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SCHOOL OF MECHANICAL & INDUSTRIAL ENGINEERING

Thesis on
Railway Timetable Stability Analysis: Case of Addis Ababa LRT

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By

Asfaw Workineh

Advisor

Dr. Gulelat Gatew

ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF GRADUATE STUDIES
POSTGRADUATE PROGRAM IN RAILWAY MECHANICAL ENGINEERING
ADDIS ABABA UNIVERSITY

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Approved by Board of Examiners

____________________	____________________	________________
Chairman of Department Graduate Committee (DGC)	Signature	Date
Dr. Gulelat Gatew	____________________	________________
Advisor	Signature	Date
Dr. Birhanu Besha	____________________	________________
Internal examiner	Signature	Date
Dr. Mengistu H/mariam	____________________	________________
External examiner	Signature	Date

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Abstract

Recently, railway traffic has increased considerably in the different parts of the world; moreover, it is expected that railway transportation will further grow for both passenger and freight transportation. These developments create needs to optimize both the utilization of the existing infrastructure and the coordination tasks inside the railway company. Specially, the process times at stations should be well monitored to deliver efficient services.

Railway timetable is affected by several factors. The fact that makes the case more serious is that a disturbance encountered one train may propagate to the whole network unless a timetable that absorbs the fluctuation has been designed. This makes the railway timetable to be the heart of railway operation. Hence, the thesis at hand is aimed to develop stability analysis method which is used to design more stable timetable to handle the disturbances occurring to the railway network. In this research, both the interior and exterior factors that affect railway timetable stability were taken into account. In view of that, at the end of the research work, a model that is used to analyze trains timetable stability has been developed. The developed model is applicable to passengers' railway network like Addis Ababa LRT.

Keywords: Train timetable, stability, exterior factor, interior factor, information entropy, disturbance

Table of Contents

List of Tables

List of Figures

CHAPTER ONE

PROBLEM AND ITS APPROACH

1.1 Introduction

In the daily life of human being, there is the demand of travelling from one place to another to fulfill ones needs. Railway is one of the means through which people and goods can be moved from one place to another. As time passes, different innovations come in to place so that the earlier mode of railway transport is significantly improved and expanded. Researches in different countries have been carried out to adjust railway services to cope with the ever growing amount of people that are using the railway transport.

Railways typically operate according to a planned (predetermined) timetable, and the quality of the timetable determines the quality of the railway service. So, mapping out a high quality timetable for diverse trains is rather important. Therefore, to ensure both the capacity and the order of the train operation, it is necessary to work out a stable and robust timetable. The stability of a timetable is the availability that the timetable can afford for the trains to recover the situation that they run as the timetable has stipulated after the trains are disturbed when running. The robustness of a timetable is the capability of a timetable to counteract the disturbances and remain its original shape as planned.

A high quality timetable not only can decide the inbound and outbound time at stations, and more importantly, it offers the possibility to recover the operation according to the planned timetable when the trains are disturbed by accidents randomly. Timetable stability is the index to measure this possibility. Timetable stability is closely related to the train number assigned to the railway sections and the time supplement distributed to each station and section, the probability that the train is disrupted at the stations and in the sections

Since trains use a common guided rail, a slightly delayed train may cause a domino effect on consecutive delays over the entire network. But, from a stability point of view, a railway timetable must be insensitive with respect to small disturbances so that it can recover from small disruptions without external control. Hence, a self-regulating timetable behavior after disruptions requires a careful distribution of recovery times and buffer times to reduce delays and prevent delay propagation, respectively.

Therefore, the thesis at hand depends on the evaluation of stability of railway timetable that will benefit both the railway corporation/organization and passengers with train timetable stability evaluation based on analysis of interior and exterior information entropy method to measure timetable stability of railway operation of the Addis Ababa Light Rail Transit (LRT).

Figure 1: Addis Ababa LRT Route at design level [38]

The timetable stability is not only related to time but also the utilization coefficient capacity of the railway network. That is to say, the networked timetable stability study requires the combination of the railway network capacity utilization and the time supplement distribution in the sections and on the stations.

In general, cities with large, well-established rail systems have significantly higher per capita transit ridership, lower average per capita vehicle ownership and annual mileage, less traffic congestion, lower traffic death rates, lower consumer expenditures on transportation, and higher transit service cost recovery. This indicates that rail transit systems provide economic, social and environmental benefits, and these benefits tend to increase as a system expands and matures. Hence, the timetable stability which plays a key role in this aspect should be well analyzed in order to have a timetable of high quality.

1.2 Statement of the Problem

In the practical operations of railway, occurrence of disturbances to timetable may happen due to several factors. The contributing factors to these fluctuations may include: train entry area, crossings, takeover duration, station area occupations, blockings, interlocking, passengers conditions etc. lead timetable to fluctuate. The frequent occurrence of this fluctuation may cause abusing of the limited transportation resources obtained by high investments. On the other hand, although the transportation resources are sufficient, the resources will be wasted without well-designed distribution plan, which may lead to weak stability of the networked timetable. Hence, a way through which we can have reliable railway transportation services that benefits both the railway corporation and railway services users are highly required. So this requires conducting research on railway timetable stability. Accordingly, the following research questions were designed.

What are the factors affecting the Addis Ababa light rail transit timetable?

What technique helps to evaluate stability of the Addis Ababa light rail transit timetable?

What are the possible methods used to keep stability the Addis Ababa light rail transit timetable?

1.3 Objective of the study

General Objective:

The general objective of the study was to develop methodology to evaluate railway timetable stability in order to provide reliable railway transportation service and sustaining this timetable. The railway timetable stability analysis has been carried out by gathering data from different sources and analyzing them.

Specific Objectives:

The general objective of the study had been achieved in performing the following specific objectives. These include:

- Factors affecting stability of railway timetable have been identified.
- The effects of the factors on railway timetable have been analyzed.

- A model used to evaluate stability of timetable has been developed.
- The developed model was applied to Addis Ababa LRT and suggestion on the stability of LRT timetable has been given.
- A monitoring model used to keep stability of Addis Ababa LRT timetable has been developed.

1.4 Significance of the study

Railway timetable is the heart of a railway system. A problem occurred to a train may propagate to the whole net work and lead to rescheduling of the whole network. This leads to lessen the profitability of the railway corporation/organization. Hence, conducting continuous analysis of timetable will benefit both the customers and railway operating organization. In this way, the railway corporation/organization will safely undertake railway operation and can sustain in the competitive market.

1.5 Scope of the study

This study concerns railway operation in Ethiopia, mainly focusing on passengers' railway transportation (LRT in Addis Ababa city).

1.6 Limitations of the study

The study was aimed to focus on major factors that influence railway timetable stability. In that manner, factors contributing minor effects to railway timetable stability hadn't been exhaustively included.

1.7 Out Come of the Study

The study resulted in the finding of appropriate model to analyze stability of timetable of Addis Ababa LRT.

1.8 Organization of the study

In this study, the contents of the research works have been organized in six chapters. The first chapter deals with problem and its approach. This chapter covers the introduction, statement of the problem, objective of the study, organization of the study, significance of the study, limitations of the study and outcome of the study. Related literature review has been discussed in the second chapter. In the third chapter, methodology of the study has been presented. In this chapter approach to answer the statement of the problem has been outlined. The fourth chapter deals about data collection, presentation and analysis. Application of the research finding has been provided in the fifth chapter. Finally, conclusion and recommendations have been organized in the sixth chapter.

CHAPTER TWO

RELATED LITERATURE REVIEW

2.1 Introduction

In order to provide a reliable railway transportation service, the railway timetable should be stable. Hence, it is necessary to carry out analysis to set a timetable of higher stability. Railway timetable stability analysis is the analysis required to carry out to measure the property that a timetable is able to recover from disturbances (due to process time variations) without rescheduling.

According to [11], a master timetable is the backbone of scheduled railway systems and determines directly or indirectly effective railway capacity, traffic performance, and quality of transport service, passenger satisfaction, train circulations, and schedules for railway personnel.

By different researchers, several factors affecting timetable stability had been identified and also methods to measure the stability of railway timetable had been developed. These will be seen in the next subtopics.

2.2 Review of factors affecting railway timetable stability

2.2.1 Time supplements

The use of time supplements in railway timetables is a trade of between attractive travel times and punctuality levels [30]. Punctuality is a key performance indicator for timetables and time supplements are therefore applied in any timetable. Time supplements [4] can be found as running time supplements, dwell time supplements and buffer times between trains.

a. Running time supplement

It is the difference between the physically possible minimum running time and the used running time in the timetable – the scheduled running time. Regular running time supplements are added to every train path in the timetable [29]. They follow the used planning rules of the given railway infrastructure manager. The running time supplement is affected by the speed of travel of a train.

In this manner, as the speed of the train increases the magnitude of the time supplement should be also increased.

b. Dwell time supplements

For the timetable planner it is difficult to know how much dwell time a train needs at a given station. This varies throughout the day and also the weekday. The applied minimum dwell times in timetables are based on empirical data and the supplements are fixed values. Dwell times are not set for each single train but for entire train categories, such as intercity trains. Changes in dwell times can occur between time specific timetable patterns. Typically one timetable pattern is used for the early morning hours and a different pattern for the morning rush hour.

Most infrastructure managers apply time supplements to the dwell times of trains. This has several advantages. Dwell times of trains can be prolonged by school classes or handicapped people embarking or disembarking the train. Time supplements can absorb these variations. If a train arrives delayed to a station and only needs the planned minimum dwell time, it can reduce or eliminate its delay and depart less delayed or on time. At important transfer stations, dwell time supplements ensure that the planned transfer can be made even though one of the involved trains has a minor delay.

A precondition for being able to apply dwell time supplements is that there is enough station capacity available in the form of platform tracks. Dwell time supplements increase the utilization of platform tracks at a given station and can make it necessary to build in scheduled waiting time in the timetable when trains approach stations. This creates longer travel times.

