as follows:

$$TSO = V_{time} + Travel\,T$$

$$V_{time} = \frac{(V_m K - V_{TSO})}{A} + \frac{(V_m K - V_{TSO})}{D} \tag{10}$$

$$Travel\,Time = (\frac{1}{V_{TSO}} + \frac{L}{V_m K}) \times 60$$

Where:

V_m = Maximum freight speed (mph)

V_{TSO}= Temporary slow order speed (mph)

K = % of time running at max speed (85%)

A = Acceleration rate (20 mph/min)

D = Deceleration rate (30mph/min)

L = Length of TSO + average train length

The relationships between "delay-volume curve" and "key parameters" were developed based on a series of regression analyses and simulation results from the RCM *[8, 10]*. The relationship between train delay and traffic volume was found to be best expressed by the following exponential equation:

$$Train\ Delay = A_o e^{B_o V} \tag{11}$$

Where:

A_o = Parametric Plant, Traffic, Operating Coefficient

B_o = Constant

V = Traffic Volume (trains/day)

Coefficient "A_o" depicts the relationship between train delay and the parametric values. "A_o" is a unique value for each combination of parameters defined by the plant, traffic and operating conditions of a subdivision.

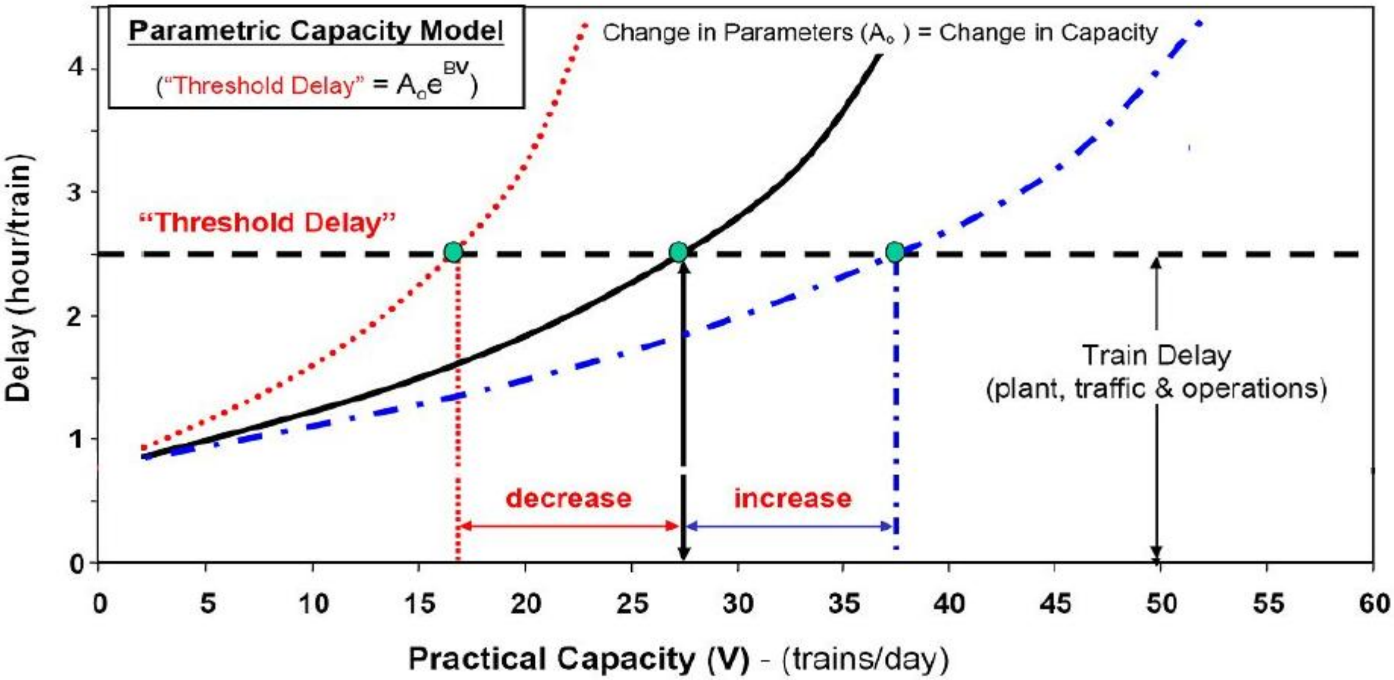


Fig.11 Delay-Volume Curve

Chapter Three

Research Methods, Conditions

3.1. Research Components and Procedures

Railroad capacity is influenced by a complex relationship of infrastructure and operational parameters. Operational factors include: average and variability in operating speed, traffic volume, stability, terminal efficiency and heterogeneity in various train characteristics. These are interrelated with, and further influenced by, infrastructure characteristics such as: siding length and spacing, crossover spacing, number of tracks, signal and traffic control system, grade, and curvature. For this work we studied the impact of operational factors, with a specific focus on train type heterogeneity. CN parametric model was used to model and simulate multiple traffic scenarios.

3.1.1. Research Components

- Related literatures
- Sebeta-Adama (double truck), Adama-Djibouti (single track)
- Modeling materials
- Measurement parameters

3.1.1.1. Description of the Study Area

Addis Ababa-Djibouti half single and half double- truck lines (107kms from Addis Ababa to Adama will be double track and the remaining 549 kms will be single track**)**

3.1.1.2. Train Types

Based on existing situation I selected the combination of freight and passenger trains to investigate because we found that this scenario resulted in the greatest delays due to heterogeneity.

3.1.1.3. Representative Rail Line

Specific characteristics of individual rail lines are unique and route characteristics influence the study of railroad operations. For our research we developed a hypothetical rail line intended to represent the characteristics of a typical Ethiopian single and double-track mainlines subdivision with the following attributes:

1. 1435mm Gauge
2. Sebeta-Adama (double truck), Adama-Djibouti (single track)
3. 0% grade and curvature
4. 100 mile subdivision
5. Electric power traction
6. Semi-automatic block type

3.1.1.4. Proposed Research Method

The main objective of this thesis is to provide some general knowledge about operative properties of single- and double-track lines. Infrastructure, timetable and delays thus appear as variables. In this paper, we use the second method of capacity estimation which use the chart called Train Dispatch Simulator (TDS), which depicts the movement of trains on the distance-time plot, or the ***time-space diagram***, the classical diagram for traffic and transportation engineers and ***CN parametric model*** techniques to develop accurate and simple regression-based delay estimation models that can then be used to investigate the impact of various operational changes on differing levels of heterogeneity on a hypothetical signalized, single-track rail line.

3.1.1.4.1. Time-space diagram

This research shows the analysis of railway capacity in different scenarios especially for single- and double-track systems based on graphical calculation from time-space diagram. The time-space diagram is considered to be a simple but powerful graphical thinking tool for transportation and traffic engineers to analyze vehicle motions and solve transportation operations problems. In this research herein, the time-space diagram is shown to solve the railway operations problems specifically for a case study in Ethiopia.

3.1.1.4.2. CN parametric model

The CN parametric model provides a system-wide measure of subdivision capacity in a rail network and enables evaluation of the effect of improvements for various alternatives. The model measures the capacity of a subdivision by predicting its relationship between train delay (hours per trip) and traffic volume (trains per day).

3.1.1.5. Capacity Metric of the study

Delay was used as the principal metric for capacity comparisons in this study. We define delay as the difference between the minimum, or unopposed, run time, and the actual run time required to traverse the route. This includes the time spent stopped for meets and passes, along with the time for braking, and to accelerate from stops. There has been some discussion about the use of delay as a metric of capacity, however for the types of comparisons and circumstances addressed in our study, delay is a generally satisfactory measure and is used throughout this paper.

3.1.2. Research Procedures

Since the research approach is mathematical, graphical and CN parametric model based, the main steps in the research process are:

1. Describe a framework for operational capacity analysis.
2. Identify relevant sub problems in the decision processes. Discussions with operation planners and dispatchers deliver insight into the challenges they are faced with when delays and disruptions occur.
3. Develop mathematical models describing the problems. Investigate possible Solution methods to solve real life size instances to the models.
4. Evaluate, demonstrate and calculate the mathematical and graphical models and solution methods.
5. Based on the analytical models using CN parametric, modeling the delay analysis on the poor capacity line. The overall methodology and research approach is explained on the diagram below.

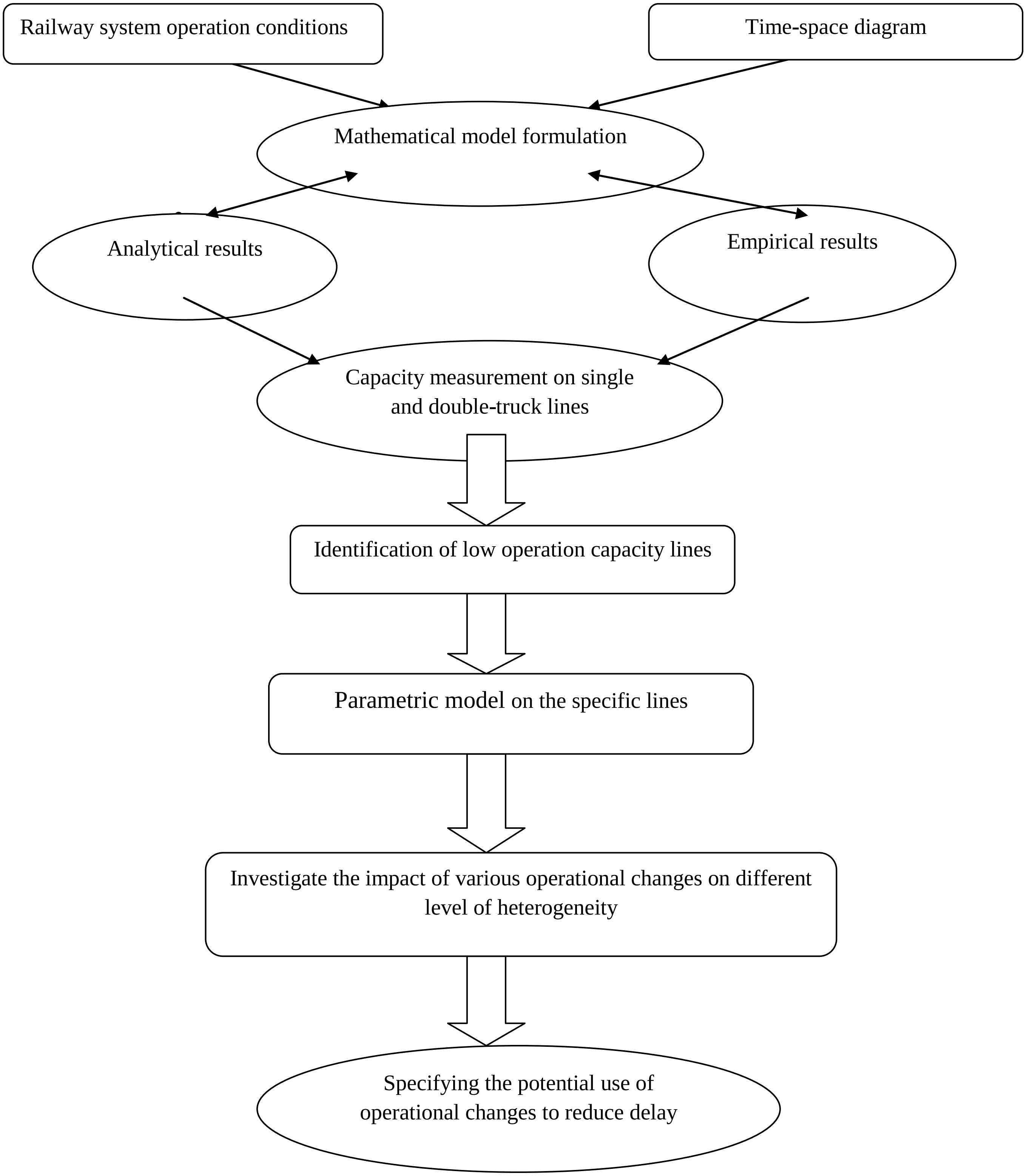


Fig.12. Research Methodology

3.1.3. Model Assumptions and Empirical Values

The Ethiopian Railway Corporation provided typical specification for various road train types. We used this information as the principal basis for the physical characteristics of the train types used in this analysis (Table 1) (Table 2) and (Table 3). The non-physical characteristic of each train is the priority assigned to it by the dispatcher. When two trains meet, priority is one factor the dispatcher will take into consideration when determining how to resolve the conflict. Generally dispatchers will try to minimize the total cost of delay, this means that the trains carrying lower value, less time sensitive freight will have lower priority and enter the siding, while the higher priority train holds the main and proceeds with little or no delay

Table1. Model Estimation Results for Time-Space Diagram Analysis

Variable	Definition	Value	
		Passenger Train (PT)	Freight Train (FT)
W	Waiting time at a train station	12 minute	12 minute
L	Distance between train stations	16.26Km	16.26Km
B	Block distance	1Km	1Km
V	Train speed	120Km/h	70Km/h
l	Train length	.85Km	.85Km
H	Headway between trains	Dependent variable in analysis	Dependent variable in analysis

For this work I studied the impact of plant, traffic, and operational factors, with a specific focus on train type heterogeneity. The information used hear are based on Addis Ababa/Sebeta – Djibouti New Standard Gauge Railway Project Feasibility Study Report According to Chinese Standard by Ethiopian Railways Corporation. CN parametric model was used to provides a system-wide measure of subdivision capacity in a rail network and enables evaluation of the effect of improvements for various alternatives. The design capacities of the line in each section in three stages are as shown in the following table:

Table 2 Design Capacities of Each Section in Three Stages

Year	Section	Design capacity(train/day)
First stage	Single truck	23train/day
Short term	Single truck	33train/day
Long term	Single truck	57train/day

Table 3 Derived Model Estimation Parameters of the Selected Subdivision

SL	MPPPS	MPPPU	ISS	%DT	TPF	SR	AS	TO	TSO
100miles	no	0.3	1	0.04	1.52	1.71	44mph	0	0

Chapter Four

Model Development

4.1. Ideal Existing Operation

Since there is no actual existing operation, to analyze the system operation it is the only option modeling an ideal existing operation considering; operational and rolling stock specifications and model assumptions with the help of time-space diagram.