Dwell time supplements themselves prolong travel times. As with running time supplements it is a trade of between attractive travel times and a robust timetable. Using a socio economic approach could lead to the finding of an optimal size of dwell time supplements at a given station.

c. Buffer times between trains

Additionally to running time and dwell time supplements, a timetable contains time buffers between planned timetable train paths. Normally, buffer times are put between any two pairs of trains following each other on a given railway line [31]. Buffer times reduce the risk of transferring delays between trains or they reduce the size of the knock on delay transferred from one train to the following train.

On railway lines with homogenous traffic with a high capacity utilization, such as metro systems, buffer times between trains are reduced to achieve a shorter headway between trains and instead a buffer path is introduced. If an incident occurs, causing small delays, the trains will run in a later timetable train path. Having one buffer path per periodicity time interval of the timetable gives an opportunity to absorb the delay before it spreads to widely in the railway system.

The use of time supplements in timetables is a trade of between attractive travel times and robustness of the timetable. When using a socioeconomic approach in combination with a railway traffic simulation tool such as RailSys or Open Track, it is possible to find an optimal size of the running time, dwell time and buffer time supplements in a given railway timetable for an investigated area.

Socioeconomic utility is calculated from the number of passengers in trains, their segmentation in passenger groups e.g. commuter, education or leisure travelers and the delays they are subjected to. Each passenger group is given a set of time values for one hour of travel time on a train, transfer time and delay. It is not socioeconomic feasible to construct timetables that are able to absorb very high levels of train delays since these occur rarely. A timetable should make it possible for trains to regenerate from smaller delays since these happen more frequently.

The international union of railways (Union International des Chemins defer = UIC) has produced a leaflet (UIC leaflet 451-1 OR) that provides its members with a series of recommendations in regards to the implementation of running time supplements in timetables. UIC recommends for all railway traffic the use of a fixed minimum running time supplement and an additional speed dependent percentage running time supplement. The size of supplements increases with speed. According to UIC, railway traffic has been divided into the following categories:

- Locomotive hauled passenger trains (≤ 300, 301-500, 501-700 and >700tons),
- Multiple units passenger trains,
- Freight trains,

For locomotive hauled passenger trains the UIC recommends a fixed 1.5min/100km distance based running time supplement plus a percentage increment as shown below. This train category is divided into sub categories according to the total weight of the train as shown in Table 1.

Weight [tons]	**Speed [km/h]**			
	≤140	141-160	161-200	> 200
≤ 300	3%	3%	4%	5%
301-500	4%	4%	5%	6%
501-700	4%	5%	6%	7%
> 700	5%	5%	6%	7%

Table 1: UIC recommended running time supplements

2.2.2 The capacity load of the sections and stations

A high quality timetable not only can decide the inbound and outbound time at stations, and more importantly, it offers the possibility to recover the operation according to the planned timetable when the trains are disturbed by accidents randomly [20]. Timetable stability is the index to measure this possibility. Timetable stability is closely related to the train number assigned to the railway sections. So while assigning the trains paths and mapping out the train schedule, we should deliberately design the train number assigned to the sections. Section capacity is the maximum number of trains that can run over the section within a certain period of time. And the capacity load of each section is the ratio of the train number running through the section according to the timetable for a day to the section capacity. If the capacity load is heavy, it is very difficult to reschedule the trains when they are disturbed and the hope to recover the status that the trains are running according to the planned timetable becomes slim. The bigger the capacity load is, the smaller the timetable stability value becomes. Station capacity is the maximum number of trains that the station can receive and send within a period of time. And the capacity load of each section is the ratio of the train number arriving at and departing from the station according to the timetable for a day to the station capacity for receiving and sending trains. Similar to the capacity load of the sections, if the capacity load is heavy, it is very difficult to reschedule the trains when the trains are disturbed and we have slim hopes to recover the status that the trains are running according to the planned timetable. The bigger the capacity load is, the smaller the timetable stability value is. And the number of conflicts is obviously determined by the train number and the section transport capacity and the station capacity [25]. Therefore, it is important to take the capacity loads of the sections and stations and the distributing plan of the trains into account while analyzing the timetable stability [20, 25, 28].

2.2.3 The timetable periodic time

The planned running trajectories of the trains are lined in the timetable graph circularly, which is called a path. The time that a path occupies is called a train graph cycle. On the single-track railway, the train graph cycle is the factor determining the capacity of the timetable. The shorter the train graph cycle is, the more stable the train timetable will be.

A periodic railway timetable defines the scheduled arrival and departure times within a basic period of length T for each periodic train line at all served stations [7]. The basic cycle time is typically one hour, which means that the same pattern of train services repeats each hour [5]. Train lines may have a higher service frequency and still fit the overall timetable cycle time. The line cycle time is then simply the overall cycle time divided by the line frequency, e.g., a train line with 4 trains per hour has a regular interval of 15 minutes.

2.2.4 The heterogeneity of the planned train traffic

Efficient planning of new capacity requires understanding how the mixture of traffic interacts to affect capacity. Different train types can have substantially different operating characteristics including maximum speed, power to ton ratio and dispatching priority. Heterogeneity in the mix of characteristics of different train types creates greater delays than if traffic is homogenous [22, 33]. In double-track lines the capacity is affected by heterogeneity more than by train speed; while in single-track lines capacity is more affected by train speed than by heterogeneity [34]. In [8, 35] it has been identified that greater heterogeneity on a line increases interference between trains and creates more delay than if all trains have similar characteristics. The run times due to heterogeneity are dependent on the train types, volume and ratio of each train type. The more the network is heterogenic is the less stable the timetable is. Hence, in the analysis of stability of railway time table heterogeneity should be considered.

2.2.5 The grade of the railway lines

The grade of the railway lines is a symbol of the line capacity [20]. The line grade determines the maximal curve on the line, the train running speed, the minimum tracking interval time between two trains, even the block system [20, 24]. These are all the factors to affect the capability of the railway network. The higher grade the railway belongs to, the bigger transport capacity it has, which means the higher stability for the timetable.

2.2.6 The blocking system type

Block Section or Section means the stretch of rail line from the starting signal at one signal box to the home signal at the next signal box [32]. Only one train should be in any one block section at a time [36]. There are mainly three kinds of blocking system today [20]: semiautomatic block system, automatic block system and moving block system. Different block systems allow different minimum tracking interval time, which enormously affects the capacity of the railway. Among three of them, the moving block system produces the largest capacity, benefiting the networked timetable stability in the farthest way.

2.2.7 The station interlocking type

Signaling has been a feature of urban rail transit from the earliest days [26]. Its function is to safely separate trains from each other. This includes both a separation between following trains and the protection of specific paths through junctions and crossovers. The facilities that create and protect these paths or routes are known as interlocking.

Today electric interlocking and computer interlocking systems are all in use [20]. The response speed of the interlocking system is the key factor to affect the station capacity of receiving and sending out trains. The deeper level reasons include the communication capability, the computing ability, the reliability and the fault-tolerant ability. Compared with the electric interlocking system, the computer interlocking system can enhance the station capacity to a better level. Accordingly, the latter can produce higher timetable stability than the former.

2.2.8 The leading locomotive traction performance

The traction of the leading locomotive determines the train speed to a certain extent, and then affects the running time at the railway sections on itself and other follower train. So the leading locomotive performance is also a factor affecting the section capability.

2.2.9 The average mileage of the sections

The mileage of the sections can affect the section transport capability to a certain extent, especially on the single-track railway. Mileage can affect the running time of trains in the sections, which will affect the timetable.

So, all the above identified factors should be taken in to account while analyzing the stability of a railway timetable. Based on this, several methods were developed to measure the stability. These methods are presented in the next section.

2.3 Review of timetable stability analysis methods

2.3.1 Max-plus algebra

Referring to [6, 7, 13], Max-plus timetable stability analysis method is based on a macroscopic model of the scheduled railway traffic system with an emphasis on the synchronization of trains. Stability depends on timetable constraints, interconnection structure, infrastructure usage, rolling stock circulations, and the distribution of slack times and buffer times over the network. The variables of interest are the train event times at stations, which are connected by activities (train runs, stops, transfers, etc.) [6, 7, 13]. We assume a periodic timetable where each event repeats at a regular interval called the cycle time T, which is usually 60 minutes. Train lines with a frequency of more than once per T minutes are modeled by separate train lines with equal characteristics but schedules that are shifted by a multiple of the line cycle time. A periodic railway timetable defines the scheduled arrival and departure times within a basic period of length T for each periodic train line at all served stations. Also through times at stations where the trains do not stop are given, as well as the scheduled through times at e.g. junctions of merging railway lines, movable bridges, and any other ‘timetable points’ in the network where a minimum headway time has to be satisfied corresponding to a safe separation distance on conflicting train routes.

A max-plus linear system is a discrete-event dynamic system where the dynamics are driven by the occurrences of events and the state variables are the event times [13]. In particular, max-plus linear systems describe the evolution of sequential and synchronized processes, like train runs and stops of individual train lines and transfer connections at stations where train lines meet, respectively. It considers periodic railway timetables corresponding to train circulations over train lines operating at regular intervals. The event times are connected to each other by activities or processes. An event can only occur if all its preceding processes have completed. For instance, a train departure can occur only if the train has arrived and the dwell process has been completed, a feeder train has arrived and transferring passengers have boarded the train, and conflicting routes of preceding trains have been released.

In other way according to [1], Max-plus algebra is a second method that is frequently used for evaluating railway timetables, next to simulation, is based on the usage of Max-plus algebra in combination with some efficient graph algorithms [15, 16, 17, 18]. Max-plus algebra allows performing a stability analysis on large networks. Stability can be viewed in two ways, locally and globally. Local stability refers only to a part of the whole network. In this sub network, trains arrive and depart. It is called locally stable if the sum of the output delays is smaller than the sum of the input delays. Input delays are hereby defined as delays of trains that start in the sub network or that enter this sub network. Output delays on the other hand are delays of trains that stop in this sub network or depart from it. Local stability thus implies that the total delay within this sub network decreases [7].

Global stability or network stability is viewed over the whole network. If initial delays in the system can be eliminated within a finite time span, the network is called globally stable.

The basic terminology of max-plus algebra is defined as follows [7]:

$$a \oplus b = \max(a,) \quad \text{and}$$

$$a \otimes b = a + b$$

This can be expanded to a matrix notation where $A=(a_{ij})$ and $B=(b_{ij})$. Both matrices A and B are square n x n matrices and can contain elements from the set of real numbers or $\varepsilon = -\infty$.

$$(A \oplus B)_{ij} = a_{ij} \oplus b_{ij} = \max(a_{ij}, b_{ij})$$

$$(A\otimes B)_{ij}=\bigotimes^{n}_{k=1}(a_{ik}\otimes b_{kj})=max_{k=1,..,n}(a_{ik}+b_{ik})$$

This algebra can be used on a square matrix A which represents a precedence graph containing the elements a_{ij}. The elements a_{ij} are the weights of the different links that run from one node to another. From this, critical paths from the network can be identified by applying the following recursive relation [7]:

$$A^{\otimes j}=A^{\otimes j-1}\otimes A \quad with\ A^{\otimes 0} = \mathrm{E}(unity\ matrix)$$

Here $A^{\otimes j}$ is the matrix with the maximal weights of paths with exactly j links. The matrix of critical paths is then the matrix with critical path weights, being the maximal weights over all paths of equal length, defined by [7]:

$$A^{+}=\bigoplus_{\mathrm{j}=1}^{\infty} A^{\otimes j}=A\oplus A^{\otimes 2}\oplus$$

Hence, stability analysis using Max-Plus algebra is as outlined above. As we have seen above, this method can only be applied to a periodic timetable of a railway network. But it fails to analyze timetables that are not periodic. Hence, it is not applicable to non-periodic type of timetable. From practical point of view, even though most of the passengers' railway transportations are of periodic timetable, there also exist non-periodic timetables. Also this method considers only the arrival and departure times for timetable stability analysis excluding other factors that were identified in the section 2.2.

2.3.2 Simulation method of measuring timetable stability

The script that is written for performing the simulation in this analysis consists mainly out of three distinct parts: the input, the processing and the output [12, 14, 19]. Each of these parts will be described below to get a better understanding of how the program works and to get the general over view of the method. When details or examples are given about a network, this refers to an example network which can be seen in Figure 2. It should be noted that the program is intended for studying one station area, rather than a network.

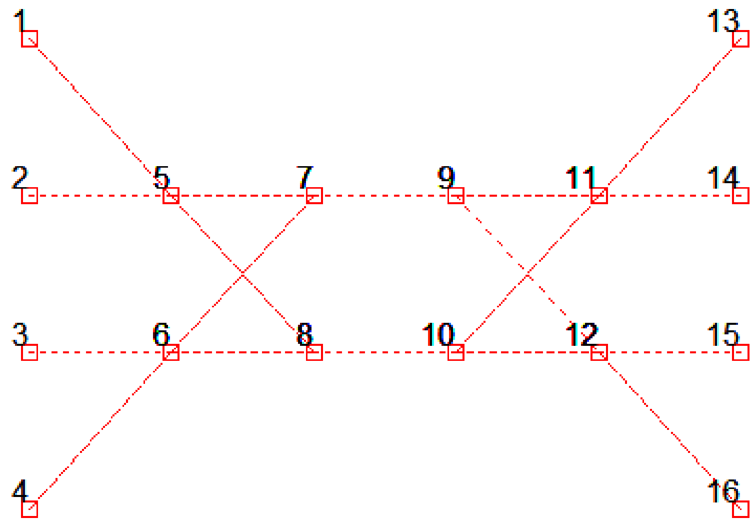

Figure 2: Example network

The input

By [12] the input of the program has two parts. First, there are multiple excel files that contain data about the network infrastructure and the trains. These data are loaded into the MATLAB R2011b program when it is started. Secondly, there are some settings that can be adjusted at the top of the script, which give the user the ability to run multiple scenario settings on the same network. An example of this is the possibility to run a given schedule deterministically or stochastically. The two parts of the input are described below in the order that they were mentioned.

The excel input introduces the different Excel files that are needed to run the program. These files serve as the basis for the program as they are loaded into different matrices at the start.

To start with, data is needed on the trains that run on the network. These data are gathered in the Excel-file Trains.xls. For each train a new row is used.

The second excel document that is used, is the Timetable.xls file. This file contains the arrival and departure time at the platform for every train, as can be seen in Figure 3.

	A	B	C
1	IC0001	44	49

Figure 3: Example of Timetable.xls

The most important thing to notice here is that the order, in which the rows are filled, should be the same as in the previous document, Trains.xls. In this example, 44 indicates that this train is expected to arrive at his platform, mentioned in the previous document, at 44 minutes past the hour and expected to depart there 5 minutes later. The schedule is considered to be cyclic so these arrival and departure times will be the same in every period, which consists of one hour here. This period can be adjusted in another part of the input which is mentioned later. When working with trains that turn at their platform, as explained above, the second train will have its arrival and departure time equal to the departure time of the first train, as in Figure 4.

	A	B	C
1	IC0001	44	49
2	1C0002	49	49

Figure 4: Timetable.xls for turning trains

At this moment, all the needed data for the trains are entered in the program. However, as the network they will be driving on has not yet been defined, the node numbers do not have any meaning yet. The Excel-file Node_Coords_X_Y.xls already gives some more meaning to these nodes. With this file, the coordinates for each node are entered, so a graphical representation is possible as in Figure 2.

With all the data input up to now, the program can be configured to work. Yet, in order to make the program more realistic, additional input is still required. With the data that is provided now the trains can run from node to node and, if needed, wait on a certain link if the next one is occupied. In real life however this is not common practice, mainly due to safety reasons that keep trains at more safe distances from each other. The system that is used in reality consists of trains running from signal to signal, instead of running from node to node. The path between two signals will be called a section from now on. A section can thus comprise multiple links, because not every node has a signal. On the other hand, every signal is a node. In order to define every section, the file section_free_links.xls is created. In Figure 5 an abstract is taken from this file.

Column A is filled with ascending section numbers and column B is again an indicator value that is used in the program. It serves the same purpose as the indicator variable for links, namely keeping track of the occupation. If the value is zero, the section is free, otherwise it will contain the number of the train that is occupying it.

	A	B	C	D
1	1	0	1	5
2	2	0	7	0

Figure 5: Example of section_free_links.xls

After the second column, the links are summed up which make up the section [12]. It should be noted here that these are links and not nodes. Sections, just as links, always have a direction. The link in column C is the start link and column D is here the end link, if that is not zero. Of course sections can comprise more than two links, which just adds columns to this table. In contrast to links, sections mostly are not the mirror image in the opposite direction. This means that the sections in the opposite direction should be checked carefully and put in as new sections. It also has to be taken care of that the correct link is put in in terms of the direction that it is used in. More precisely, if a third section would exist in this example, which is the same as the first one but in the opposite direction, it cannot be put in as the sequence 5-1. The correct way to do it is to first put in the complementary link of link five, then the complementary link of link one. The second section in this example only consists of one link. All columns after the final link are put to zero so all rows have as much elements as the row containing the longest section.

Scenario settings

By [12] the first setting that can be adjusted is the $P_{lotting}$*_on* variable. When this variable is set to 1 the program does not run immediately until the end but halts every time step and outputs a graphical representation of the current state of the network. The user should be aware of the fact that this reduces the speed of the program tremendously and thus should only be used to get a view on a certain situation.

The following two parameters have to do with the deterministic or stochastic character of the scenario that has to be evaluated. These variables, Stochactic_start_times and Stochastic_dwell, can be put to 1 if the scenario should use stochastic start and/or dwell times instead of the deterministic ones. Otherwise it should be put to zero. The magnitude of the variability that is put on those times is determined by the values of Stdev_start_time and Stdev_dwell_time, and are the same for all trains. These variables, which are expressed in minutes, apply a standard deviation to the deterministically given or calculated start and minimal dwell times. They do not necessarily have to be integers. The start times are hereby defined as the times at which each train enters the station area and the minimal dwell time is the minimal amount of time a train should spend at the platform, independent of when it arrived there. In the current state of the program the deviations are applied following a normal distribution of the times.

The next settings that can be chosen have to do with the length of the simulation. The first one is the number of hours per day, hrs_per_day, while the second, Eval_period, indicates how many repetitions of that day should be performed. The Modulo variable indicates the length of one cycle in the schedule, and is expressed in minutes. Usually schedules repeat every hour which means a modulo of 60 in this case. Successively the minimal dwell time is set, together with the minimal turning time. This minimal dwell time is the minimal time a train has to wait at a platform, as mentioned before. The minimal turning time applies to trains that change direction at a platform and go back the way they came from. For those trains this minimal time is applied for having to stay at the platform. In real life, this is the time during which the driver changes sides for example.

Processing

By [12] this is the main part of the script. Given the input data from the first part, the simulation should be run enough times to get statistically relevant output data. What this running actually entails, is elaborated in this section. This step is quite extensive, so in order to get a better view on the entire process, a flow chart can be found in Figure 6 as a quick overview.

The input data that comes from all the Excel-files, together with the settings on the first lines of the Main Program.m file form the starting point for this step. Based on these data an event queue is made. The event queue consists of six columns. The first one indicates which train is affected by the event. The second and third determine the time at which this train should undergo the action. Hereby the second column indicates the minutes and the third column indicates the period, thus the hour of the day. The fourth and fifth column should be looked at together. In case of a normal event, where a train is propagated, the fourth column contains the node where the considered train is present at the specific time (indicated in column two and three). In this case, the fifth column will have the value zero. On the other hand, when the event is not a normal event, but rather one to clear links, the fifth column will have a value other than zero. In this case, the fourth and fifth column together indicate what link and complementary link should be released at the given time. The sixth column finally indicates the original starting period of the train. This only comes into use when a train starts his journey in one period but ends it in another. In order to attribute the collected data to the right train, this value helps to identify the train. A row abstract of the event queue is given in Figure 6.