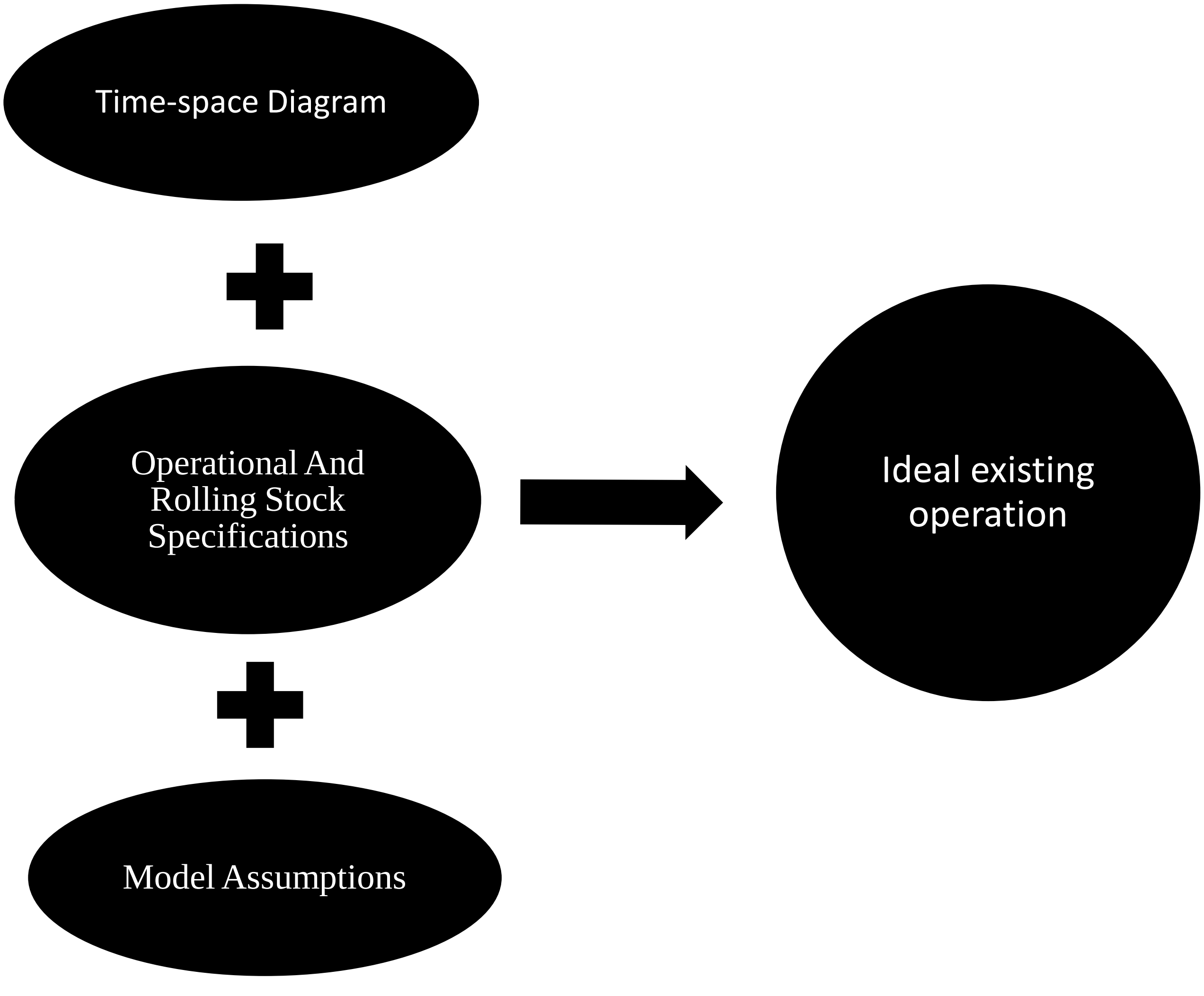


Figure 13 model developments for ideal existing operation

4.2. Modified Ideal Existing Operation

By using the inputs from time-space diagram model, to perform specified analysis the ideal existing operation has been modified as follows;

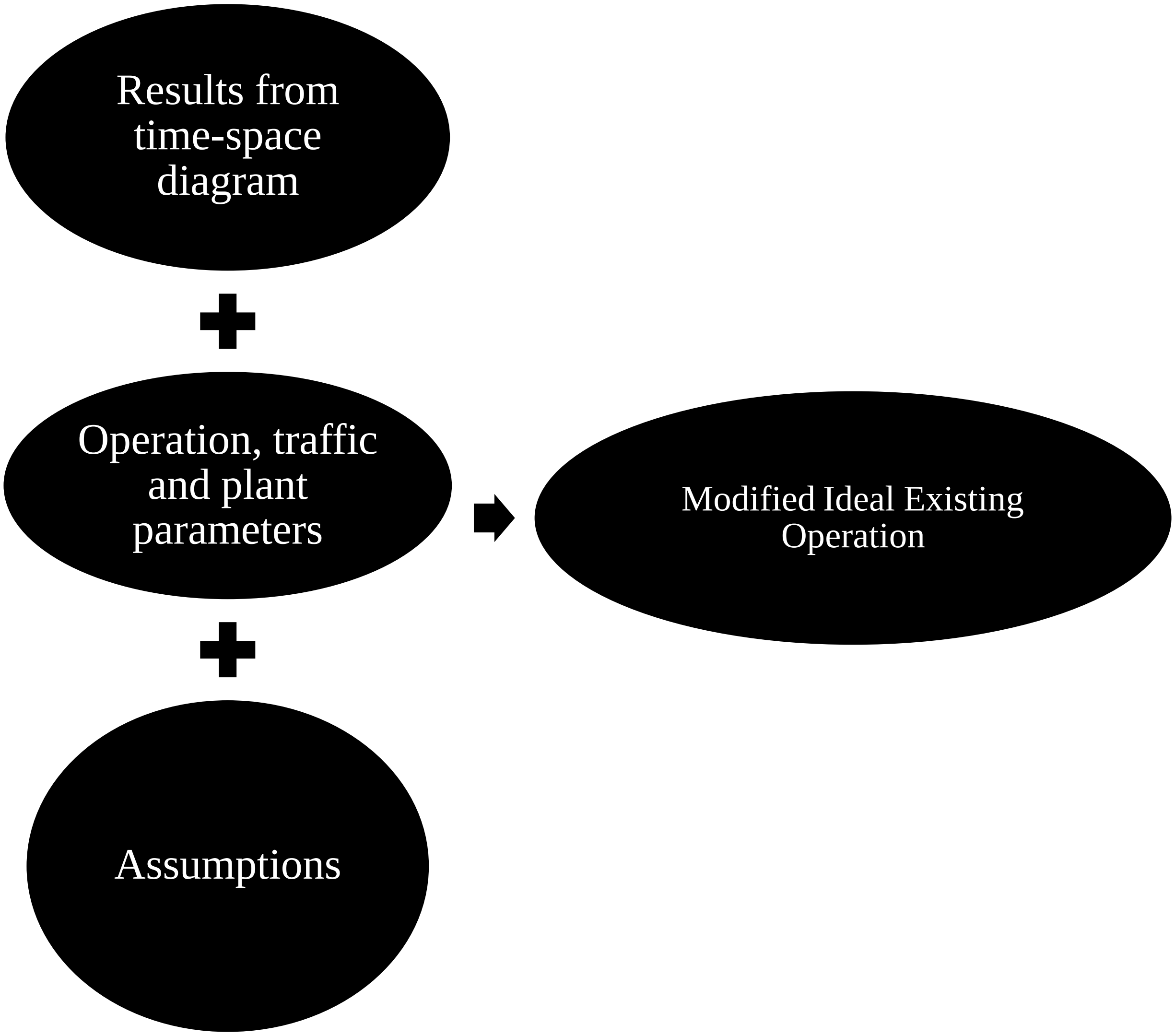


Figure 14 the modified ideal existing operation

4.3. Capacity Expansion Model

To improve the capacity of modified ideal existing operation, capacity expansion alternatives are modeled which are explained on the figure below.

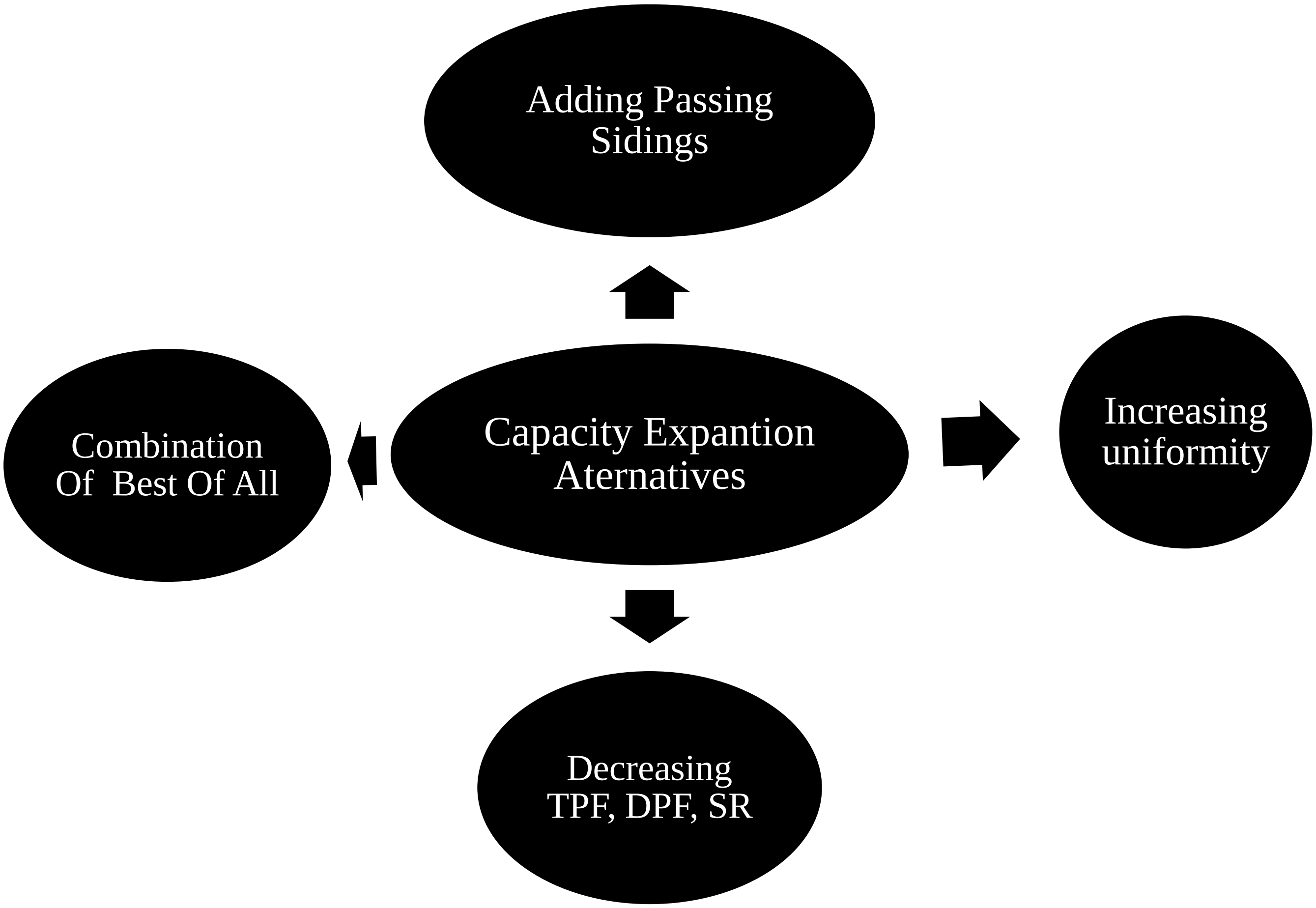


Figure 15 capacity expansion alternatives

4.4. Best Railway Capacity Model

By taking best rail line capacity from adding passing sidings, increasing uniformity, decreasing TPF, DPF, and SR, best railway capacity model had been modeled.

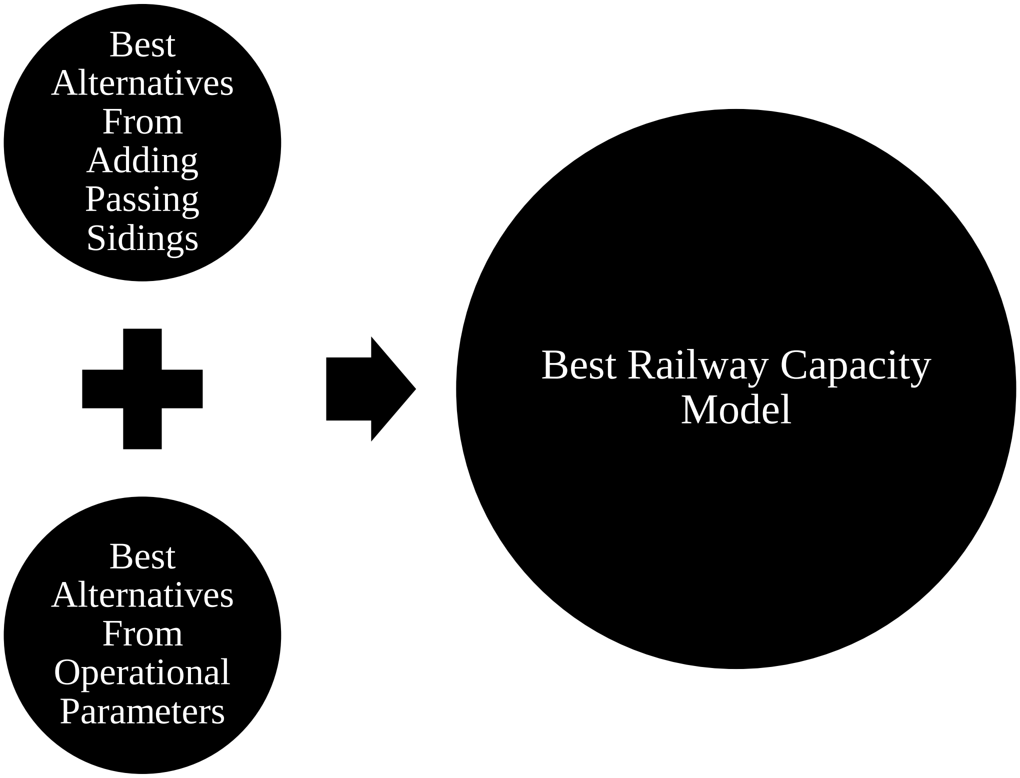


Figure 16 the Best Railway Capacity Model

Chapter Five

Results and Discussion

5.1. Time-Space Diagram Analysis Model

5.1.1. Analytical Results

This section will show the analytical results from time-space diagram analysis in different scenarios. We now define the term "homogeneous system" if all trains in the same direction travel at one speed, or are in the same type, i.e., all passenger trains or all freight trains. This includes the case if all passenger trains travel from A to B and all freight trains travel from B to A. The system is called "non-homogeneous system" if there are more than one type of train traveling in the same direction. The description of analysis will start from the homogeneous system for easy understanding.

4.1.1.1. Analysis of Homogeneous System

A. Double-track scenario

Total railway capacity from the time-space diagram shown in Fig.3 *[12, 16]*

$$\text{Railway capacity} = \frac{1}{H_1} + \frac{1}{H_2} = \frac{1}{w+\frac{B+l_1}{V_1}} + \frac{1}{w+\frac{B+l_1}{V_2}} \tag{12}$$

Where,

l_1, l_2 = Train length in directions 1 and 2, respectively

v_1, v_2 = Speeds of trains in directions 1 and 2, respectively

B. Single-track scenario

let each group go alternately instead of an individual one, i.e., let N1 trains in A to B direction go first and alternate with N2 trains in B to A direction go (N1:N2 ratio) as shown in Fig. 5. The railway capacity in this case can be calculated by the equation; *[11, 18]*

$$\text{Railway capacity} = \frac{N_{1+}N_2}{\left(N_{(n-1)}\right)\left\{w+\frac{B+l_1}{V_1}\right\}+\left(N_{(n-2)}\right)\left\{w+\frac{B+l_2}{V_2}\right\}+\frac{L}{v_1}-\frac{L}{v_2}} \tag{13}$$

From Equation 13, it should be noted that if N1 >> N2, the capacity of single-track system will approach the double-track system since no opposing train can travel on this track. In addition, the storage for waiting trains at each station is limited. In practice, the “total time”, the maximum allowable time to change the train direction, must be given. *[8, 14]*

C. Single-track scenario with side track

From Fig.5, we could imply that if trains on both directions travel at the same speed, side tracks must be locate at equal distance along the single track. If the numbers of side tracks are not fitted or not evenly located, the effect of capacity increase will be reduced *[13, 19]*. Equation 14 shows the number of side tracks (*n*) that would fit for the operations as follows.

$$\mathrm{n}=\frac{L}{H_2}\left(\frac{1}{v_1}+\frac{1}{v_1}\right) \tag{14}$$

Where,

H_2=train headway for the less-priority direction (higher headway)

Since the distance between side tracks should be even for maximum effect, the ratio between the headway for the higher-priority direction and the one for the less-priority must be an integer, i.e., $H_2 = mH1$, where m is a positive integer. However, since

$\mathrm{H}_1=\frac{1}{w+\frac{B+l_1}{V_2}}$, Therefore we can determine H_2 from equation 15 below.

$$\mathrm{H}_2=\min\{\frac{1}{w+\frac{B+l_1}{V_2}},m\left(\frac{1}{w+\frac{B+l_1}{V_1}}\right)$$

After that, the railway capacity for homogeneous single-track system with side tracks can be determined by substituted H_1 and H_2 in Equation 12.

$$\text{Railway capacity} = \frac{1}{H_1} + \frac{1}{H_2} = \frac{1}{w+\frac{B+l_1}{V_1}} + \min\left\{\frac{1}{w+\frac{B+l_1}{V_2}}, m\left(\frac{1}{w+\frac{B+l_1}{V_1}}\right)\right\} \quad (15)$$

4.1.1.2. Analysis of Non-Homogeneous System

The non-homogenous system is a boarder and more complex case when trains on the same direction travel in different speeds and need to overtake one another to increase higher capacity. To simplify this system, we assume that there are only two types of trains, i.e., freight or "slow" trains and passenger or "fast" trains. Each track scenario is shown below.