	1	2	3	4	5	6
1	1	2.1652	0	2	0	0

Figure 6: Abstract from the Event_Queue

In the main loop of the script, the first event in the queue is evaluated, adjusted and the queue is sorted again so that the earliest occurring event comes at the first line of the queue. This loop is executed during the set number of hours per day and the number of evaluation repetitions that is desired.

The event that has to be evaluated can be of two types. Either the event is one to release a link or otherwise it is one to (try to) propagate a train. When the event has to release a link, it will also release the necessary nodes. At what time a link has to be released, is determined in clear_links.m. When a train is propagated to the next node it is checked whether or not the length it covers on the next link is large enough so the tail of the train leaves one or more links by moving this distance. For these links, events will be scheduled [2, 21]. The nodes represent switches so they have to be cleared at the right time too. The link can either be a real link or a ghost link. This ghost link is an artificial link at the beginning and end of the network where all trains start and end. If the link is the last one of its section that is occupied by this train, the section can also be released [12].

The second possibility is that the event tries to propagate the train to the next node on its route. Therefore it is first needed to find which node is next, which (complementary) link is next and of course what (complementary) link the train is currently on. If the next node of the train happens to be its destination, different actions should be taken then when the next node is a normal one along the path. The destination can be at the end of a network and then the train can be put on the ghost link and removed from the queue. It is however also possible that this destination is at the same time the platform for the train. This is the case when a train turns at its platform. In the program, these trains are split up into two trains, one arriving and one departing. For the first one, the destination will thus also be the platform node. Then the program has to make sure that the train spends its required time at the platform first, before it can be removed from the network. When the next node of the train is a normal node along the path, a search has to be performed to see whether or not a new section will be entered, which section that is and if that section is free [12].

The first output that the user can get is a plot that depicts the current state of the network during the run. Depending on the setting of the variable Plotting on, the program makes a new plot in every time step. As mentioned before this is computationally very hard and thus slows down the program significantly. It should therefore only be used to investigate certain situations. The plot represents which sections are reserved in blue and which links are occupied in black. For the occupied links, an indication is given which train is on it. This is illustrated in Figure 7 [12].

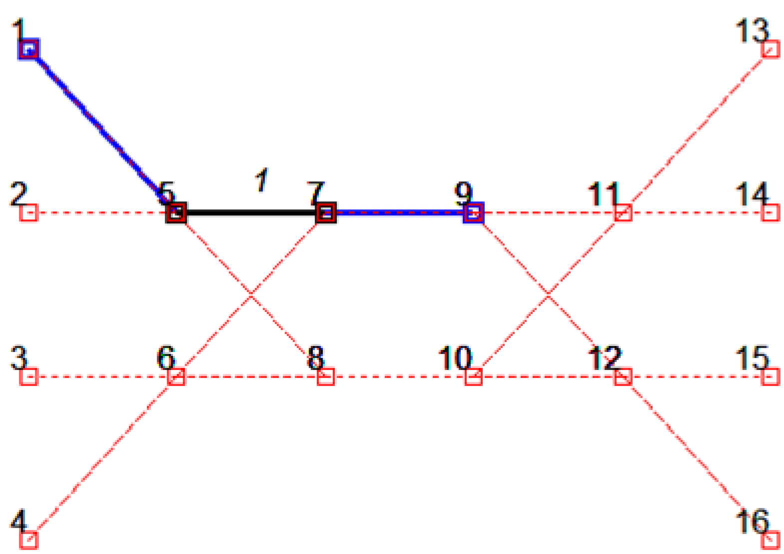

Figure 7: Example of occupied network

A second output that can be obtained during the run is in text form and appears in the command window of MATLAB R2011b. When the two first events of the event queue are on the same node, this might be an indication of a deadlock situation. However, this is not necessarily the case. When a deadlock situation does occur, one train tries to propagate, but is obstructed by the other and vice versa. So both trains keep on getting delayed by each other, and neither one of them moves. Off course, such a situation should never occur in a schedule, so this check is merely added to make sure the program is still running and to give an explanation when it does not continue. In that case, a text message as in Figure 7 appears. It is only when the indicated time of the warning, in this example minute 124.03 on day one of five, does not change in successive warning messages that a deadlock occurs. In other cases, the message can be ignored. Even though then it can still have a use, as the message will appear from time to time. This way, the user can see that the program is still running and how far along it is in the total execution. After accomplishing all activities from input, process and output that we can have the intended result [12].

In doing those activities, the input requires lots of data, to the processing and then to the output the program requires large processing time. Similar to the Max-plus algebra (as in the first type of analysis) this method is only applicable to the periodic timetable. On the other hand the simulation program cannot represent the safe movement of the trains that really need great attention. Also, it does not include all the major factors affecting the railway timetable in the simulation. In addition, in this simulation, only one station can be analyzed, not the networked stations. For these reasons its applications are limited. Hence, other type of analysis method is required in this aspect. Therefore, the thesis at hand gave a solution for this.

2.3.3 Information entropy method of measuring timetable stability

The analysis of railway timetable stability in this approach is based on analysis of both interior and exterior factors affecting timetable stability [20].

The interior factors affecting railway timetable stability are the total time supplement for running in the sections, the total time supplements for dwelling on the stations, the timetable periodic time, the buffer times between train paths, the capacity load of the sections and the capacity load of the stations. And the exterior factors affecting railway timetable stability are the grade of the railway lines, the blocking system type, the station interlocking type, the leading locomotive traction performance and the average mileage of the sections [20].

In this method, the factors of timetable are related through Shannon information entropy theory to measure the stability of railway timetable. Shannon pointed out that redundancies occur in all kinds of information [20]. The size of the redundancy is related to the ratio of each character or the uncertainty. He proposed the definition of information entropy and the equation calculating the entropy. If pi is the probability of a specified signal, the summary information of several signals is $-\sum pi \ln pi$. Then $H = -c\sum pi \ln pi$ *is* defined as the information entropy, where c is a proportionality constant. In this case, it hires entropy theory, which is also a branch of thermodynamics to study the timetable stability [20].

In this analysis, e_i is assumed to be the factor affecting timetable stability, $i = 1,2, \cdot\cdot\cdot ,N$. The interacting determinants of factor k on factor j is $f_{k\,j}$, $k = 1,2, \cdot\cdot\cdot ,N$, $j = 1,2, \cdot\cdot\cdot ,N$. Then the interacting determinants form a matrix F. The affecting index number of factor e_i is p_i , then

$$P_i = \frac{\sum_{k=1}^{N} f_{ki} + \sum_{j=1}^{N} f_{ki}}{\sum_{i=1}^{N}(\sum_{k=1}^{N} f_{ki} \sum_{j=1}^{N} f_{ij})} = \frac{\sum_{k=1}^{N} f_{ki} + \sum_{j=1}^{N} f_{ki}}{2\sum_{k=1}^{N}(\sum_{k=1}^{N} f_{kj}}$$

In this equation the numerator is the summary of the interacting determinants of factor e_i acting on other determinants and received from other determinants. The denominator is the summary of all the interacting determinants between the factors. Then the information entropy of train timetable stability is

$$S = -c\sum Pi \ln Pi$$

where $c = 1/\ln(N)$, which is the proportionality constant to define the timetable stability. N is the number of the factors which affect the timetable stability. The timetable stability entropy is the key index to evaluate the train timetable stability [20]. When the timetable is stable, the factors are balanced and then the information entropy is high. When the factors present an ordered appearance, the information entropy is low.

The information entropy can be normalized by the membership degree functions, as follows [20].

$$G = q(S), \qquad 0 \le q(S) \le 1$$

The triangle function is selected to map the relationship from timetable stability entropy to timetable stability index as follows.

$$G = \begin{cases} 0 & S \leq M \\ \dfrac{S-M}{L-M} & M < S < L \\ 1 & S \geq L \end{cases}$$

M is the lower bound of *S* and *L* is the upper bound of *S*. Of course, other membership degree functions can be used to define *q*, such as the trapezoidal function, Sigmoid function and Gauss function.

The timetable stability is affected by two kinds of factors, the interior factors and the exterior factors [20]. So the information entropy can be divided into two kinds. One is the interior factor timetable stability index $G^{interior}$, the other is exterior factor timetable stability index $G^{exterior}$. Then the timetable stability value is defined as follows.

$$W = G^{\mathrm{interior}} \times G^{\mathrm{exterior}}$$

As reviewed above, the analysis in this method accommodates both the interior and exterior factors affecting railway timetable stability. In this aspect it is very appreciable and advance. However, it hadn't considered other factor such as the heterogeneity of the trains that contributes major effect to the stability of railway timetable as reviewed in section 2.2.. This condition makes the applicability of this method lesser. Hence, this draw back gets solution in the thesis at hand.