A. Double-track scenario

When a fast train is followed by a slow one, it can overtake a slow one through three strategies as follows.

(1) Use an opposing track for overtaking

(2) Overtake at stations only: The calculation of one-way capacity with fast and slow trains is analogous to the one of two-way capacity in homogeneous single track without a side track scenario *[8, 10]*. The strategy to maximize capacity is to group the same train types, i.e., a group of fast trains and a group of slow trains, together and alternate them, according to the illustration in Fig.8. The railway capacity in this case can be calculated by Equation 16 below.

$$\text{Railway capacity} \frac{N_1+N_2}{(N_1)\left\{w+\frac{B+l_1}{V_1}\right\}+(N_2)\left\{w+\frac{B+l_2}{V_2}\right\}+\frac{L}{v_1}-\frac{L}{v_2}} \quad (16)$$

(3) Use side tracks:

The number of side tracks (*n*) that would fit for the operations are shown in Equation 17:

$$\text{n}=\frac{L}{H_2}\left(\frac{1}{v_1}-\frac{1}{v_1}\right) \quad (17)$$

H_2 = train headway for the less-priority direction (higher headway)

In this case, the ratio between the headway for the higher-priority direction and the one for the less-priority must be an integer, i.e., $H_2 = m H_1$, where *m* is a positive integer.

$$\mathrm{H}_2 = \min\left\{\frac{1}{w+\frac{B+l_1}{V_2}}, m\left(\frac{1}{w+\frac{B+l_1}{V_1}}\right)\right\} \tag{18}$$

After that, the railway capacity for non-homogeneous double-track system with side tracks can be determined by substituted H_1 and H_2 in Equation 12.

B. Single-track scenario

Without a side track, the operation is similar to the homogenous single-track without a side track.

5.1.2. Empirical Results

Table 4 empirical capacity results based on the substitution the values of variables from Table 1

System	High priority	low priority	total	High priority	low priority	total	High priority	low priority	total
Homogeneous system	PT vs. PT			FT vs. FT			PT vs. FT		
Double-truck	110	110	220	105	105	210	110	105	215
Single-truck without side trucks*	62	12	74	26	12	38	41	14	55
Single-truck with side trucks**	110	110	220	105	105	210	110	105	215
Non homogeneous system	PT vs. PT			FT vs. FT			PT vs. FT		
Double-truck without side trucks*	Not applicable						93	93	186
Double-truck with side trucks on Both sides	Not applicable						217	217	434

Note:

PT=Passenger train;

FT=Freight train

*Assume that the maximum allowable time to change the train direction, or “total time”, is 2 hours

**Assume that side tracks are located strategically and evenly to yield maximum possible rail capacity.

Table 4 shows empirical capacity results based on the substitution the values of variables from Table 1 or actual operating data in Equations 12-18. This table assumes 2 hours of the maximum Allowable time to change the train direction, or “total time” in Figs.2 and 5, and that the positions and numbers of side tracks are ideal and yield maximum possible rail capacity.

5.1.3. Results Discussion

The time-space diagram that demonstrated in literature review shows analysis technique for creating models comparing single- and double-track railway system capacities, with the empirical data from Ethiopian Railway Corporation. It uses graphical illustration to determine the relationships among operating variables into a set of simple equations. These equations could be used to roughly determine railway capacities in different scenarios.

The empirical results show that double-track system yield almost three times as much as the one for single-track without side tracks. With side tracks, it is possible that the capacity of single track system could be increased as much as the double-track one. Nevertheless, these simple calculations do not take the delay due to deceleration or waiting time at the side tracks into consideration. Also, it might not be feasible to build side tracks at all strategic locations due to geographic, land-use, or financial constraints. Therefore, for real situations, the capacity of single-track system with side tracks could be 30-50% much less than the ideal condition *[8, 22]*.

In summary, this model has some limitation. First, some variables that affect operations such as slow-down when moving to side tracks were excluded. Second, the number of side tracks in Equations 14 or 18 might not be a whole number or side tracks are not located in equidistance manner, this would significantly reduce capacities. In addition, this model did not take the stochastic effects of train speeds, waiting times at stations, etc, into the calculations. So for further feasible research direction, more related operating variables should be added for more realistic scenarios in CN PARAMETRIC MODEL.

5.2. CN Parametric Model

In the model described here, three common types of capacity expansion alternatives are built into this module: (i) adding passing sidings, (ii) increasing uniformity, and decreasing (iii) TPF, DPF, SR, and AS but other options could be included if desired. For the single track scenario, increasing the number of sidings can reduce meet and pass delay, and shortening block length and the consequent decrease in signal spacing, can reduce the headway between trains, thereby increasing line capacity.

For each subdivision, the enumeration module calculates all possible combinations of expansion alternatives until it reaches the limit of minimal siding spacing or maximal number of signals per spacing specified by the user. For example, consider a 100-mile subdivision, no existing sidings, and no intermediate signals. The minimum siding spacing is set to ten miles and the maximum number of intermediate signals between sidings is two The largest number of sidings that can be placed on this subdivision is 9 (H100/10 – 1), and the largest number of intermediate signals that can be placed (between two sidings) is two *[8, 22]*.

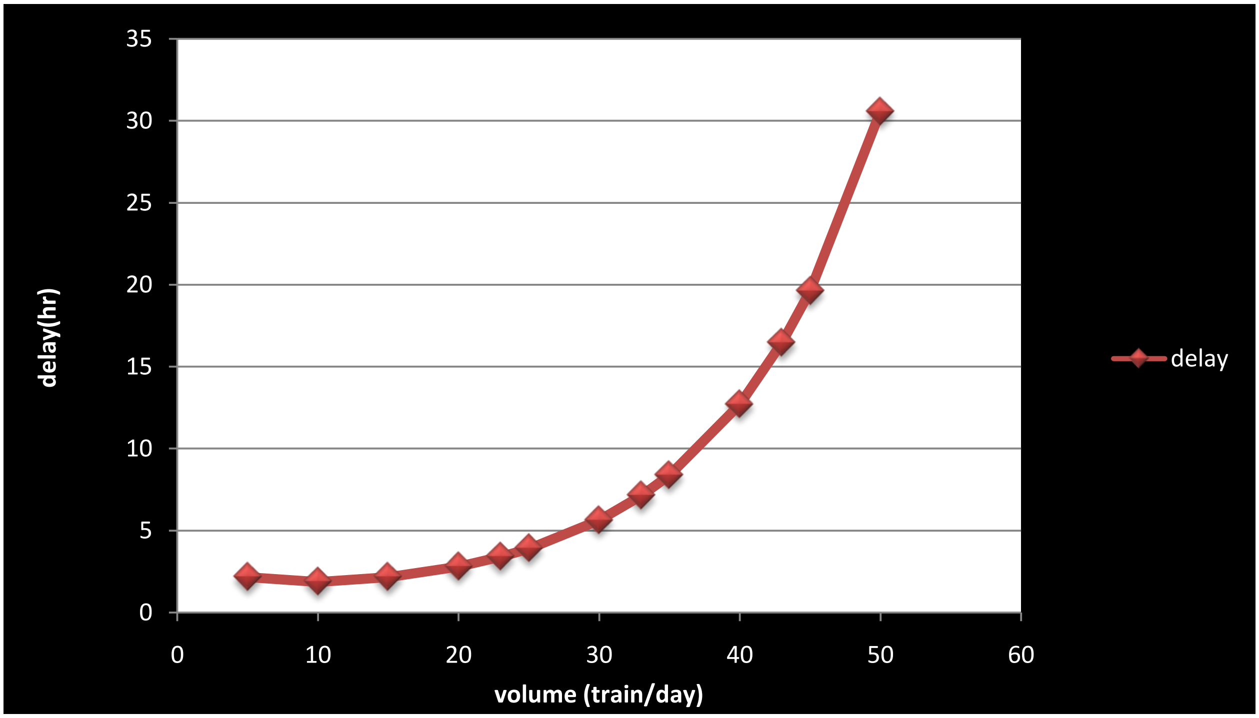


Figure 17 Delay-Volume Plot for idealized existing operation

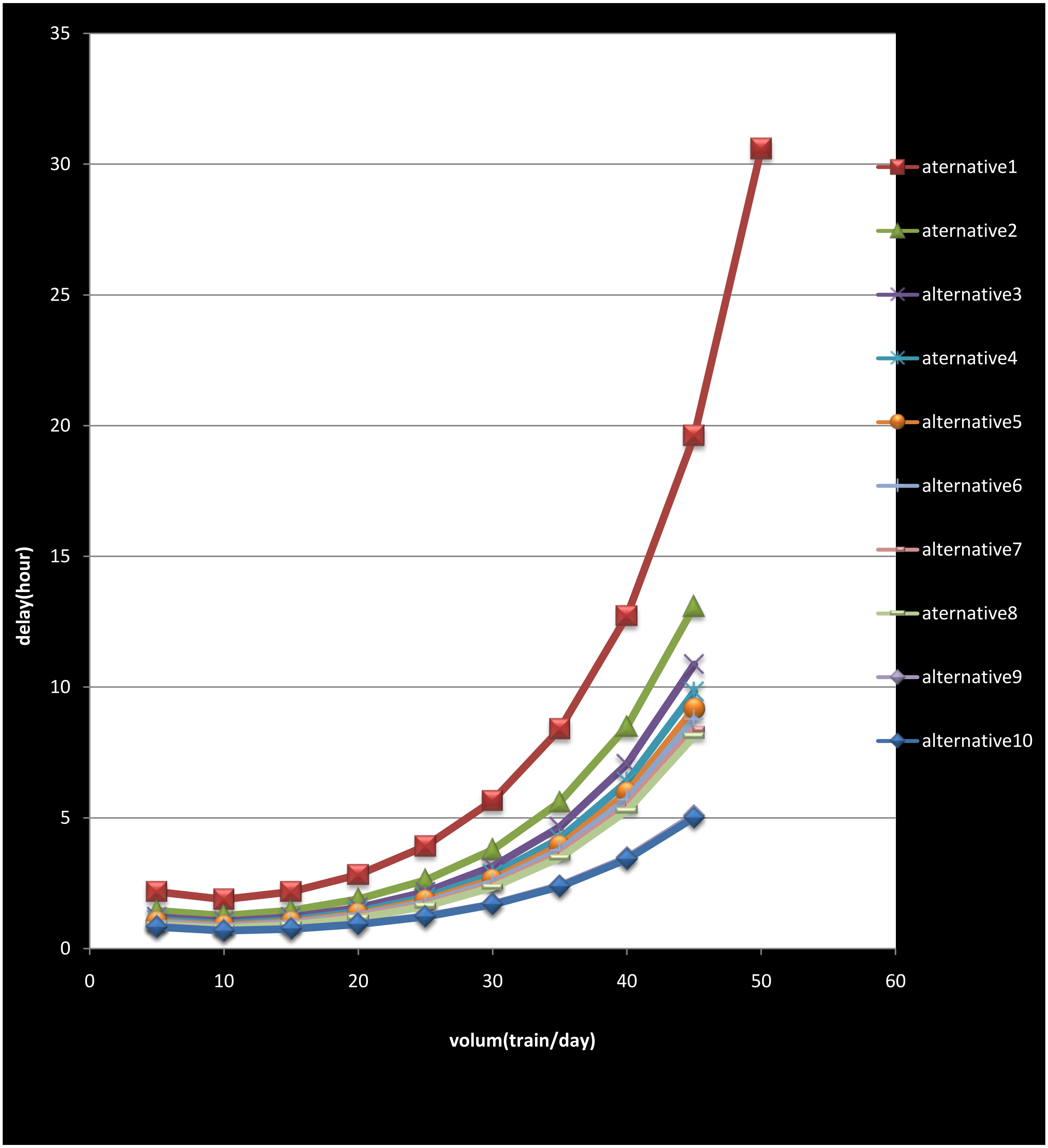


Figure 18 Delay-Volume Plot for adding passing sidings

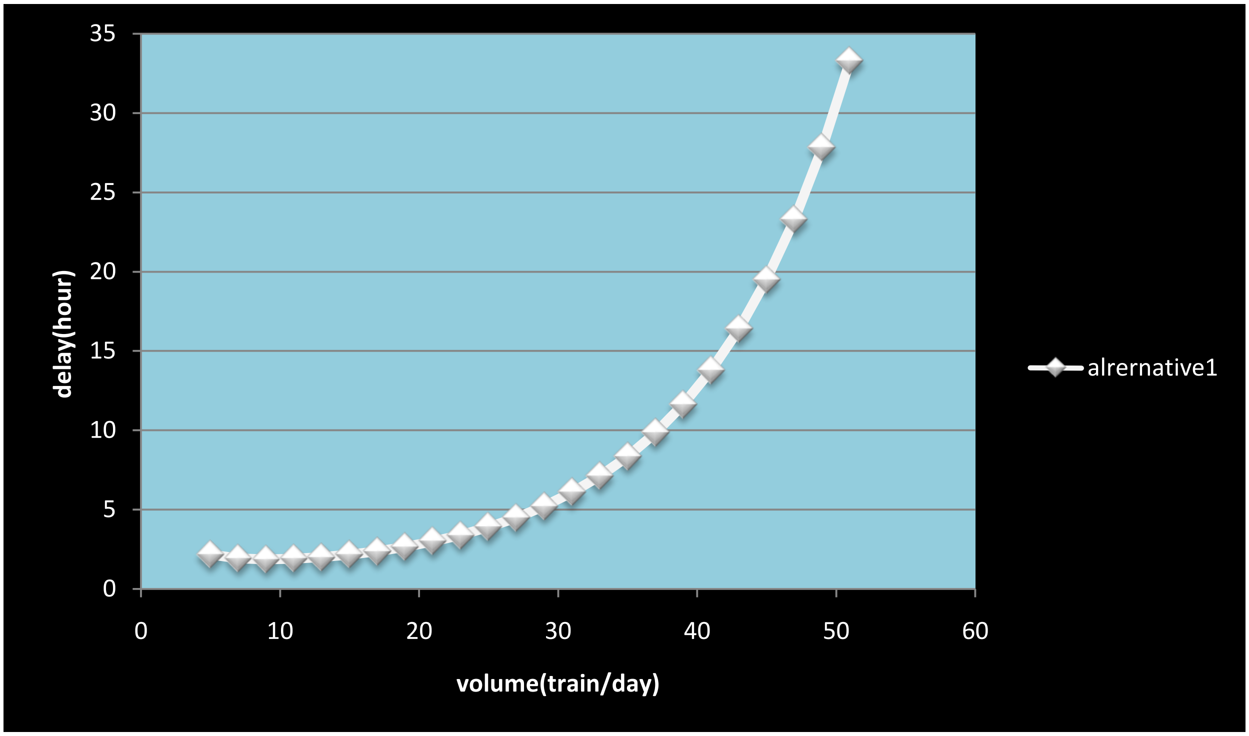


Figure 19 Delay-Volume Plot for uniformity (MPPPU=0.3)