2.3.4 Probabilistic method of timetable stability measures

In this method [10], consider a timetable perturbation (X,*V*,Q), in which *V* consists of initial nodes only, *i. e.* (X,*V*,Q) denotes a perturbation on the departure time of the trains at their initial nodes. Moreover, assume that for all trains *i* an individual and independent probability distribution $P(X_i \leq d)$ is given. For each train there is a physical barrier that defines a lower bound on the negative delays, since a train has a technical speed limit that cannot be exceeded. For an upper bound there is no such physical barrier, yet the further focus will be on small delays. Now, consider two routes r_{ij} and r_{kl} of two different trains *i* and *k* as well as the corresponding delays X_i and X_k. Depending on these delays, the routes do not need to be compatible. Therefore, introduce the following random variable $Y_{i\,j,kl}$

$$Y_{ij,kl} = \begin{cases} 1 & \text{If } r_{ij} \nleftrightarrow r_{kl} \text{ according to } X_i, X_k \\ 0 & \text{If } r_{ij} \leftrightarrow r_{kl} \text{ according to } X_i, X_k \end{cases}$$

$Y_{ij,kl}$ indicates, whether or not two selected routes are compatible according to the delays X_i and X_k. Consider any draft schedule L and the corresponding assignment of trains to routes. This assignment is not assumed to be feasible, *i. e.* the assigned routes might be incompatible, even if each train runs on time. Denote with $\hat{r}_i$ and $\hat{r}_k$ the assigned routes of trains i and k respectively and with $\hat{Y}_{i,k}$ the corresponding indicator variable that shows, whether or not the two assigned routes $\hat{r}_i$ and $\hat{r}_k$ are compatible [10].

In order to evaluate schedules, several probabilistic stability measures will be developed and explained in the following paragraphs. All are based on the definition of $Y_{ij,kl}$ and $\hat{Y}_{i,k}$ respectively. The corresponding problems can be visualized in the following extended graph model below: Each route r_{ij} correspond to a vertex v_{ij}. Each vertex v_{ij} is now connected to all other vertices v_{kl} . Introduce the following weights on the edges [10]:

$$w_{ij,kl} = \begin{cases} \infty & \text{If } i = k, \text{ i.e. if the trains are equal} \\ 1 & \text{If } r_{ij} \nleftrightarrow r_{kl} \text{ for } X_i = X_k = 0, \text{ i.e for incompatible routes} \\ P(r_{ij} \nleftrightarrow r_{kl}) & \text{If the routes are feasible for } X_i = X_k = 0 \end{cases}$$

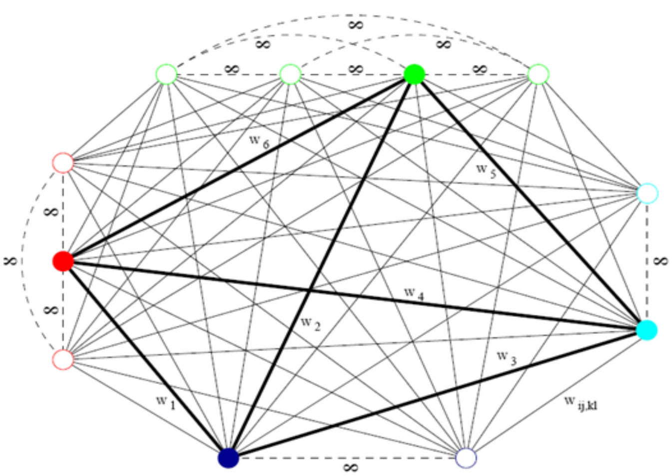

Figure 8: Extended conflict graph

- Expected Number of Conflicts

It is of particular interest to know the expected number of conflicts that have eventually to be settled for a given schedule *L*. If the expected number of conflicting routes is small, the schedule is expected to be insensitive to deviations and hence is assumed to be stable. A large expected value indicates a high sensitivity to perturbations. Moreover, if this value is too high, then the schedule is assumed to be non-operational as there are often deviations causing conflicts that have to be solved. The goal is to find a feasible assignment that minimizes this expected value. Let *L* be any given draft schedule—not necessarily feasible—and $\hat{Y}_{i,k}$ the random variables that indicate whether the routes of train *i* and *k* are compatible or not. Let Y_C be a random variable defined as [10]:

$$Y_C = \sum_{i,k} \hat{Y}_{i,k}$$

Y_C indicates the number of conflicting routes for a timetable perturbation (X,*V*,Q) in an assignment *L*. Of course in a feasible assignment and assuming all delays to be 0, Y_C is equal to zero. Yet, in the infeasible case Y_C is larger than zero. Hence, Y_C counts the conflicts in a schedule for given delays $X_1, \ldots, X_n$. The expected number of conflicts is the value $E[Y_C]$ which gives an indication on the stability of the schedule.

It is calculated as follows:

$$\mathbb{E}[Y_C] = \mathbb{E}\left[\sum_{i,k} \hat{Y}_{i,k}\right] = \sum_{i,k} \mathbb{E}\hat{Y}_{i,k} = \sum_{i,k}\left(P\hat{Y}_{i,k=1}\right) = \sum_{i,k} P(\hat{r}_i \nleftrightarrow \hat{r}_k)$$

- Schedule Failure Probability

The expected number of conflicting routes $E[Y_C]$ is an indicator of whether the schedule might be stable or not [10]. The schedule becomes infeasible as soon as the trains have delays such that on some track segment *e* the scheduled routes of at least two trains become incompatible. If for a schedule *L* and a timetable perturbation (X,*V*,Q) the random variable Y_C is zero, then the schedule *L* is still feasible, whereas $Y_C \geq 1$ means that the schedule fails. Hence, the value $P(Y_C \geq 1)$ is of crucial interest. The probability $P(Y_C \geq 1)$ is called the Schedule Failure Probability. Due to the dependence of the random variables $\hat{Y}_{ik}$, it is difficult to calculate $P(Y_C \geq 1)$ directly.

However, lower and upper bounds can be given that indicate whether or not a schedule is likely to fail.

As shortly discussed above, the probabilistic method of timetable stability measures [10] depends more of on the expectation of the occurrences of disturbances. In this method, it is very difficult to calculate the probability that two routes are in conflict with each other unless the delay probabilities are assumed to be independently distributed. These also make its applicability very less. Hence, it requires appropriate solution.

2.3.5 Other methods that are used to measure timetable stability

These include: Delay propagation method [9] of analyzing stability of timetable is another type of simulation which requires large number of input data that requires large computational time. It is also only applicable to a station area. Hence, these conditions limit its applicability. In general, the following conclusion has been made.

2.4 Conclusion to the literature review

From the review made above, we have observed the several factors affecting railway timetable stability and the methods developed to analyze railway timetable stability. In all the methods reviewed, we have observed their limitations. However, the method of "Information Entropy Method" is more advance over the others and is the very recent developed one. In that, it considers both the interior and exterior factors that affect railway timetable stability. It also helps to evaluate the stability of a network rather than treating only a single railway section or station. This makes the method to be more feasible and reliable. In the contrary, this method has its own draw back. It only considers limited interior and exterior factors in the analysis with excluding a factor that has significant effect on the stability of railway timetable. As reviewed in section 2.2, we have observed the factor such as the heterogeneity of train traffic has significant effect on railway timetable stability. Hence, this factor should be considered in the development of appropriate method for the analysis of railway timetable stability.

CHAPTER THREE

METHODOLOGY OF THE STUDY

3.1 Introduction

In this chapter, the methodology used to analyze stability of a railway timetable has been given. In this methodology, first by identifying the determining factors of railway timetable stability, timetable data were collected and the relationship between those factors have been established to set method to analyze railway timetable stability for the railway operations. Hence, the following strategies of data collection were followed.

3.2 Data Collecting Strategies

a. Collecting necessary data from literatures:

In this method of data collecting, necessary data have been gathered from the review made in the related literature review section.

In this case methods previously developed to analyze the stability of railway timetable have been identified. In line with these, the several factors affecting railway timetable are correspondingly reviewed.

b. Data collection from Addis Ababa LRT Project:

In this method of my research data collecting, actual available data were collected from Addis Ababa LRT Project regarding the initial phase of the project. The Addis Ababa LRT's network consisting of two routes were identified with their design data.

3.3 Data Analysis Procedure

The data collected in the above manner have been processed in a way that they can answer the problem of the research topic.

In this case, an appropriate model was aimed to be developed so that we can measure the timetable stability of passengers' railway operations. In such a manner among the known methods of railway timetable stability analysis, the more practical method was selected for benchmark purpose.

Benchmark method selection criteria

Though, there were several methods had been developed to evaluate the timetable stability, the varies methods have different approach and limitation. Hence, the selection of the appropriate benchmark method is based on the following criteria.

- The wideness and type of the timetable affecting factors it considers in the evaluation of stability
  Several factors do affect the stability of railway timetable. One of the qualities of stability measurement is the inclusion of more factors in the evaluation method. Since there are interior factors and exterior factors affecting railway timetable, a method that is capable for analyzing both types of factors is selected over the others.
- The capability of its application to analyze a railway network timetable
  Different methods have limited application. Some of the methods are only applicable to a station rather than evaluating the whole network. In this aspect, a method that is applicable to the whole railway network has more advantageous.
- The type of periodicity of timetable
  There are two types of railway timetable. These are the periodic and the none-periodic timetable. Several methods of railway timetable stability analysis methods are only applicable to periodic timetable only. However, a method which is applicable to both the periodic and the none-periodic timetable has more advantageous.
- The complexity and time taking of the evaluation process of the methods
  Some methods that are used to measure the railway timetable stability require longer processing and process time. Accordingly, methods with shorter process times are of greater demand.

Based on those criteria, the benchmark method of timetable stability has been identified. The "Information Entropy Method" of railway timetable stability analysis fulfills all the above criteria. That is, the method of Information Entropy Method considers both the interior and exterior factors affecting railway timetable stability; it evaluates the stability of the whole railway network; and it can also be applicable to both the periodic and none-periodic railway timetable. Accordingly, this method has been selected to be used as a benchmark method of railway timetable stability analysis method for the thesis at hand. Taking into account this benchmark method, a mathematical model has been developed as identified as follows.

Model development approach

From the above, it has been identified that the "Information Entropy Method" is more advance over the others and is the very recent developed one. In that, it considers both the interior and exterior factors that affect railway timetable stability. It also helps to evaluate the stability of a railway network rather than treating only a single railway section or station. In addition, the method is applicable to a periodic and a none-periodic timetable. These all make "Information Entropy Method" to be a more feasible and reliable one. In the contrary, this method has its own draw back. It only considers limited interior and exterior factors in the analysis with excluding a factor that has significant effects on the stability of railway timetable. That is, the researchers of this method hadn't exhaustively considered all the factors affecting railway timetable stability as they recommend for further work.

As reviewed in section 2.2, we have observed the factor such as the heterogeneity of train traffic has significant effect on railway timetable stability. However, this factor was left unconsidered by the previous researchers of the "Information Entropy Method" of railway timetable stability analysis. Hence, the heterogeneity of train traffic has been considered in the development of appropriate method for the analysis of railway timetable stability in the thesis at hand.

Hence, in the thesis at hand the method of information entropy has been employed with the inclusion of the heterogeneity of train traffic as one of the factors affecting railway timetable stability.

CHAPTER FOUR

DATA COLLECTION, PRESENTATION AND ANALYSIS

4.1 Data Collection

The data required to analyze the railway timetable stability were collected using the strategies mentioned in chapter three. These are the following.

4.1.1 Data collected from literatures

From literature review, all the following factors are identified to affect the stability of railway timetable. These factors are categorized under interior and exterior factors affecting railway timetable stability. The interior factors affecting railway timetable stability are the total time supplement for running in the sections, the total time supplements for dwelling on the stations, the timetable periodic time, the buffer times between train paths, the heterogeneity of the planned train traffic, the capacity load of the sections and the capacity load of the stations. And the exterior factors affecting railway timetable stability are the grade of the railway lines, the blocking system type, the station interlocking type, the leading locomotive traction performance and the average mileage of the sections.

4.1.2 Timetable data collected from Addis Ababa LRT

The following are the data collected from Addis Ababa LRT regarding the analysis of LRT timetable stability analysis in line of the review made. The network has the following data.

- The LRT of Addis Ababa city has a railway network which has two routes. These routes are the East– West line (the route from Ayat to Torhailoch) and the North – South line (the route from St. George church/Minelik II Square to Kality) as depicted in the figure 9 with the red color for initial stage of infrastructure construction. Each route has double line. Within a section of 2.8 kilometers the two routes share the same track (from Legehar to Lideta Light).

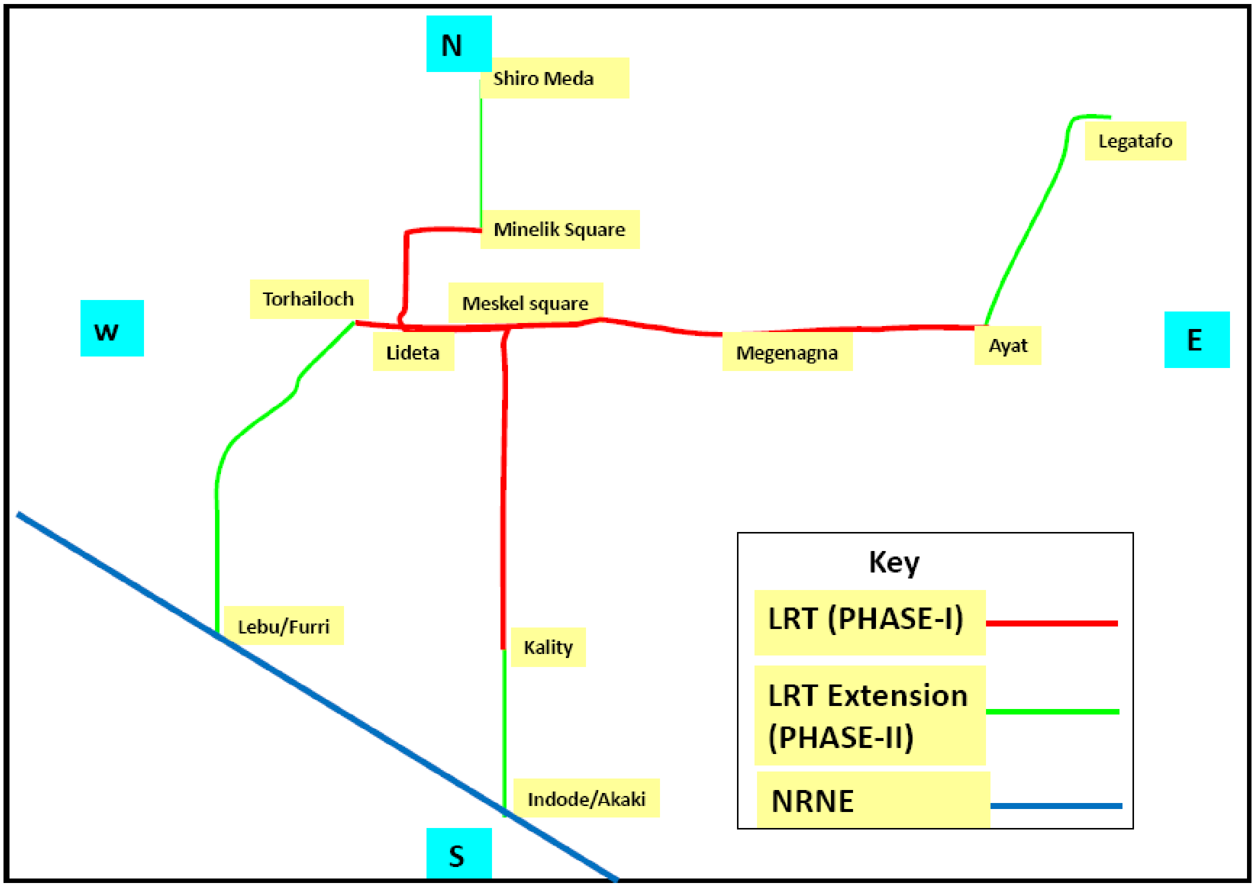

Figure 9: Addis Ababa City LRT alignment with extension [37]

- The network has computer type stations interlocking system and automatic type blocking system.
- The time designed for one person to board or alight a train is averagely 2seconds for the LRT.
- The time table of Addis Ababa LRT project is a periodic type.
- The Addis Ababa LRT project has a total length of 34.4km and total sections of 39.
- The vehicles for LRT are operated in two directions and have only one unit of coupled tramcar marshalling. All are almost of the same performance/characteristics.

Figure 10: Types of rail vehicles of Addis Ababa LRT in the initial project case [37]

- The maximum unidirectional section passenger flow of Line E-W in peak hours will take place in the road section from Lideta Light to Legehar shared with Line N-S. The total unidirectional section passenger flows are 38,462 persons/day, or in peak hours 5000 persons/hour.
- A tram has 64 seats and has loading capacity of 6 persons/m^2, 286 persons
- Each tram length is 28400mm
- Average acceleration for start-up: 1m/s2 （0-40Km/h）
- Average deceleration for braking: from 80Km/h to stop
- The Average deceleration of normal braking with rated load （including control response time）: ≥1.0m/s2
- The average deceleration of emergent braking with rated load （including control response time）: ≥1.5m/s2
- Limited speed: 80km/h
- Average travelling speed: 18km/h
- Total weight of a train going to serve in this line is 43 ton
- Headway time is 6minutes

- Over 98% reliability factor of operation
- Working hours of train traffic, 16-18 hours per day

The other data specific to each route related to timetable analysis are presented below.

a. The East- West line has the following unique data

- There are 22 stations along this route.
- One-Day Unidirectional Passenger Flow: Persons/day is described in Table 2.

Sections	Unidirectional Persons/day (A)
Torhailoch～Lideta Light	15885
Lideta Light～Legehar	38462/2
Legehar～Adwa Square	19262
Adwa Square～CMC	7031
CMC～Ayat	5531
Total	**66940**

Table 2: One-Day Unidirectional Passenger Flow in the East- West line

- Unidirectional Passenger Flow Forecast in Peak Hours Unit:Persons/h is shown in Table 3.

Road Section	Passenger Flow in Single
Torhailoch～Lideta Light	2065
Lideta Light～Legehar	5000
Legehar～Adwa Square	2504
Adwa Square～CMC	914
CMC～Ayat	719

Table 3: Unidirectional Passenger Flow Forecast in Peak Hours in the E-W line

- Operation Information of East-West line is described in Table 4.

Parameters		Values
Operation length (km)		17.4km
Train marshalling		One unit
Rated number of person （person/set）		286
Hourly traffic volume in peak hour pair/hour）	Sharing section for two directions	20
	Other section in this line	10
Minimum operating interval （minute）	Sharing section for two directions	3
	Other section in this line	6
Transport capacity （10,000 person/hour）	Sharing section for two directions	0.57
	Other section in this line	0.29
Train allocation	Operating car	19
	Standby and inspecting car	2
	Total	**21**

Table 4: Operation Information of East-West Line

b. The North – South line has the following unique data

- There are 17 stations along this route.
- Total length of 16.8km
- One-Day Unidirectional Passenger Flow: Persons/day has been presented in Table 5.

Sections	Unidirectional Persons/day (A)
Minelik II Square～Merkato	11623
Merkato～Lideta Light	13008
Lideta Light～Legehar	38462
Legehar～Gotera	17708
Gotera～Kality 16323	16323
Total	**97124**

Table 5: One-Day Unidirectional Passenger Flow: Persons/day

- Unidirectional Passenger Flow Forecast in Peak Hours Unit:Persons/h is given in Table 6.

Road Section	Passenger Flow in Single Direction: person/h
Menellk ll Square～Merkato	1511
Merkato～Lideta Light	1691
Lideta Light～Legehar	5000
Legehar～Gotera	2302
Gotera～Kallti	2122

Table 6: Unidirectional Passenger Flow Forecast in Peak Hours in the N-S line

- Operation Information of North - South Line is given in Table 7.

Parameters		Values
Operation length km)		16.8 km
Train marshalling		One unit
Rated number of person （person/set)		286
Hourly traffic volume in peak hour (pair/hour)	Sharing section for two directions	20
	Other section in this line	10
Minimum operating interval （minute)	Sharing section for two directions	3
	Other section in this line	6
Transport capacity （10,000 person/hour)	Sharing section for two directions	5.7
	Other section in this line	2.9
Train allocation	Operating car	18
	Standby and inspecting car	2
	Total	**20**

Table 7: Operation Information of North - South Line

Using the data related to both routes of the Addis Ababa, the values of the other factors affecting timetable have been calculated from the given parameters as shown below.