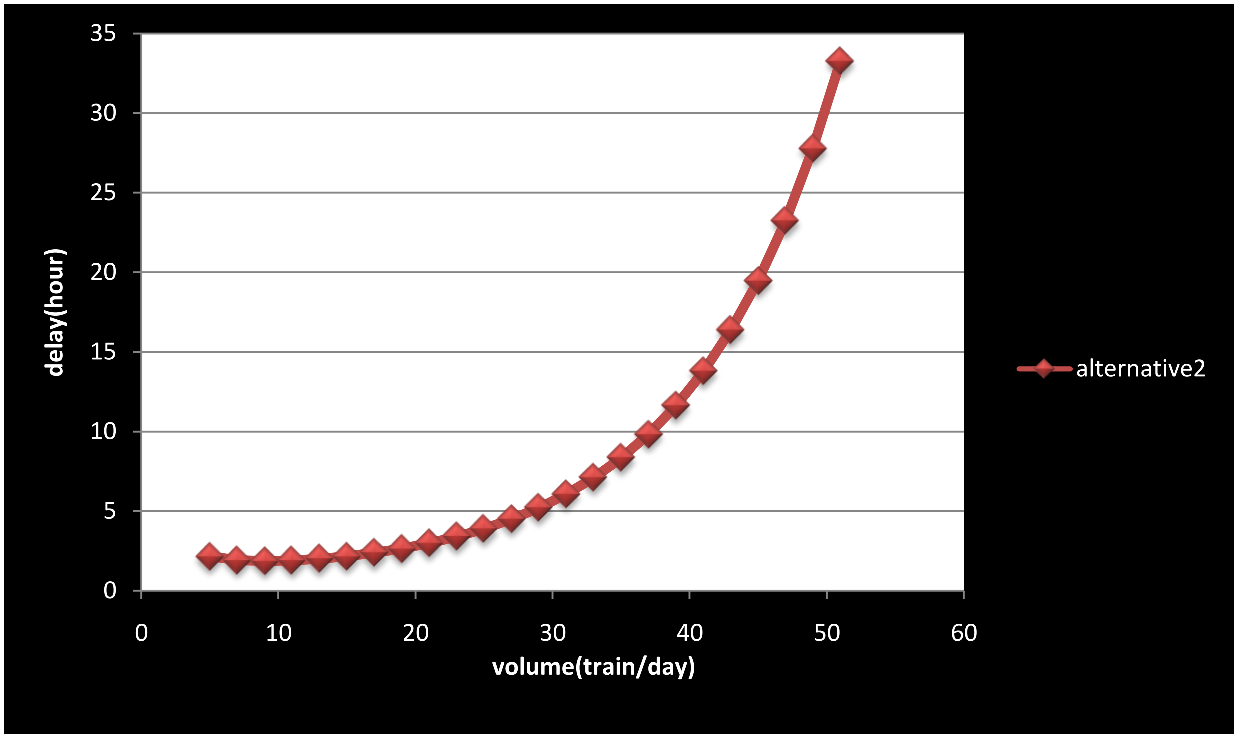


Figure 20 Delay-Volume Plot for uniformity (MPPPU=0.2)

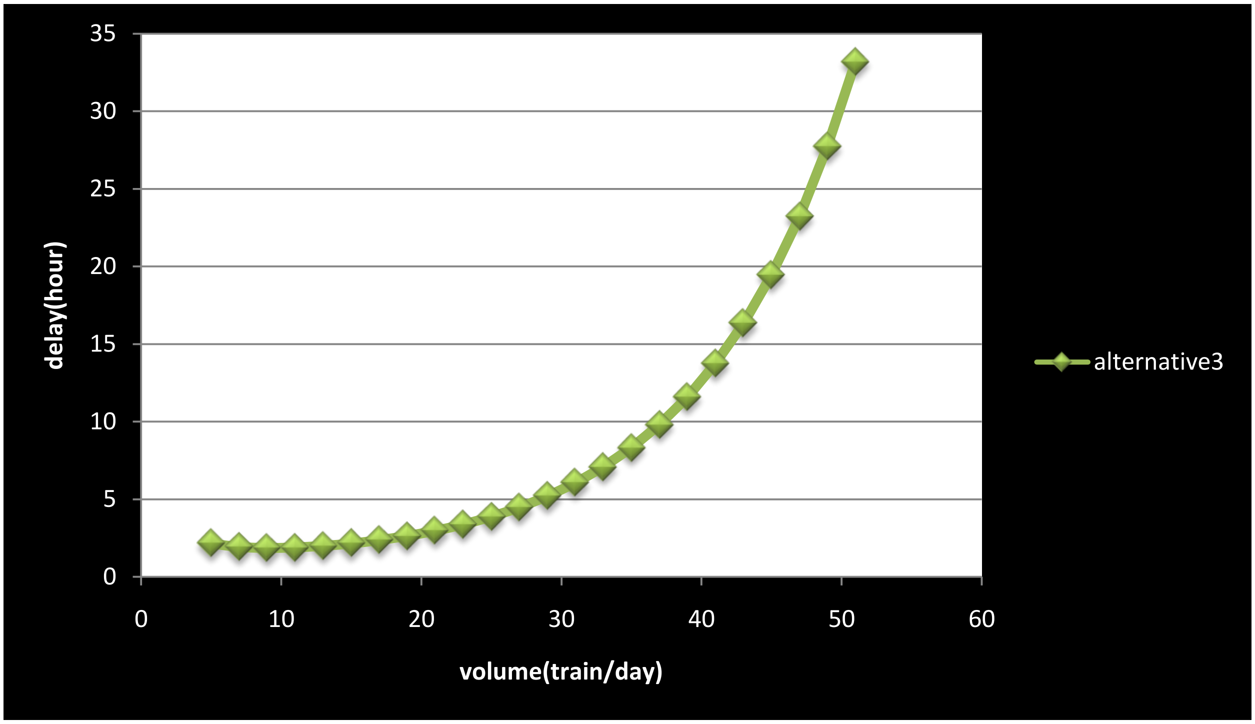


Figure 21 Delay-Volume Plot for uniformity (MPPPU=0.1)

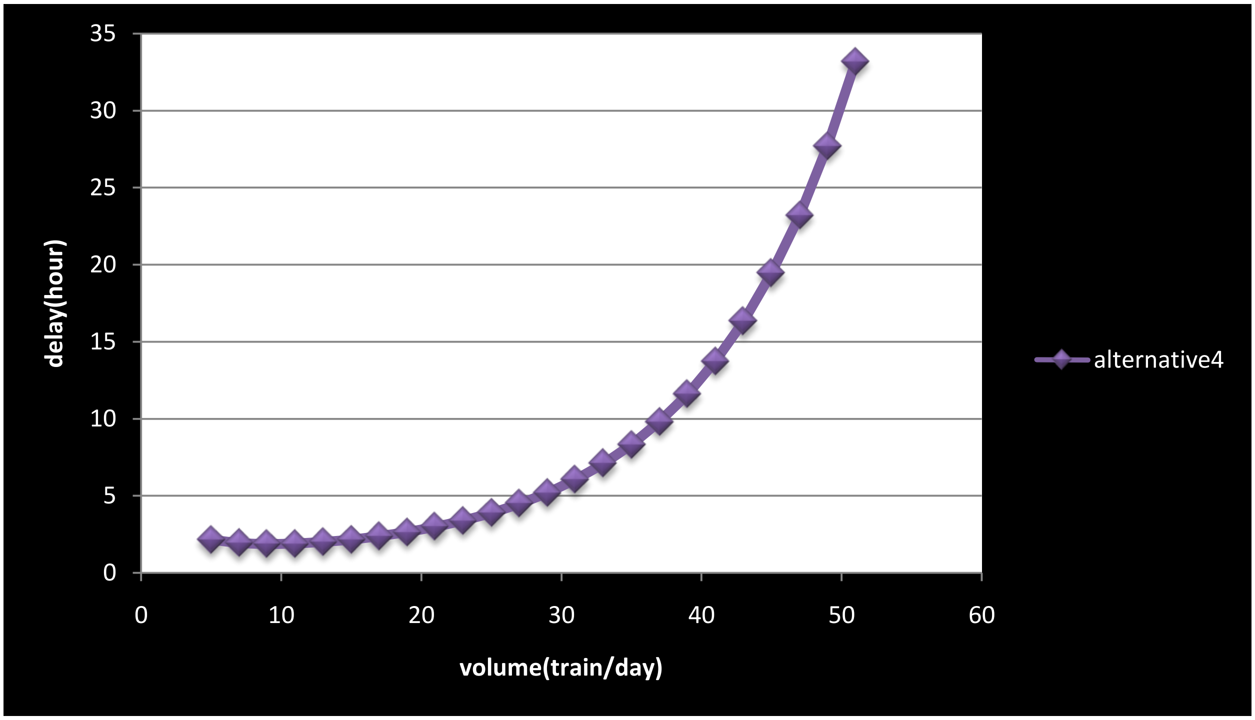


Figure 22 Delay-Volume Plot for uniformity (MPPPU=0)