Running time supplement for the E-W line,

As described under section 5.2,

- Average travelling speed is 18km/h and
- Distance is 17.4km

From these two values the time of travel for the given distance and running at the given speed is 17.4km/(18km/hr) which is equal to 0.966 hour or about 1 hour for a single trip for a train. Accordingly, the running time between two consecutive stations (considering average distance) is 60minute/21station separations which gives 2.86 minutes. And total number of trips the trains perform within day for the E-W line should be determined first to get the total running time of a train within a day.

The number of trip depends on the section with higher volume of passenger flow. In this way, the higher load is located between Legehar～Adwa Square which is 19,262 passengers per day. But the capacity of one train is 286 persons and there are 19 trains along this line. Therefore, the total trip per day for the whole trains will be 19,262/(286*19) which is equal to 3.54 times which means 4 times for each trains in the E-W line.

Since, for a single trip the time required is about 1 hour, hence for 4 single trips it requires 4 hour and for 4 round trips it will be doubled and gives 8 hours of running time for a train per day.

Accordingly, from [30] the running time supplement for a passenger train of total weight less than or equal to 300 ton and speed less than or equal to 140 km/hr the running time supplement is given by 1.5minute + 3% of running time. In Addis Ababa LRT the maximum train speed is 80km/hr and total maximum weight of a train is 43ton. Hence, the running time supplement can be calculated as 1.5minute+3%*8hours which is 15.9 minutes for a train per day. And for a single trip it is about 2 minutes for a train. Accordingly, the running time supplement between two consecutive stations (considering average distance and 21 station separations for E-W line) will be 2*60/21 equals 5.7 seconds. The total time supplement for the 19 trains will be 302.1minutes/day or about 5 hours/day.

Running time supplement for the N – S line,

From the data identified in section 5.2, we have,

- Average travelling speed is18km/h and
- Distance is 16.8km

From these two values the time of traveling for the given distance and running at the given speed is 16.8km/(18km/hr) which is equal to 0.933hours or about 56 minutes for a single trip for a train. Accordingly, the running time between two consecutive stations (considering average distance) is 60minutes/16 station separations which is 3.5 minutes. And the total number of trips the trains perform within a day for the N-S line should be determined first to get the total running time of a train within a day.

The number of trip depends on the section with higher volume of passenger flow. In this way, the higher load is located between Lideta Light～Legehar which is 38462/2 i.e 19,231 passengers per day. But the capacity of one train is 286 persons and there are 18 trains along this line. Therefore, the total trip per day for the whole trains will be 19,231/(286*18) which is equal to 3.7 times that is equivalently 4 times for each train in the N-S line.

Since, for a single trip the running time required is about 1 hour, hence for 4 single trips it requires 4 hour and for 4 round trips it will be doubled and gives 8 hours of running time for a train per day.

Accordingly, from [30] the running time supplement for a passenger train of total weight less than or equal to 300 ton and speed less than or equal to 140 km/hr, the running time supplement is given by 1.5minute + 3% of running time. In Addis Ababa LRT the maximum train speed is 80km/hr and total maximum weight of a train is 43ton. Hence, the running time supplement can be calculated as 1.5minute+3%*8*60minutes which is 15.9 minutes for a train per day. And for a single trip it is about 2 minutes. Accordingly, the running time supplement between two consecutive stations (considering average distance and 16 station separations for N-S line) will be 7.05 seconds for a train. The total time supplement for the 18 trains will be 288 minutes or about 4.8 hours for N-S line.

In general, the total running time supplement for the network of Addis Ababa LRT is the sum of the total running time supplement along the line E-W and N-S. Accordingly it will give 9.8 hours.

Headway time supplement on both routes

In Addis Ababa LRT, the time between successively traveling trains is 3minutes at shared rail and 6minutes at other sections. And also the network is having only two routes which show that it is not dense network. Having this we can neglect the headway time and then the headway time buffer.

Total time supplements for dwelling on the stations of E-W line

It is the summation of the dwelling time supplement for every train in all the stations for a day.

- The time designed for one person to board or alight the train is averagely 2seconds.

Sections	Unidirectional Persons/day (A)	Dwell time (A * 4): seconds/day
Torhailoch～Lideta Light	15885	63540
Lideta Light～Legehar	38462/2	76924
Legehar～Adwa Square	19262	77048
Adwa Square～CMC	7031	28124
CMC～Ayat	5531	22124
Total	**66,940**	**267,760**

Table 8: Dwell time values at stations of E-W line

Therefore, the total dwelling time for the Ayat – Torhailoch is 227,760 seconds or 74.38 hr for 19 trains per day. Accordingly, for one train the dwell time per day will be about 4 hours. For a single trip it is 4/8hours which is 0.5hour or 30 minutes. Hence at every 22 stations (considering average value) it will be 30/22 minutes which is 1.36minutes.

The headway time between two consecutive trains is designed as 6minutes. Considering two consecutive trains, the dwell time supplement for each of these two trains can be obtained by subtracting the summations of the values of running time, running time supplement, headway time, headway time supplement, and dwell time between these stations. Hence, substituting the values determined above, we do have a dwell time supplement of 6-(2.86+5.7/60+1.36) minutes which equal to 1.69 minutes for each train along the E-W line at a station. Since we have 22 stations, then the dwell time supplement for a train for a single trip is 22*1.69 which is equal to 37.18 minutes. Then for 4 round trip of a day the total dwell time for a train will be 297.44 minutes. Accordingly, for the 19 trains the total dwell time supplement for a day is 297.44*19 minutes which is equal to 5,651.36 minutes or about 94.19 hours in E-W line.

The total time supplements for dwelling on the stations of N-S line

- The time designed for one person to board or alight the train is averagely 2seconds.

Sections	Unidirectional Persons/day (A)	Corresponding dwell time is (A * 4) unit in seconds/day
Menelik II Square～Merkato	11623	46492
Merkato～Lideta Light	13008	52032
Lideta Light～Legehar	38462/2	76924
Legehar～Gotera	17708	70832
Gotera～Kality	16323	65292
Total	**77893**	311,572

Table 9: Dwell time values at stations of N-S line

From Table 9, the dwell time in the Kality – St George church is 311,572 seconds or 86.55 hours for the 18 trains per day. Hence, for one train the dwelling time per day will be 4.82 hours. This shows at each station it has an average dwell time is 4.82/(8*17) which is 2.12 minutes for a train at a station.

But the time of operation between two consecutive trains is designed as 6minutes. Considering two consecutive trains, the dwell time supplement between these trains can be obtained as subtracting the summations of the values of running time, running time supplement, headway time, headway time supplement, and dwell time between these stations. Hence, substituting the values: 6- (3.5 + 7.05/60 + 2.12), we do have a dwell time supplement of 15.75 seconds for a train at station along the N-S line. Since we have 17 stations, then the dwell time supplement for a train for a single trip is 17*15.75 seconds which is equal to 4.46 minutes. Then for 4 round trip of a day the total dwell time for a train will be 35.7 minutes. Accordingly, for the 18 trains the total dwell time supplement for a day is 35.7*18 minutes which is equal to 10.71 hours in N-S line.

Then, the total dwell time supplement of the Addis Ababa LRT will be the summation of the span of dwell time supplement in the two lines. Hence, it is 94.19 hours + 10.71 hours which is 104.90 hours of total dwell time supplement of the total network for a day. Averagely for a train the dwell time supplement is about 2.8 hours per day.

Capacity load of the sections

Block section or section is the stretch of rail line from the starting signal at one signal box to the home signal at the next signal box.

Section capacity load is the ratio of the train number running through the section for a day according to timetable to the section capacity. Where, the section capacity is the maximum number of trains that can run over the section within a certain period of time, usually one hour. Considering a period of one hour, the maximum number of trains that can run over the section within an hour for LRT at the busiest section is 20 as per the data obtained from Addis Ababa LRT project. And from the previously determined values, the total daily operation of the trains is about 17 hours (which is found between the designed time of operation 16-18hour). That is, in the E-W line there is 8hours running time, 2minute running time supplement, 4 hours dwell time and 4.95minutes dwell time supplement. Hence the total will be about 17 hours. Now assuming the total operation hours of the railway network within a day is from morning 12:00 local time to at night 4:00 local time, the total hours of operation within a day will be 16 hours. Accordingly, the section capacity will be 17 times 20 that give 340 trains/day considering peak hours operation status. For our analysis let the average section capacity be 300 trains/day. Therefore, the capacity load of the section will be given as follows [20].

$$\text{Capacity load of the section} = \frac{\text{[the train number running through the section for a day according to timetable]}}{\text{[the section capacity]}} = \frac{300}{20}$$

$$= 15 \text{ number of trains run over the section in day/maximum number of trains run over the section in an hour .}$$

Hence, as the capacity load of the sections gets bigger and bigger the timetable stability will decrease. This is due to the fact that it is very difficult to reschedule the trains when they are disturbed and the hope to recover the status that the trains are running according to the planned timetable becomes slim.

Capacity load of the stations

The capacity load of each station is the ratio of the train number arriving at and departing from the station according to the timetable for a day to the station capacity for receiving and sending trains. In the case of Addis Ababa LRT project, there are only two routes having common shared rail for about 2.8km length. The stations at this location are the determining ones for the stability of timetable than other parts of the routes. Accordingly, these stations receive and send trains only over this shared common rail of the sections. Due to this, the capacity load of the station will be equivalent to the capacity load of the sections at the shared rail. Hence, in this manner the capacity load of the stations will be 15 trains in a day/in an hour. Similar to the capacity load of the sections, as this value gets increased the stability of the timetable gets smaller.