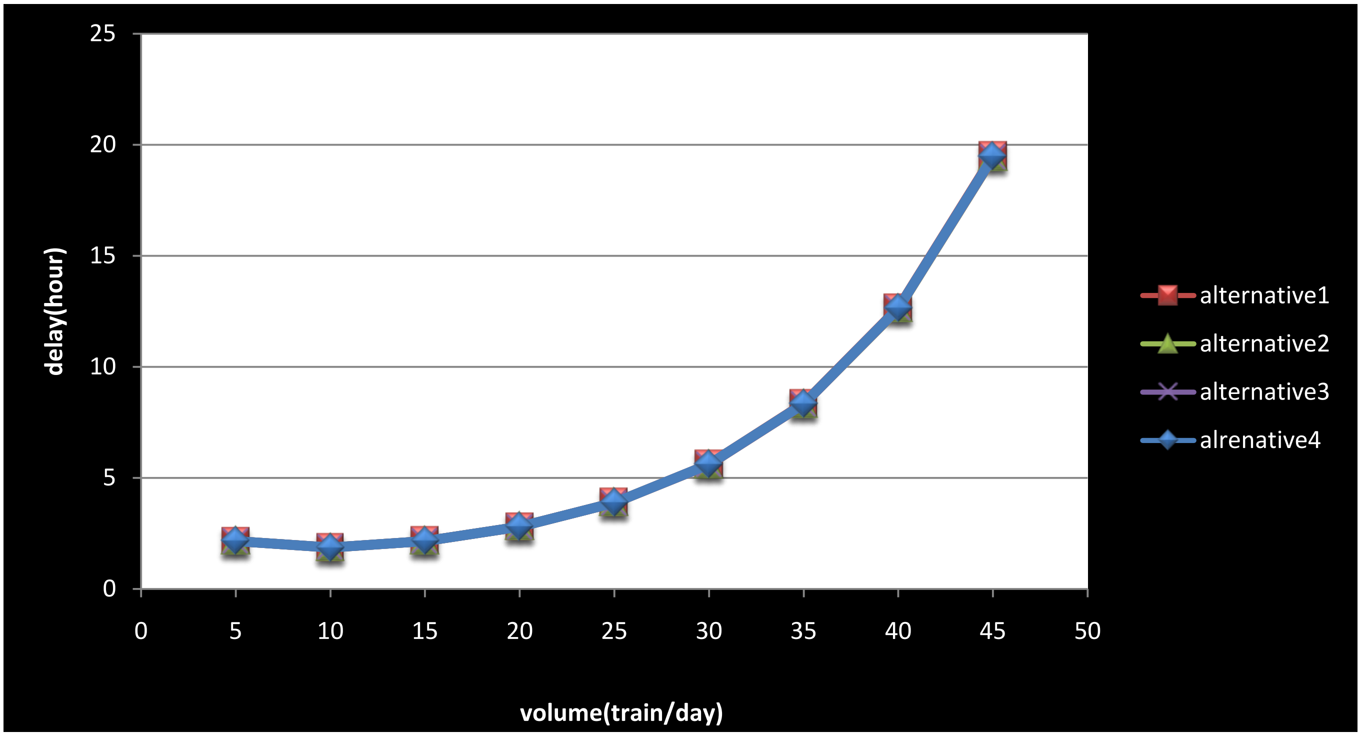


Figure 23 Delay-Volume Plot for increasing uniformity

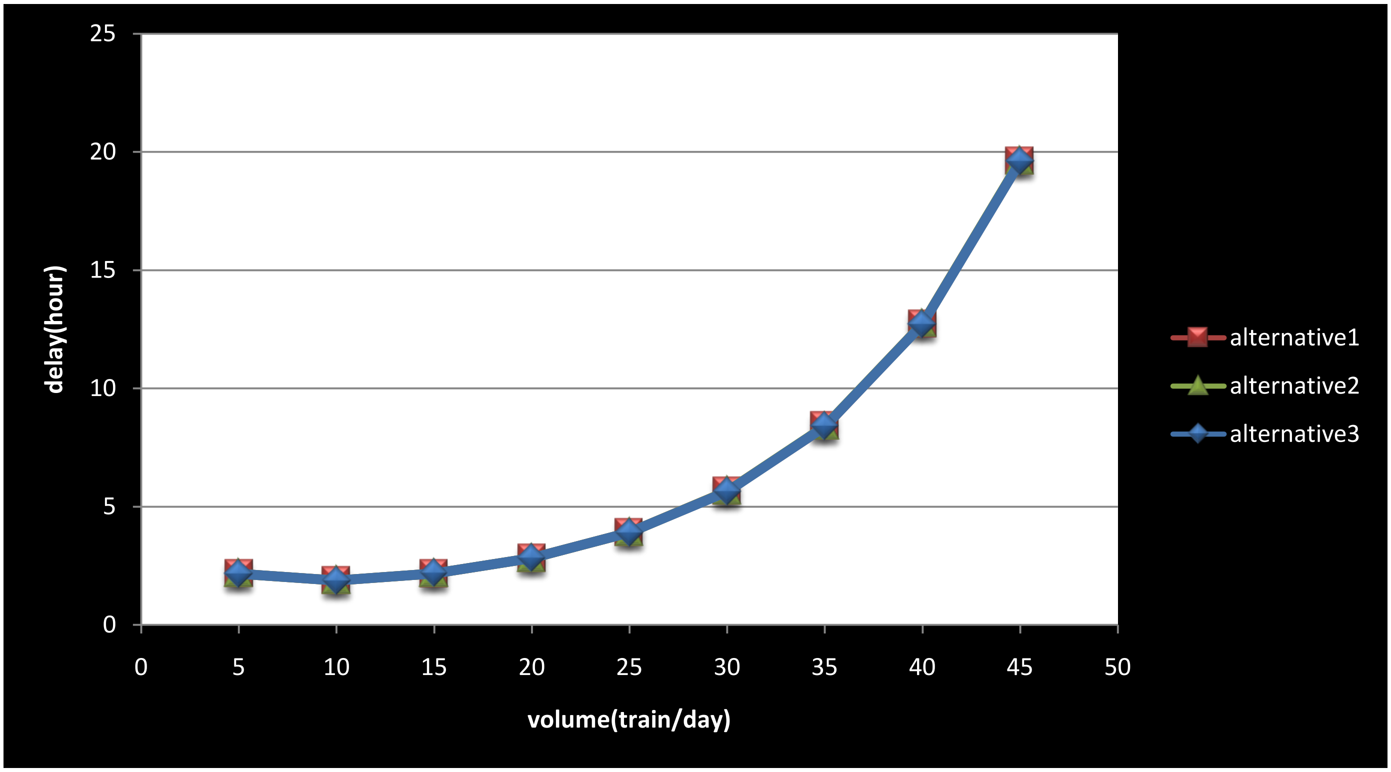


Figure 24 Delay-Volume Plot for decreasing (Removing Priorities) DPF

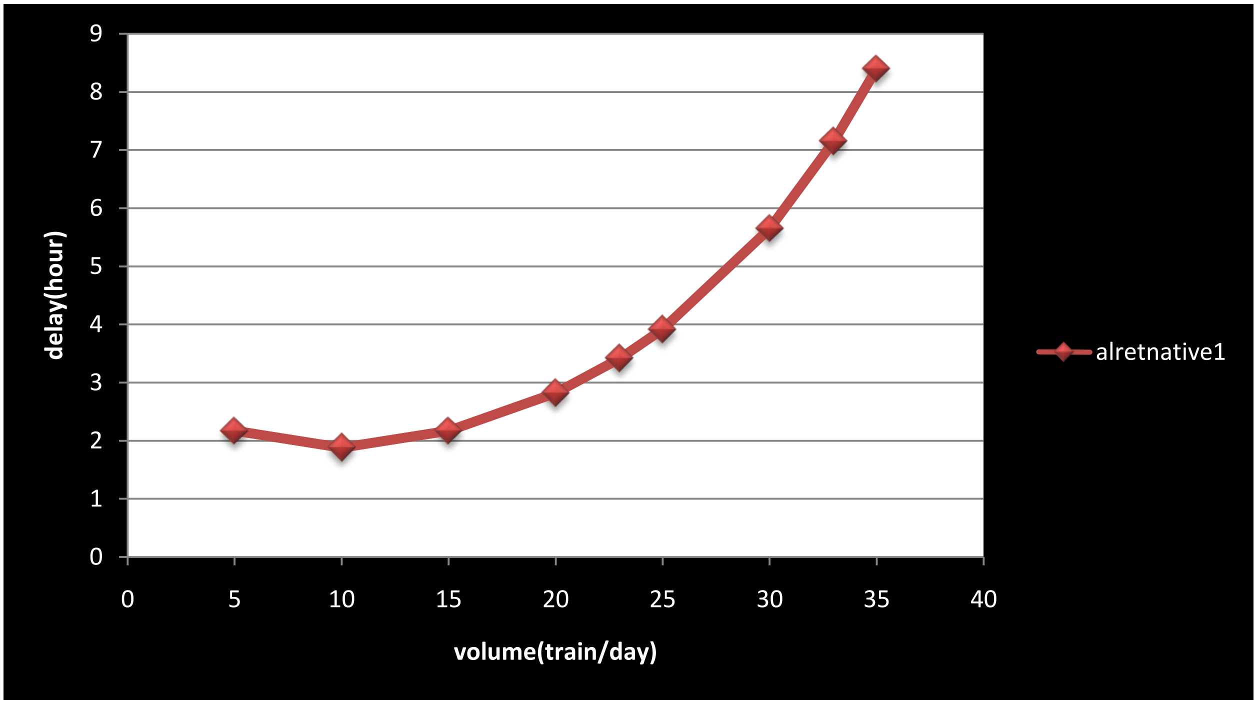


Figure 25 Delay-Volume Plot for TPF=1.4

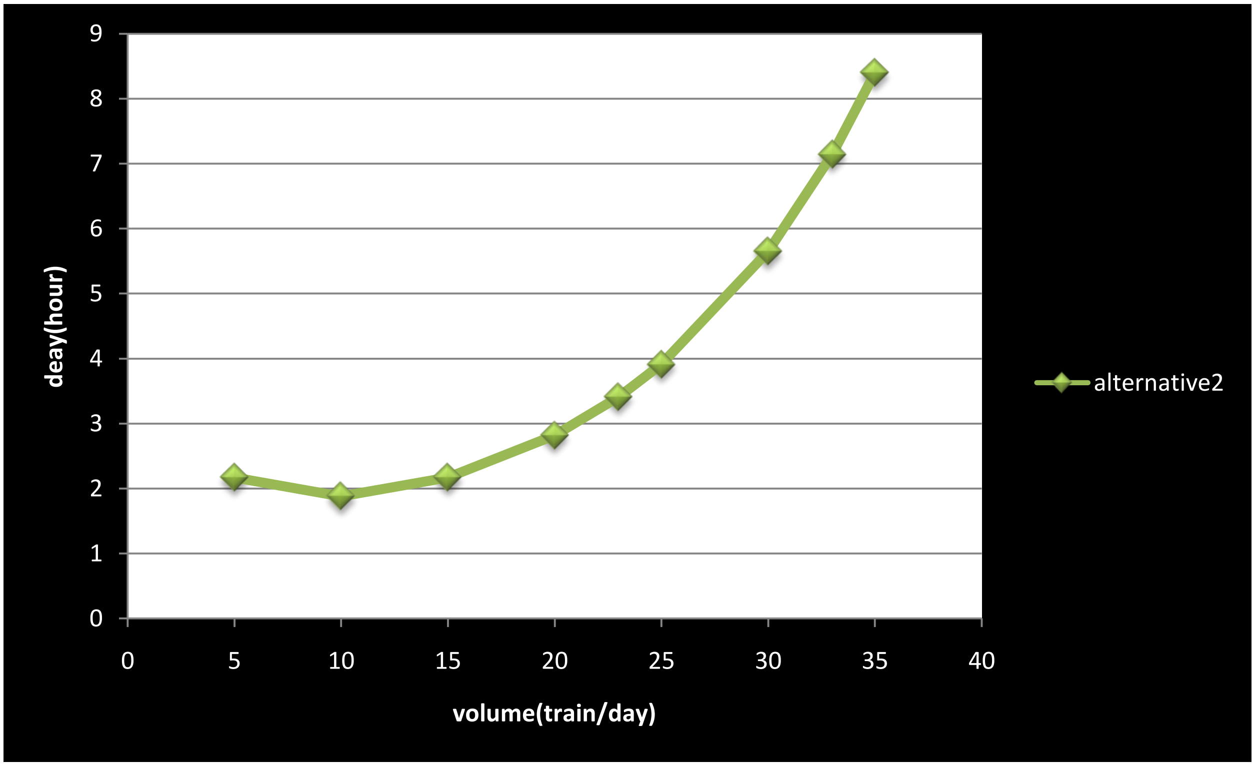


Figure 26 Delay-Volume Plot for TPF=1.3

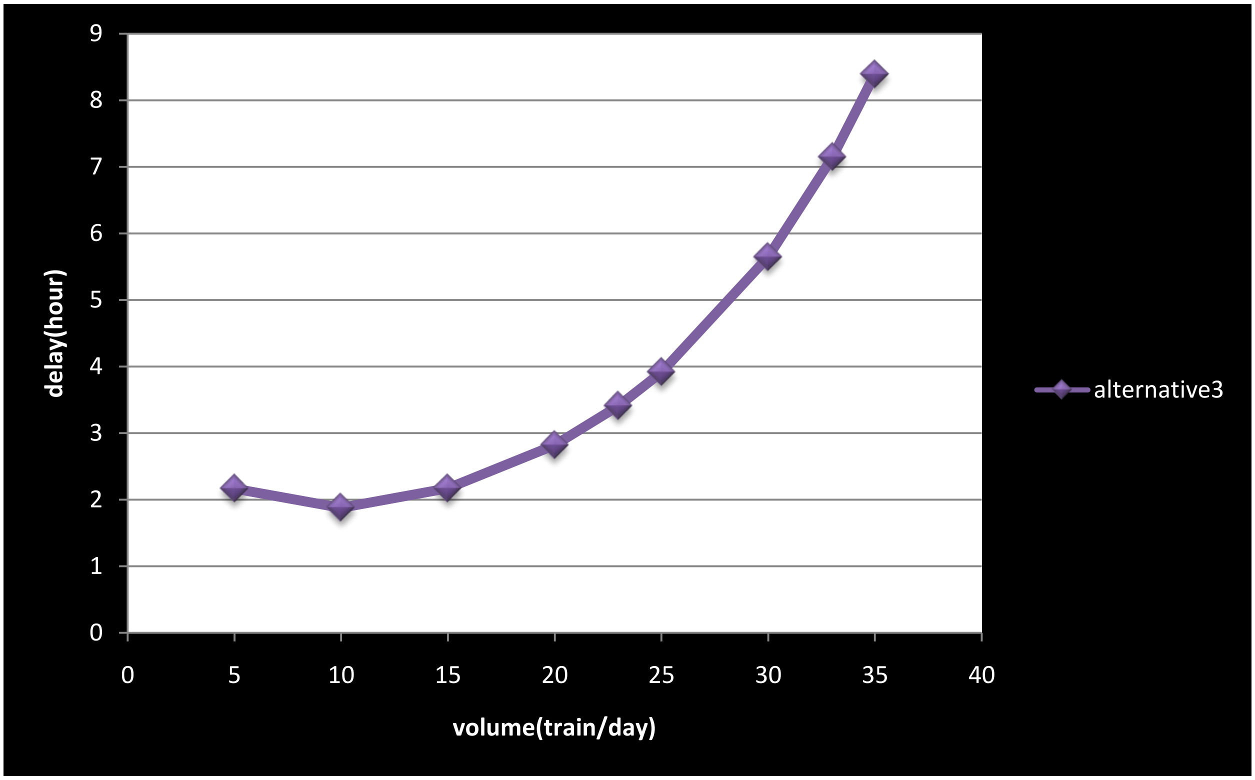


Figure 27 Delay-Volume Plot for TPF=1.2

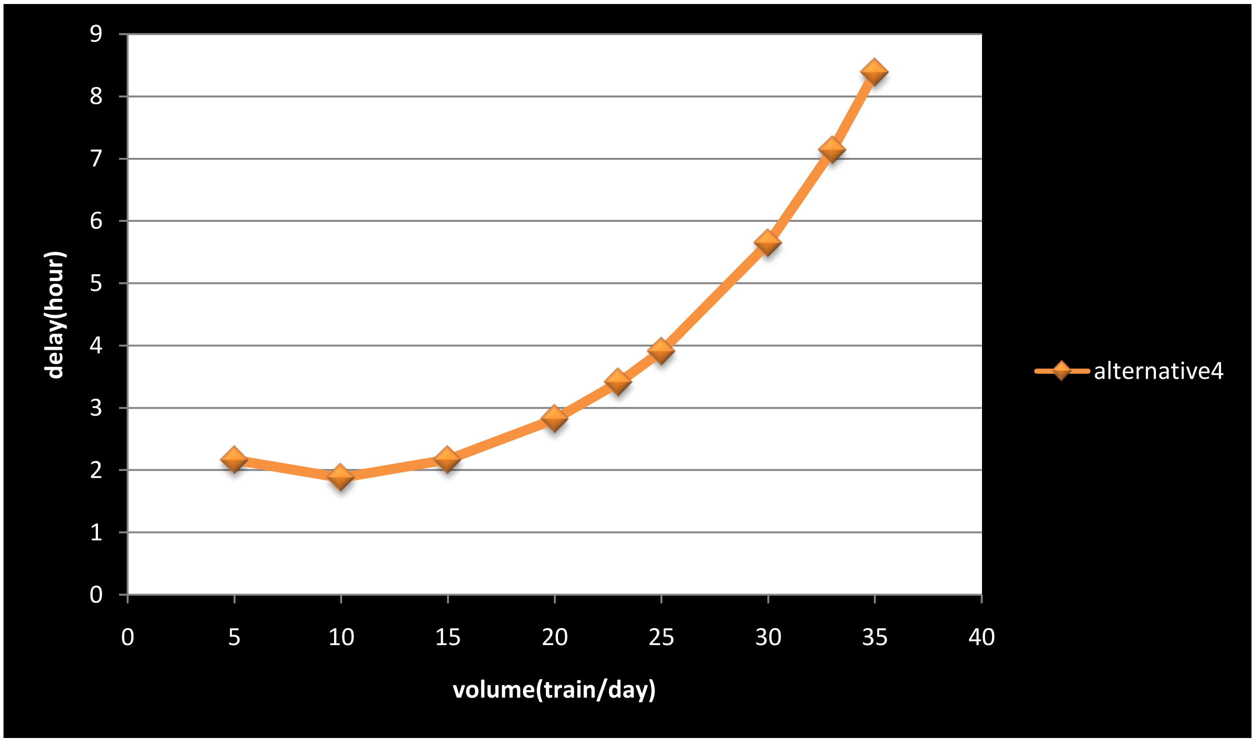


Figure 28 Delay-Volume Plot for TPF=1

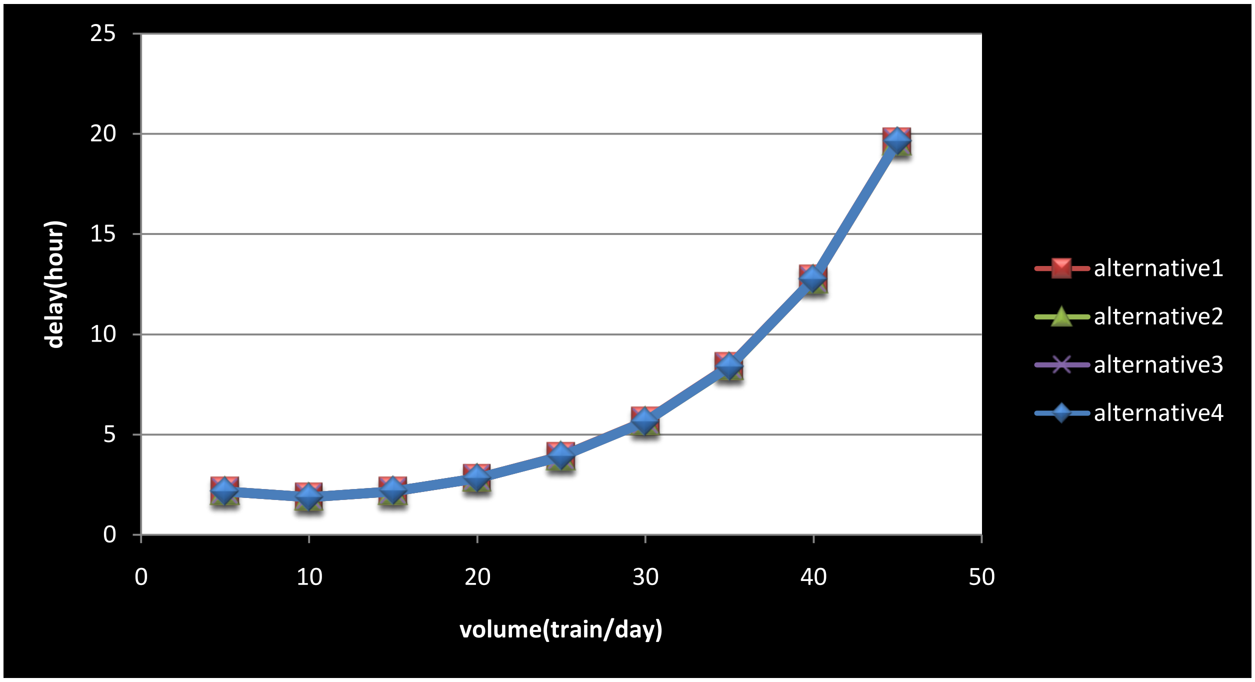


Figure29 Delay-Volume Plot for decreasing Peak Traffic Levels (TPF)

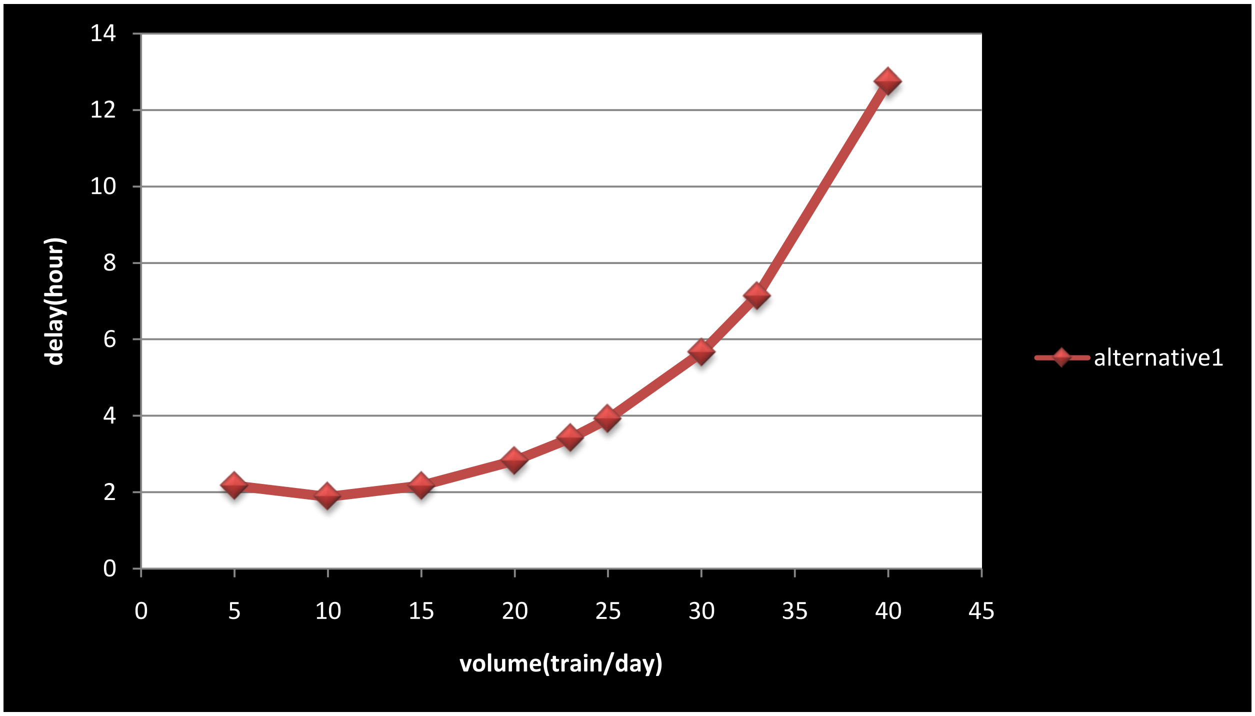


Figure 30 Delay-Volume plots for SR=1.7

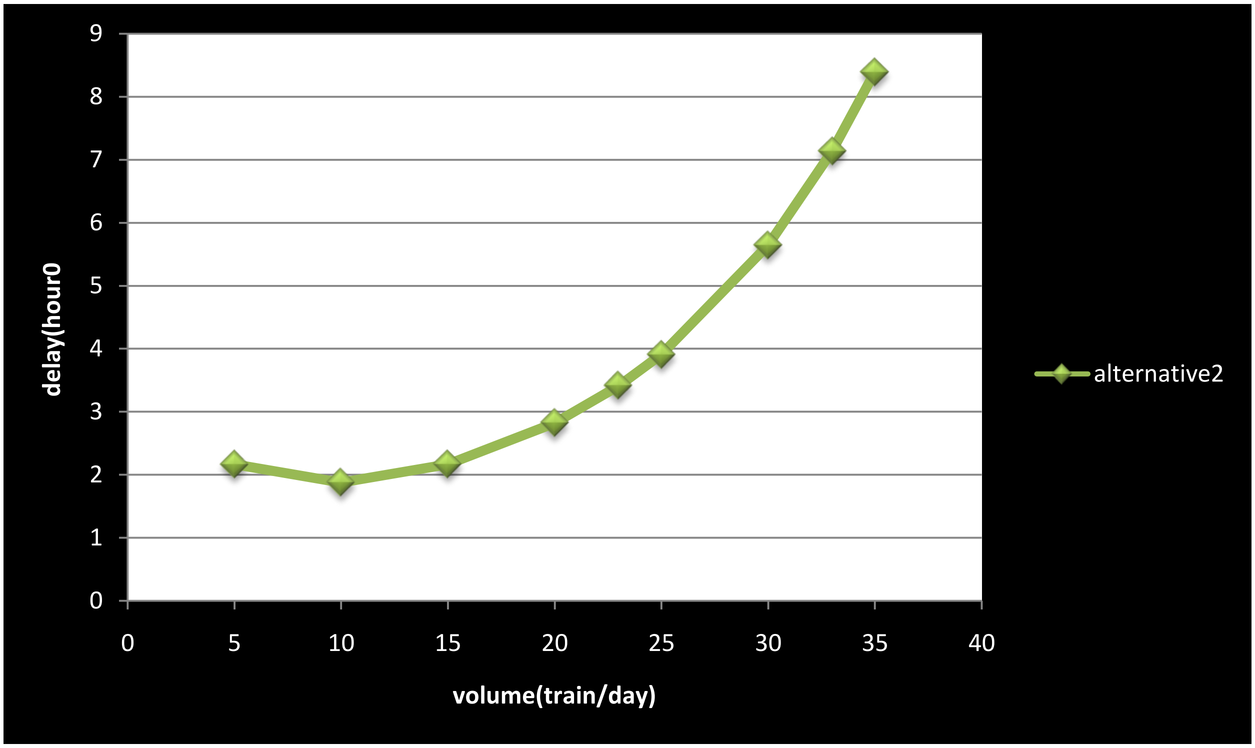


Figure 31 Delay-Volume plots for SR=1.6

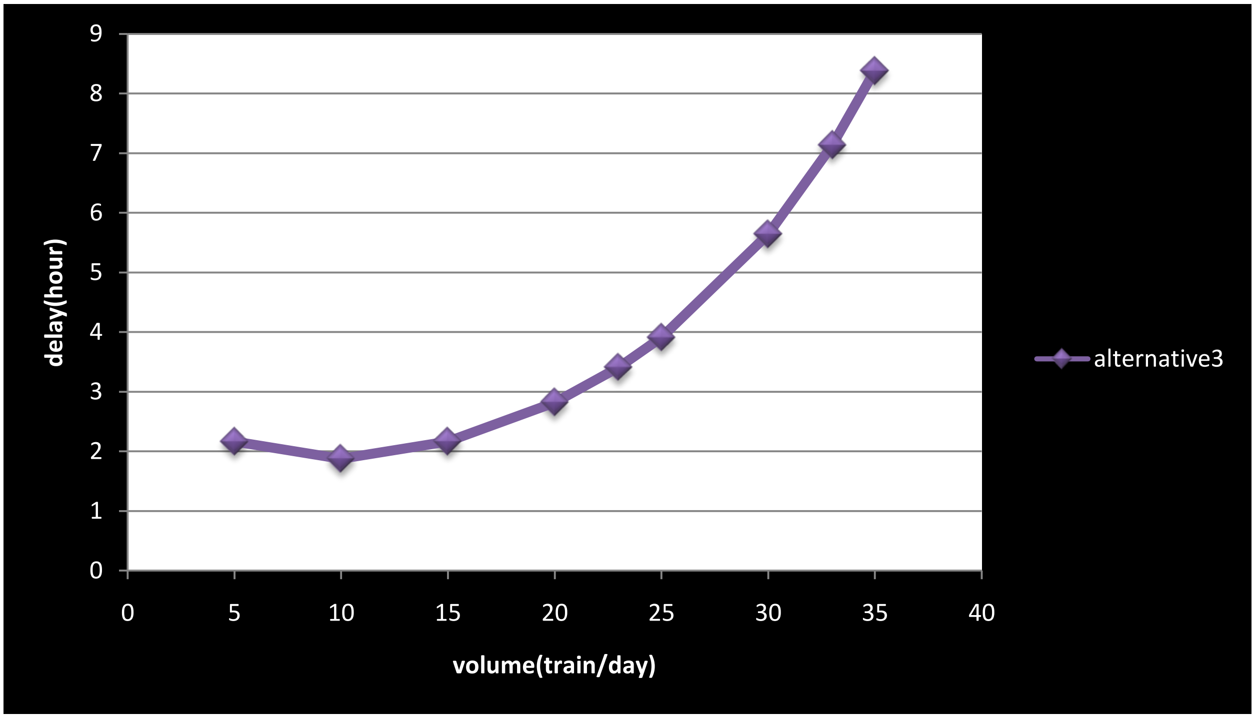


Figure 32Delay-Volume plots for SR=1.5

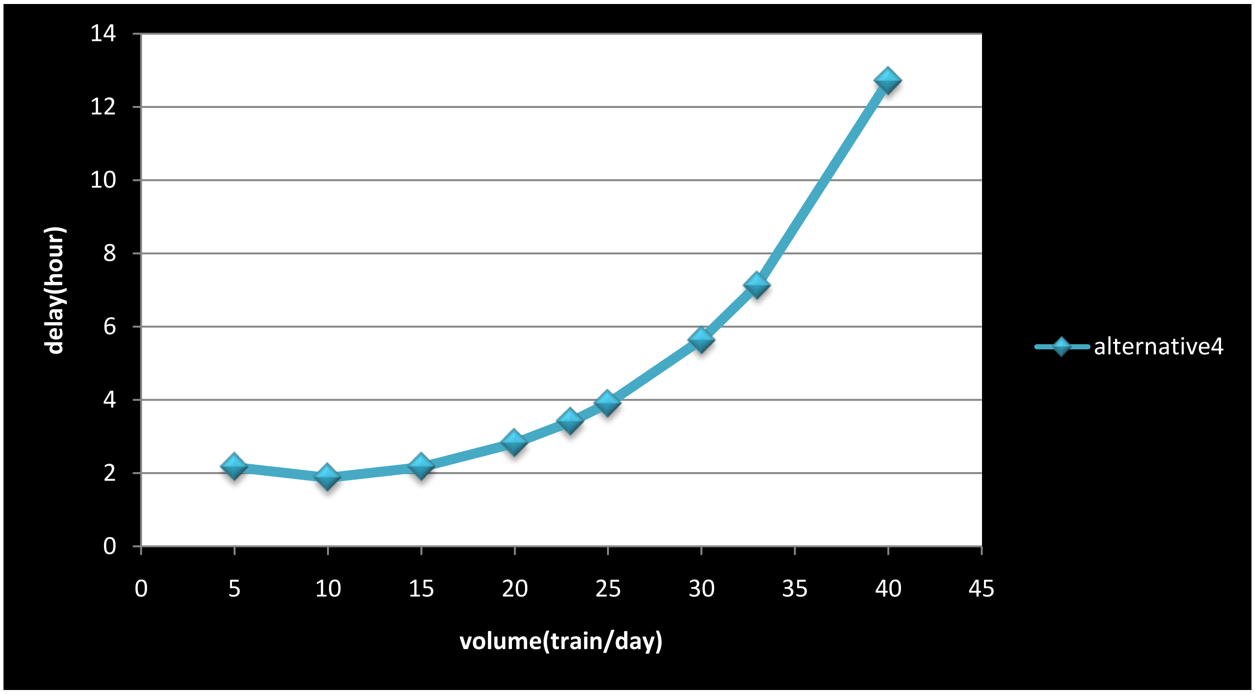


Figure 33Delay-Volume plots for SR=1.3

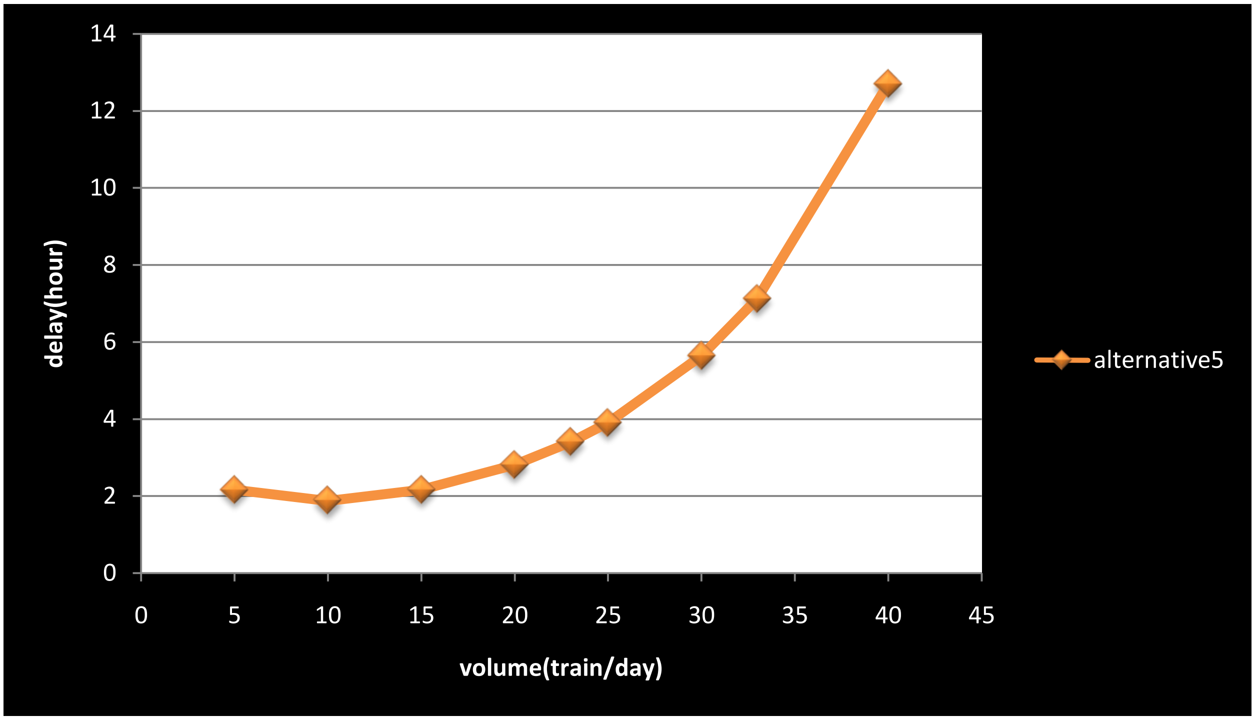


Figure 34Delay-Volume plots for SR=1

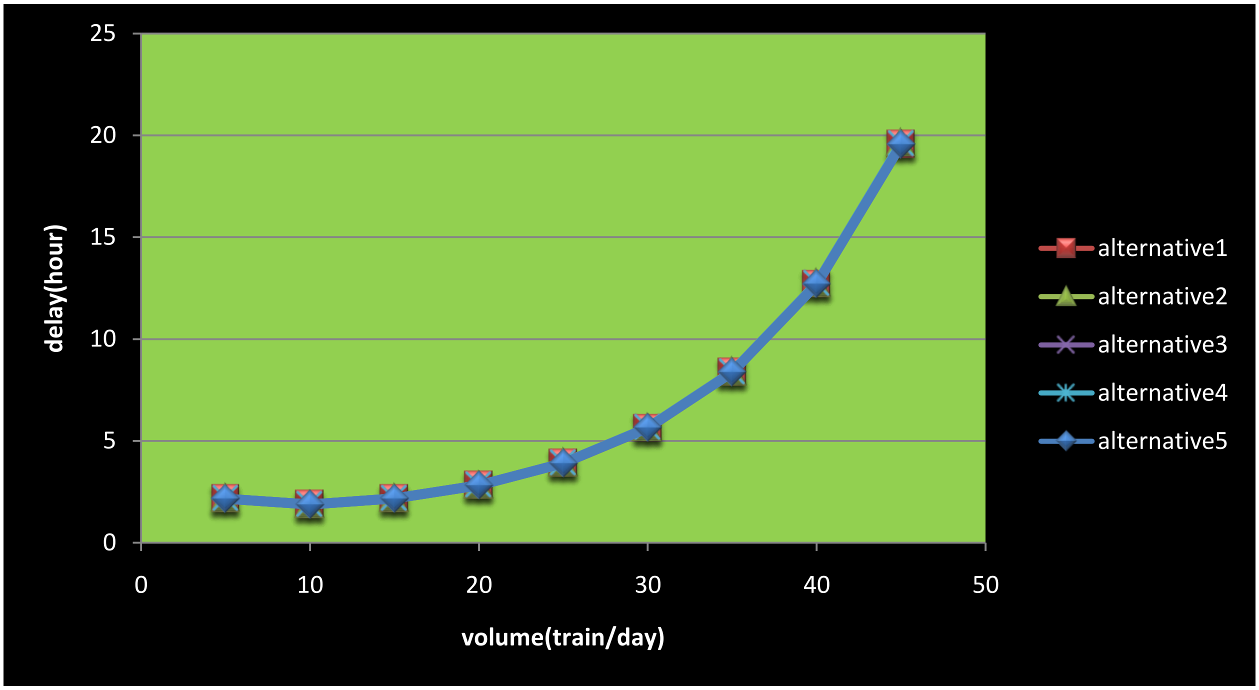


Figure 35 Delay-Volume plots for Reducing Heterogeneity in Speed (SR)

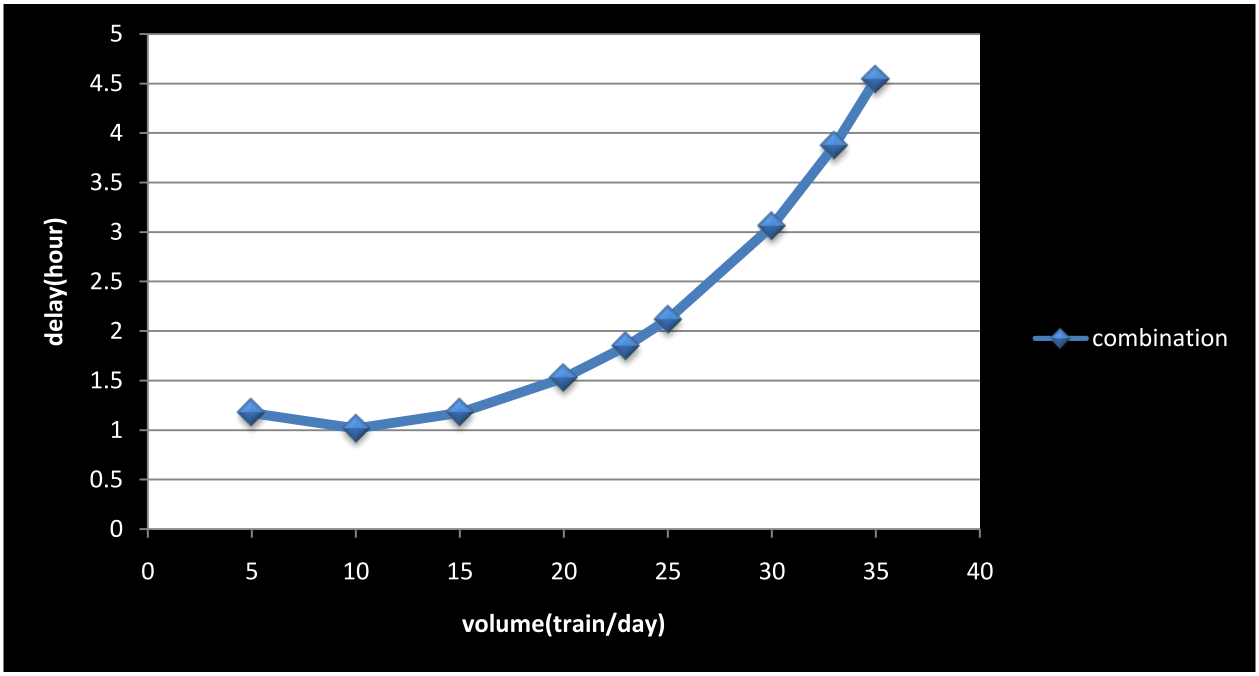


Figure 36a Delay-Volume Plot for best combination of plant and traffic alternatives (for beginning demand stage)

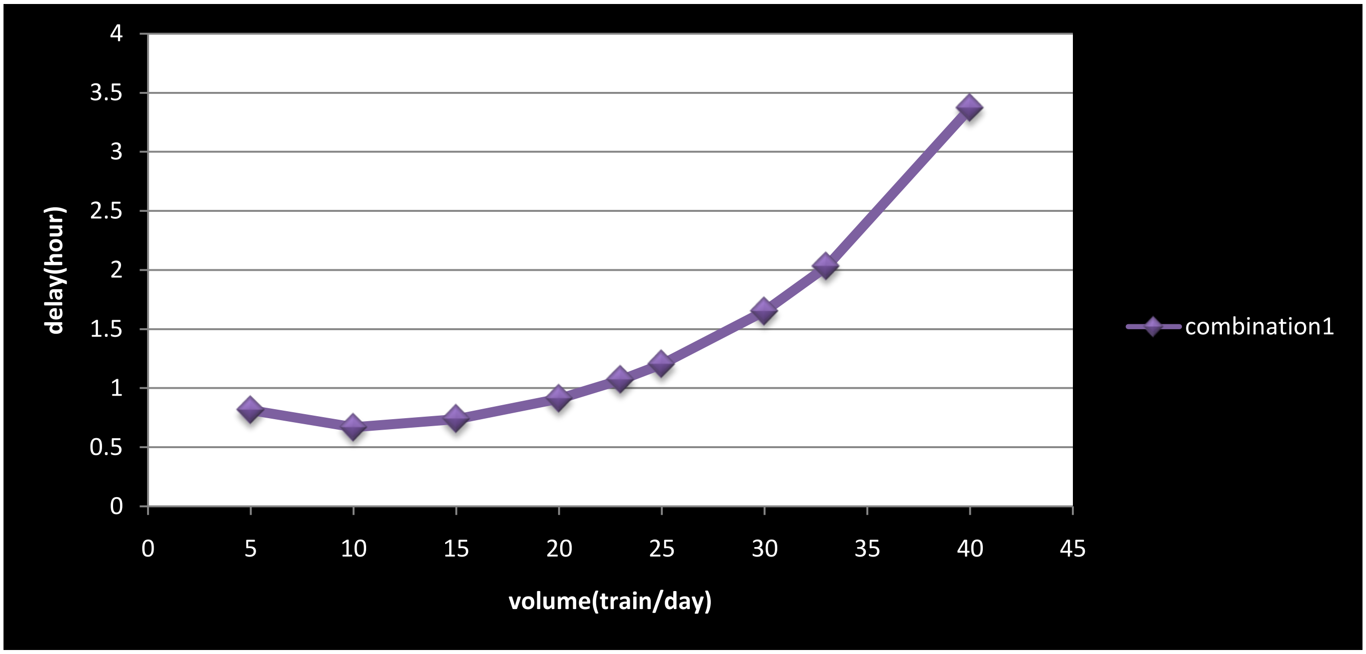


Figure 36b Delay-Volume Plot for best combination of plant and traffic alternatives (for short term demand stage)

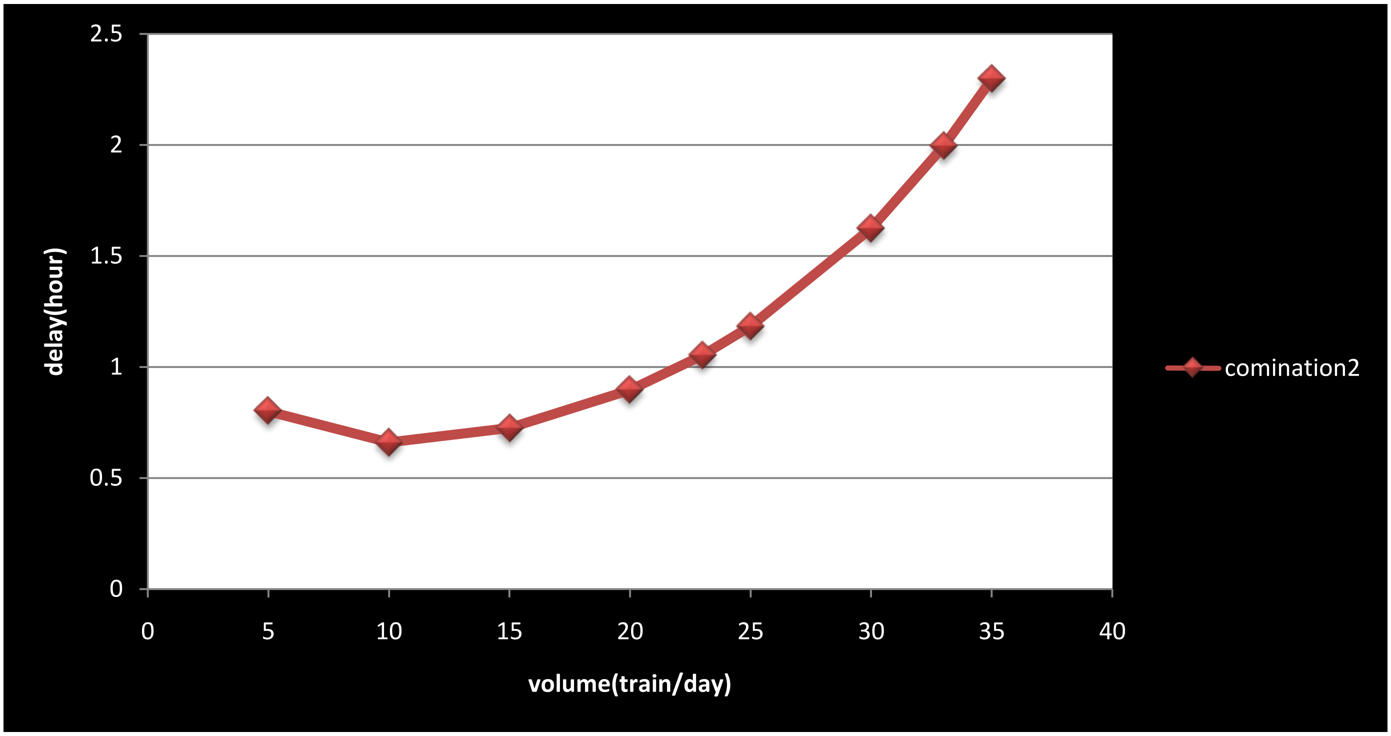


Figure 36c Delay-Volume Plot for best combination of plant and traffic alternatives (for short term demand stage

5.2.1. Impacts of Train Type Heterogeneity

Railroad capacity is influenced by a complex relationship of infrastructure and operational parameters. Operational factors include: average and variability in operating speed, traffic volume, stability, terminal efficiency and heterogeneity in various train characteristics. These are interrelated with, and further influenced by, infrastructure characteristics such as: siding length and spacing, crossover spacing, number of tracks, signal and traffic control system, grade, and curvature.

With heterogeneous traffic, delay is also caused by conflicts that occur as a result of differences in train characteristics, some of which also increase meet frequency and duration. Additional sources of delay with heterogeneous traffic include:

- Train delayed by a slower train
- Train delayed by a train with slower acceleration
- Trains experience longer meets waiting for higher priority trains
- Train delayed waiting for another train to pass
- Trains experience more meets due to lower average speed, which can be caused by lower speed, lower power and/or lower priority.

The magnitude of these delays is dependent on the specific train mix, volume and amount of heterogeneity. Operational changes were considered as methods to reduce train delay due to heterogeneity.

Capacity planners usually have an idea of the current line capacity based on empirical experience. These empirical values can be used to determine the current LOS (=acceptable delay) by adjusting the acceptable delay to match the capacity values from the delay-volume relationship. If empirical values are not available, the default setting is to use the maximum trip time of 10 hours or an acceptable delay of 2 hours to calculate the capacity *[8, 22]*.

I. Evaluation of Model Idealized Existing Operation

Table 5 Delay-Volumes Relationship for Idealized Existing Operation

Volume (train/day)	10	15	17	20	23	25	33	40	43	45
Delay (hour)	1:28	1:45	1:59	2:25	3:00	3:30	6:44	12:19	16:04	19:12

As we have seen from fig.17 and since the base of this study is Addis Ababa/Sebeta – Djibouti New Standard Gauge Railway Project Feasibility Study Report, to attain the line capacity forecasted (23train/day) for the beginning ,one must wait for the train about 3:00 hour.
And to attain the short term line capacity (33 train/day) it is needed to wait about 6:44 hour, which is the worst.

So, the delay-volume plot helps users determine the additional capacity provided by each alternative with a specific LOS (=acceptable delay). It also demonstrates what the capacity will be if the threshold for acceptable LOS is increased or decreased. The capacity of this model ideal operation is about 17 trains per day with a 1:59-hour average delay which is equivalent to LOS.

Then for this implication, the subdivision’s current capacity is about 17 trains per day with specific LOS, and the estimated future demand is 23 trains per day for the beginning, and 33trai/day for short term demand. So the question is how to increase capacity by 6 trains per day and 16train/day respectively.

According to the input data in Table 5, CN PARAMETRIC MODEL generates possible expansion alternatives by adding sidings, increasing uniformity, Reducing Heterogeneity in Speed, decreasing Peak Traffic Levels, and decreasing (Removing Priorities) with their increases in capacity. So, this study has developed different alternatives to attain the estimated future demand with increasing capacity.

II. Adding New Sidings

Among the different alternatives, the larger the difference between two alternatives, the greater the difference in capacity performance will be. For instance, there is a substantial difference between the existing alternative1 (which is modeled an ideal existing operation) and any of the other alternatives. As we have seen from fig.18, as the number of additional sidings is increased, the capacity of the line increased. For instance, alternative2 has 1:52 hour delay to attain 23train/day line capacity and will delay about 6:16 hour for short term demand.

The following table will show the relation between number of sidings and delay with respect to demand forecasted on Addis Ababa/Sebeta – Djibouti New Standard Gauge Railway Project Feasibility Study Report.

Table 6 Summery of Addition of Sidings on Future Demand Capacity

Alternatives	Demand Stages		
	Beginning (for 23tain/day) Delay(hour)	Short Term (for 33train/day) Delay(hour)	Long Term(for 57train/day) Delay(hour)
Alt2	1:52	4:16	38:15
Alt3	1:25	3:33	31:36
Alt4	1:14	3:10	28:36
Alt5	1:11	2:56	26:40
Alt6	1:06	2:47	25:31
Alt7	1:03	2:39	24:21
Alt8	0:58	2:33	23:35
Alt9	0:43	1:51	12:44
Alt10	0:40	1:38	12:43

From the above table, we can see that, to attain the first stage line capacity alternative 2 is the best option which is accompanied by adding one siding within 100 miles subdivision. For the record all alternatives have increasingly very effective line capacity without considering its construction cost.

In the case of short term demand stages, alternatives 9 and 10 have 1:51 and 1:38 delay hour could save 0.09 and 0.12 hours respectively for the van age of LOS. On the other hand, when we come to the long term demand stage, to attain the respective capacity considering adding sidings only is not enough.

III. Reducing Peak Traffic Levels (TPF)

Traffic density and higher delays due to heterogeneity are directly related. If traffic can be more evenly distributed throughout the day total train delay can be reduced. As it is indicated through figure 25 up to 28, TPF (concentration of traffic within a short time frame) values from1.4 to1 has been considered for this study. Delays were reduced in all traffic configurations as we have seen from Figure 25. As TPF decreases the line capacity has been increased little. For this case the last alternative (TPF=1) is has been founded to be the best alternative by giving 2:56 hour delay time for beginning demand stage, and providing 6:42 hour delay time for short term demand stage which is illustrated as alternative 4 in the figure 24 and in table 7. There is typically an exponential relationship between delay and volume and higher volumes correspond to smaller headways. Due to the exponential nature of this relationship an increase in headway may result in a disproportionately larger reduction in delay. Smaller headways result in more meets and increase the possibility of a following train being delayed by a preceding train.

Table7 Delay-Volumes Relationship for TPF=1

Volume (train/day)	10	15	20	23	25	30	33	35	40	43	45	50
Delay (hour)	1:19	2:44	2:16	2:56	3:25	5:08	6:42	7:55	12:11	15:58	19:05	30:03

Increasing headways provides benefits to all train types under all traffic mixes and will increase reliability, by increasing the ability to absorb delays due to typical operational incidents. To increase headways trains must be rescheduled in order to more evenly distribute traffic over the day. This requires planning and may require changing yard operations and other factors affecting scheduling in order to release trains at different times. Reducing peak traffic levels to reduce delay due to heterogeneity has benefits under all traffic conditions and should be among the first options considered as a way to increase capacity.

IV. Reducing Heterogeneity in Speed (SR)

Heterogeneity in train speed leads to additional conflicts between traffic. To test the influence of heterogeneous speeds on delay the speed ratio between 1.714(which is speed ratio of modeled practical operation) and 1 has been considered, while all other parameters were held constant (figure 30 to 34). For this case the last alternative (SR=1) is has been founded to be the best alternative by giving 2:58 hour delay time for beginning demand stage, and providing 6:43 hour delay time for short term demand stage which is the same result with REDUCING PEAK TRAFFIC LEVELS and illustrated as alternative 5 in the figure 35 and table 8. Reducing the speed of the intermodal traffic eliminates the speed difference among the train types thereby making them more homogeneous and reducing delay. When trains travel at different speeds both the faster and the slower trains may be delayed. The faster train will be delayed when it approaches a slower train and must reduce speed to maintain a safe headway until it reaches a siding and can pass. The slower train will be delayed while waiting to be passed and due to the more frequent meets at higher volumes, these trains may never be able regain top speed between sidings. Therefore reducing their maximum speed will have little effect on the observed run time and greater homogeneity in speed will not affect capacity. When combined with a decrease in maximum speed this results in increased run times and thus reduced capacity.

Table 8 Delay-Volumes Relationship for SR=1

Volume (train/day)	10	15	20	23	25	30	33	40	43	45	50
Delay (hour)	1:20	2:46	2:18	2:58	3:27	5:10	6:43	12:13	16:00	19:01	30:04

Heterogeneity in speed creates the need for overtakes and passes. However, the results of the CN parametric model that reducing this heterogeneity had little or no benefit, and might even reduce overall line capacity due to lower speeds. It is unlikely that the benefits of reduced delays will offset the increased run times. Additionally, the reduction in speed may not change operations if, as happens with high volumes, trains never get to their top speed due to the many meets. However there may be additional, non-capacity benefits including reduced fuel consumption. If train speeds can be increased instead of reduced, the benefits will be greater; however, it may not be possible without additional locomotives.

V. Removing Priorities (DPF) and Increasing Uniformity (MPPPU)

The last characteristic considered was the dispatching priority assigned to trains. Passenger trains with their higher value merchandise and greater customer demand for fast, reliable service are typically given higher priority by railroad dispatchers. To test the effect of differential train priority on capacity, the dispatching priorities were removed for the two train types. In the baseline scenario, delay increased with increased heterogeneity. As it is indicated on figures 19 to 22, when individual train-type priorities were removed the delay decreased as we have seen from fig.23 and 24. For this case the last alternative (DPF=0) is has been founded to be the best alternative (as indicated on table 9) by giving 3:02 hour delay time for beginning demand stage, and providing 6:47 hour delay time for short term demand stage which is the same result to reducing MPPPU (fig.23 increasing uniformity which is the measurement of uniformity in siding spacing). When there are no priorities the first train to reach a siding will enter it for the meet. However with differential dispatching priorities the lower priority train may enter an earlier siding in order to prevent delays to the higher priority on-coming train. This will result in greater dwell times for the lower priority train and increase overall delay.

Table 9 Delay-Volumes Relationship for DPF=0 or MPPPU=0

Volume (train/day)	10	15	20	23	25	30	33	40	43	45	50
Delay (hour)	1:24	2:50	2:22	3:02	3:31	5:14	6:47	12:17	16:04	19:05	30:08

Removing differential train priorities and increasing uniformity was effective method of reducing average train delay. Removing dispatching priorities has no additional cost but the increased run times for the higher priority traffic may be unacceptable to customers. This method is most effective when the higher priority trains are a majority. In this model removing priorities, prevents lower priority trains from having excessive delays due to more and longer meets and passes.

VI. Best Alternatives for Beginning Demand Stage

As we have seen from table 10 below, 23train/day which is the beginning demand stage has been attained by 1.51hour. This mean if we construct one siding, and making (TPF=1, DPF=0, MPPPU=0 and SR=1) we can even improve the LOS (fig.36a). Beyond that we could attain 25tain/day within 2:02 delay hour by gaining additional three trains in addition to six trains (= 9trains/day) with combination of these alternatives.

Table 10 Best volume-delay alternatives for beginning demand stage

Volume (train/day)	10	15	20	23	25	30	33	35	40	45	50	57
Delay (hour)	1:00	1:10	1:28	1:51	2:02	3:02	3:46	4:30	6:48	10:34	16:31	31:22

VII. Best Alternatives for Short Term Demand Stage

As we have realized from previous discussion, beyond its construction cost, increasing sidings evenly is the most satisfactory parametric option for capacity improvement. Likewise, the tables below indicate this reality helpfully.

Table 11A best volume-delay alternatives for short term demand stage

Volume (train/day)	10	15	20	23	25	30	33	35	40	45	50	57
Delay (hour)	0:16	0:20	0:30	0:40	0:48	1:08	1:37	1:55	2:57	3:26	6:06	12:28

The outcomes in table 11A are modeled by considering eight sidings with other parameters which are mentioned as best of each alternative (fig.36b). So we could see that for short term demand stage, the delay time is reduced to 1:37 hour which saves 0.13 hour for waiting compared to LOS. In addition to that, we could get a capacity of 2trains/day with 1:55 delay hour beyond the required 16 trains (= 18trains/day). With nine sidings and the same other alternatives like table 11A, the delay hour could came 1:16 by taking the van age of 0.34 delay hour as table 11B shows. With 2:02 hour we can even add 4trains/day on the demanded 16trains/day (20trains/day) and we could of make the line capacity over satisfactory (fig.36c).

Table 11B best volume-delay alternatives for short term demand stage

Volume (train/day)	10	15	20	23	25	30	33	35	37	40	45	50
Delay (hour)	0:11	0:15	0:24	0.38	0.47	1:10	1:16	1:07	2.02	2:25	3:00	5:58

5.2.2. Summary of Discussion

The increased delays due to heterogeneity are caused by a combination of factors including headway, difference in speeds, sidings, uniformity and priorities. Changing any of these can reduce delays and potentially increase capacity. However operational changes can also result in higher costs. The tradeoff between practices that reduce delay to freight trains but increase delays to passenger traffic needs to be carefully considered. These methods have the potential to help in niche environments and to relieve short-term capacity constraints.

For the beginning, the subdivision's current capacity has been calculated and is about 17 trains per day with specific LOS, and the estimated future demand is 23 trains per day for the beginning and 33trains/day for short term. And the specific additional demand has to be 6 trains per day and 16train/day respectively.

For this capacity desire increasing headways, removing dispatching priorities, reduces the number of meets, equalizing train speeds, and increasing uniformity were effective method of reducing average train delay by shortens the time lost in meets and pass. But adding siding could have relatively great assurance to attain the required capacity. To attain the first stage line capacity alternative 2 is the best option which is accompanied by adding one siding within 100 miles subdivision and all alternatives have increasingly very effective line capacity without considering its construction cost. In the case of short term demand stages, alternatives 9 and 10 have 1:51 and 1:38 delay hour.

After all if we could add one new siding within 100 miles subdivision, and making (TPF=1, DPF=0, MPPPU=0 and SR=1), 23trains/day which is the beginning stage demand can be attained with 1:51 delay hour and we even could improve the capacity to 25trains/day with 2:02 delay hour by adding 2 trains beyond the required 6trains/day. For the short term constructing eight siding, and making (TPF=1, DPF=0, MPPPU=0 and SR=1), within 1:37 delay hour, it is possible to gain additional 16trains/day with saving unexpected 0.13 hour for waiting. Beyond that without exceeding the LOS, i.e. with 1:55delay hour we can even add another 2train/day, totally 18trains/day. With adding one siding, and making it nine sidings within 100 miles subdivisions and kipping other alternatives the same, we could improve the capacity to 37trains/day with 2:02delay hour adding 4trains/day on the required 16trains/day. And in this case we could attain the required capacity range by using effective time tables and schedules.

On the other hand, when we came to long term demand, the respective capacity considering increasing headways, removing dispatching priorities, reduces the number of meets, equalizing train speeds, increasing uniformity and even adding sidings only is not enough unless we consider constructing another track to make the single-truck double.

Chapter Six

Conclusions and Recommendation

6.1. Conclusion

The project, short and long-term demand for rail freight transportation and expanded rail passenger service on Ethiopia - Addis Ababa-Djibouti railroads will require considerable capital investment in new infrastructure. Investing this capital efficiently requires understanding the different operational characteristics of the intended traffic and consideration of possible operational changes that will enable more efficient use of infrastructure.

I performed analyses using time-space diagram to model the ideal existing operation and CN parametric model was used to investigate the impact of various operational changes on differing levels of heterogeneity, since it is a major source of delay and understanding how the characteristics of new traffic will affect capacity is vital to capacity planning, on a hypothetical signalized, single-track rail line using delay as capacity metric unit.

From time- space diagram model results, double-tuck lines yield almost three times as much as the one for single-track without side tracks. And this value with respect to the forecasted first, short and long-term feature demands would indicate that, the modeled double-truck could have the required capacity without longer improvements.

For desire capacity, separately, increasing headways, removing dispatching priorities, reduces the number of meets, equalizing train speeds, and increasing uniformity were effective method of reducing average train delay by shortens the time lost in meets and pass. But adding new siding within 100 miles subdivision could have relatively great assurance to attain the required capacity for first stage and short term demand stages, which implies that possibility of infrastructure changes to increase the demands on single-truck lines be considered as an option due to the effectiveness even if longer times to implement and generally higher capital investment needed.

Since on a single-track route, the main source of delay and principal consumer of capacity are meets and passes; therefore, to improve capacity, the number of, or delay during, meets or passes must be reduced. So, best operational factors combining with infrastructure factors especially adding new sidings which has been effective method of reducing average train delay by shortens the time lost in meets, the feature demand could be attained and would greatly improved.

For the record operational changes have the advantage that they can be implemented more rapidly than infrastructure changes offer more flexibility in response to changing traffic levels and patterns, may provide relief during short periods of high traffic volumes, or as an interim measure while additional infrastructure is built and generally lower capital investment needed, even if infrastructure changes has a vital and in compensable effective benefit.

6.2. Recommendation

For Adama-Djibouti (single track) line within 100 miles subdivision, I highly recommend that to have least one siding to attain the required capacity for first stage and side tracks should be located in equidistance manner to have relatively great assurance to attain firs and short term demand stages with additional new sidings in combination with effective operational changes. On the other hand to attain the long term demand we should deal with infrastructure factors, especially constructing new additional rail-truck, on this Adama-Djibouti singe-truck line beyond the improvement of operational factors. Even if operational and infrastructure changes could provide benefits due to reduced delays and increased capacity; however, they come with additional costs and this tradeoff should to be considered especially in constructing new sidings.

For future research direction, more related operating variables should be added for more realistic scenarios and the following ideas should be considered.

1. Since, in practice, side tracks could be expensive and could not be built at all strategic locations, the benefit-cost analysis of adding more side tracks and finding the most economically suitable locations could be useful for rail transportation planners and designers
2. Including adding new intermediate signal as one of the alternatives on the model development, since adding signals is usually less expensive than adding new sidings.
3. Instead of modeling an ideal operation, using an actual railroad route and traffic volumes for case study with computer simulation to investigate the stochastic effect of independent variables as well as do sensitivity analysis.

Reference

1. Ambre, R. (2005), Capacity Studies on Transportation Network, Master Thesis, Industrial Engineering and Operation Research. IIT Bombay, Mumbai.www.dlib.aait.edu.et
2. Geological Map of Ethiopia(2nd edition)
3. Harrod, S. (2009), Capacity factors of a mixed speed railway network, Transportation Research E, 45, 830-841
4. Johri, M. (2003), Railway scheduling and Capacity Planning: A Simulation Based Approach, Master's Thesis, Interdisciplinary Program in Industrial Engineering.
5. Ethiopian Herald. 10 March 2013.
6. Railways Africa. 2 October 2013. Retrieved 2013-11-25.
7. Vromans, M.J.C.M., Dekker, R. Kroon, L.G. 2006, "Reliability and heterogeneity of railway services", European Journal of Operational Research, vol. 172, no. 2, pp. 647-665.
8. Burdett, R. L., and Kozan, E. Techniques for absolute capacity determination in railways. Transportation Research Part B 40 (2006), 616{632}.
9. Gibson, S., Cooper, G., and Ball, B. Developments in transport policy: The evolution of capacity charges on the UK rail network. Journal of Transport Economics and Policy 36 (2002), 341{354}.
10. Koutsopoulos, H.N., Wang, Z., "Simulation of urban rails operations. Application framework", Journal of the Transportation Research Board No. 2006, Washington DC, pp 84-91, 2007.
11. Bronzini M.S. and D.B. Clarke. Estimating Rail Line Capacity and Delay by Computer Simulation, Tribune des Transports, Vol. 2, No. 1, 1985, pp. 5-11.
12. Gorman, M.F. Statistical Estimation of Railroad Congestion Delay, Transportation Research Part E, 2008, doi:10.1016/j.tre.2008.08.004
13. Kroon, L.G., Romeijn H.E. & Zwaneveld P.J., "Routing trains through railway stations: complexity issues", European Journal of Operational Research, vol. 98, pp. 485-498, 1997.

14. Liebchen, C., “Symmetry for periodic railway timetables”, Electronic Notes In Theoretical Computer Science, vol. 92, pp. 34-51, 2004.

15. Lindfeldt, O., “Evaluation of punctuality on a heavily utilized railway line with mixed traffic”, In: Allan, J., Arias, E., Brebbia, C.A., Goodman, C.J., Rumsey, A.F., Sciutto, G., Tomii, N., (eds.), Computers in Railways XI, pp. 545-553, WIT Press, Southampton, 2008.

16. Myers, R.H., Montgomery, D.C., Response Surface Methodology, John Wiley & Sons, Inc., USA, ISBN 9787-0-471-41255-7, 2002.

17. Nachtigall, K., “Periodic network optimization with different arc frequencies”, Discrete Applied Mathematics, vol. 69, pp. 1-17, 1996.

18. Schwanhäußer, W., “Die Bemessung der Pufferzeiten im Fahrplangefüge der Eisenbahn“. Veröffentlichungen des Verkehrswissenschaftlichen Instituts der RWTH Aachen, vol. 20, PhD Thesis, 1974.

19. Siefer, T., “Simulation“, In: Hansen, I.A., Pachl, J., eds. Railway timetable and traffic, ch. 9, pp. 155-169, Hamburg: Eurailpress, 2008.

20. Daganzo, C. F. (1997), Fundamentals of transportation and traffic operations, Elsevier, New York., pp. 1-33. Transportation Research C, 16, 232-245.

21. Mussone, L. and Calvo, R.W. (2013), an analytical approach to calculate the capacity of a railway system, accepted in the European Journal of Operational Research.

22. D’Ariano, A., Pacciarelli, D., and Pranzo, M. (2008), Assessment of flexible timetables in real-time traffic management of a railway bottleneck,

23. Törnquist, J., “Railway traffic disturbance management – An experimental analysis of disturbance complexity, management objectives and limitations in planning horizon”, Transportation Research, A 41, pp. 249-266, 2007.

24. Törnquist, J., Persson J. A., “N-tracked railway traffic re-scheduling during disturbances”, Transportation Research, B 41, pp. 342-362, 2007.

25. Abril, M., Barber, F., Ingolotti, L., Salido, M.A., Tormos, P. and Lova, A. (2008), an assessment of railway capacity, Transportation Research E, 44, 774-806.

26. Harrod, S. Rail Capacity and Management Planning, Ph.D. Dissertation, Department of Quantitative Analysis and Operations Management, University of Cincinnati, Cincinnati, OH, 2007.

Appendix

Appendix1

Parametric model calculations for modified ideal existing operation:

$$Train\ Delay = A_o e^{B_o V}$$

Where:

A_o = Parametric Plant, Traffic, Operating Coefficient

B_o = Constant (=.11)

V = Traffic Volume (trains/day)

Ao = Plant + Traffic + Operation

Parameters

Plant	*SL*	*MPPPS*	*MPPPU*	*ISSR*	*%DT*
	100miles *(160.9344km)*	*No*	*0.3*	*1*	*0.04*

Traffic	TPF	DPF	SR	AS
	1.52	0.33	1.71	44mph

Operation	TO	TSO
	0	0

Appendix2

Parameters for adding passing sidings

$$Train\ Delay = A_o e^{B_o V}$$

Where:

A_o = Parametric Plant, Traffic, Operating Coefficient

B_o = Constant (=.11)

V = Traffic Volume (trains/day)

Ao = Plant + Traffic + Operation

Traffic + Operation = constraints

Plant = SL +MPPPS +MPPPU +ISSR + %DT

SL + MPPPU +ISSR + %DT = constraints

$$\text{MPPPS} = \frac{length\ of\ subdivision}{(number\ of\ MPPP + 1)}$$

$$number\ of\ MPPP = (1 - 9)$$

Appendix3

Parameters for best combination of alternatives:

$$Train\ Delay = A_o e^{B_o V}$$

Where:

A_o = Parametric Plant, Traffic, Operating Coefficient

B_o = Constant (=.11)

V = Traffic Volume (trains/day)

Ao = best alternative from Plant + best alternative from Traffic + best alternative from Operation

⇓

Best Railway Capacity