Heterogeneity of the planned trains' traffic

The variety of trains characteristics such as in sizes, service life, performance and others also affect the railway timetable stability. However, currently for the Addis Ababa LRT the sizes of the tramcars, service life, and performance are expected to be the same, since the trains are of brand new and of the same brand. Hence, we can avoid the effect of heterogeneity for instance at the initial phase of Addis Ababa LRT project.

Grade of the railway lines

The material used for the rail of the Addis Ababa LRT is U71Mn. This material is a steel grade type having tensile strength and yield strength being not less than 880MPa and 457MPa respectively, which enables it to enjoy mature welding technology and total-length hardening process.

Station interlocking type

The stations interlocking type in the case of Addis Ababa LRT is the computer interlocking type. Hence, it has a system response time ≤ 0.22second.

Performance of the leading locomotive

Having that the trains to be operated on the Addis Ababa LRT are of brand new, hence with consideration of some tolerance for any possible technical problem let consider the performance of the leading locomotive be 95%. And, lastly the average mileage of the sections has been seen.

The average mileage of the sections

The total length of the railway network is about 34.4km and there are 39 stations. Assuming one section between two consecutive stations, the average mileage of the section will be 34km/38 sections. Hence, it is 0.91km.

All the factors identified so far have significant effect on the stability of railway timetable. Hence, they are summarized and presented in the next section for analysis purpose.

4.2 Data Presentation

Generally, the data identified and collected from review made in the literature section and from Addis Ababa LRT Project were summarized and presented in Table 10 below.

A	**Interior Factors**		
Sn	Factors affecting railway timetable of Addis	Descriptions	Remark
1	The total time supplement for running in the	9.8hrs/day	Refer sec. 5.1
2	The total time supplements for dwelling on the	94.19hrs/day	Refer sec. 5.1
3	Timetable periodic time	525meter/trip	Trains No*length)
4	The buffer times between train paths	0	Refer sec. 5.1
5	The heterogeneity of the planned train traffic	0%	Trains are similar
6	The capacity load of the sections	17 trains in a day/an hour	Refer sec. 5.1
7	The capacity load of the stations		Refer sec. 5.1
B	**Exterior Factors**		
1	The grade of the railway lines	U71Mn	Steel grade
2	The blocking system type	Automatic	Refer sec. 5.1
3	The station interlocking type	Computer interlocking	
4	The leading locomotive traction performance	95% (assumed value)	
5	The average mileage of the sections	0.91km	

Table 10: The summary of data affecting timetable of Addis Ababa LRT.

4.3 Data Analysis

In this section, the effects of the factors identified and presented in Table 10, on the railway timetable for the case of Addis Ababa LRT have been analyzed.

a. The time supplements

During timetable design, it is not possible to take into account all the possible incidences that every train may face. A number of unforeseen events may cause disturbances to a train or to the whole railway network through disturbance propagation and may lead to instability to the LRT timetable. In addition, by now the technology of railway transportation to Ethiopia is new, every factor identified above has very significant effect on the LRT timetable to cause disturbances. Hence, enough tolerance time of train traffic operation should be added on the schedule of the timetable. However, introducing very high time supplement, on the other hand, causes to have longer travel times. Therefore, based on the socio economic approach and with the application of simulation technique an optimal size of running time supplement, dwelling time supplement and buffer time between train paths should be supplemented during the design of the Addis Ababa LRT timetable to enhance the stability of the timetable.

b. The timetable periodic time

The timetable periodic time shows the extent of occupation of the railway line with the operational trains through a given time. If there is longer occupation, this shows the higher density of trains on the line. Hence, as the length of occupation increases the interaction between trains increase and in such a manner the timetable may have higher probability to become unstable. Therefore, it should be treated well while designing the timetable of Addis Ababa LRT.

c. The heterogeneity of the planned train traffic

The vehicles for LRT have all the same characteristics. Hence, there is no heterogeneity in the initial project. But if there exist trains variety in the network that may be in trains performance, lengths, or other conditions, a lower performing train may affect the performance of a better performing train especially while they are travelling successively. This is due to the fact that successively traveling trains share a common guided rail that hinder the overtaking possibility between the trains. Hence, as the heterogeneity of the trains increases the timetable stability gets decrease.

d. The capacity load of the sections and stations

Stations and sections do have limited capacity in supporting railway traffic operation. Beyond the optimal limit, the supporting capacity of the stations and sections become weak. This leads the railway traffic network to have a higher interaction. During such interaction, the possibility of the occurrences of disturbances will be higher and their effect will easily propagate and may cause schedule failure. Hence, instability to timetable may happen. For this reason, trains should be assigned to each station or section with the consideration of these facts. Specially, in Addis

Ababa LRT the rail sections from Legehar to Lideta light are shared by both E-W and N-S lines. Therefore, this location should get more attention in the timetable design consideration.

e. The grade of the railway lines

The grade of the railway line limits the travelling speed of a train in a rout. This causes to lower the possible recovery time of a better performing train. Hence, the material selected for the rail of Addis Ababa (U71Mn of steel grade) will have impact on timetable stability.

f. The computer type stations interlocking

The Addis Ababa LRT network has computer type stations interlocking system. This is a better technology for the stations interlocking as the system takes only a fraction of second for giving response for an event. In general, if the response time of the interlocking system gets smaller, the network will have good efficiency. Hence, the stability of timetable will increase.

g. The block systems type

The blocking type of the Addis Ababa LRT is the automatic one. The minimum time interval that the automatic block system can recognize a section passage of a leading train and send the signal to show that block section is free for the follower train do affect the timetable. If the time it requires for blocking gets smaller, the travel time of a train will be shortened, so that the stability of the timetable will increase.

h. The leading locomotive traction performance

Since trains share a common guided way, hence, while traveling successively, if the performance of the leading train is found to be lower, whatever the high performance a follower train has, it is forced to act to the performance level of the leading train as far as both are on a common rail. This may bring a significant amount of delay in time to the better performing follower train. In this condition the better performing train may encounter a disturbance to its scheduled time. Again, this may on the other hand, propagate to other trains in passengers transfer connection. Therefore, Addis Ababa LRT should take into account this effect while assigning trains to each route.

i. The average mileage of the sections

If the average mileage of the sections is shorter, trains are forced to brake, stop and start many times. In this case the braking and starting situation in combination with the performance of the train operator bring a significant time effect to the timetable. Hence, average mileage of the sections of Addis Ababa which is 0.91km should be taken into effect while designing the railway operation timetable.

Developing model to evaluate stability of LRT timetable

From the review made in the literature, we have concluded that the best model selected for the analysis of railway timetable stability is the information entropy method [20]. Based on this, train timetable should be analyzed by considering both the interior and exterior factors. But, in this case, other limiting factor such as the homogeneity of train types was not considered. However, as we have seen in the literature review section 2.2, this factor has a significant effect on railway timetable. Hence the model developed in [20] should be altered to include this factor. This has been done as follows.

The timetable stability affecting factor e_i include all the seven interior factors and five exterior factors summarized in Table 2 above. Then, when these factors are related as follows, the stability index P_i, will be obtained, where the P_i is given by

$$P_i = \frac{\sum_{k=1}^{N} f_{ki} + \sum_{j=1}^{N} f_{ij}}{\sum_{i=1}^{N}(\sum_{k=1}^{N} f_{ki} \sum_{j=1}^{N} f_{ij})} = \frac{\sum_{k=1}^{N} f_{ki} + \sum_{j=1}^{N} f_{ij}}{2\sum_{k=1}^{N}(\sum_{j=1}^{N} f_{kj})} \quad \text{..................................} \quad (1)$$

Where, $k = 1,2, \cdot \cdot \cdot ,N$, $j = 1,2, \cdot \cdot \cdot ,N$, N is the total number factors affecting railway timetable stability analysis. And *fki, fij and fkj* are the interacting determinants of factor k on factor i, factor i on factor j and factor k on factor j, respectively. Then the interacting determinants form a matrix.

In equation (1) the numerator is the summary of the interacting determinants of factor e_i acting on other determinants and received from other determinants. The denominator is the summary of all the interacting determinants between the factors. Values of the interacting determinants among the factors are given by the researchers and experts. Researchers and experts marked the values in light of their experience, knowledge and the relative data of the timetable.

Then the information entropy of train timetable stability S will be

$$S = -c\sum Pi \ln Pi \quad \text{..........} \quad (2)$$

Where $c = 1/\ln(N)$, which is the proportionality constant to define the timetable stability and N is the number of the factors which affect the timetable stability.

The timetable stability entropy is the key index to evaluate the train timetable stability. When the timetable is stable, the factors are balanced and then the information entropy is high. When the factors present an ordered appearance, the information entropy is low.

According to [20], the information entropy value should be normalized by the membership degree functions G, as follows.

$$G = q(S), \qquad 0 \leq q(S) \leq 1,$$

and

$$G = \begin{cases} 0 & S \leq M \\ \dfrac{S - M}{L - M} & M < S < L \\ 1 & S \geq L \end{cases} \quad \text{..........} \quad (3)$$

Where, M is the lower bound of S and L is the upper bound of S. The values of M and L have been set to 0.9 and 1 for M and L respectively by [20].

Since the timetable stability is affected by two kinds of factors, the interior factors and the exterior factors. So the information entropy should be divided into two kinds. One is the interior factor timetable stability index $G_{interior}$.; the other is exterior factor timetable stability $G_{exterior}$. Then the timetable stability value is given by

$$W = G_{interior} \times G_{exterior} \quad \text{..........} \quad (4)$$

Hence, as pointed out in the above manner the developed model can be applied to the LRT timetable to evaluate is stability. Accordingly, the extent of timetable stability is the value given by equation (4).

CHAPTEFR FIVE

APPLICATION OF THE RESEARCH FINDING

5.1 Introduction

The aim of this research was to develop a method to evaluate the stability of a railway timetable. To this end, the research aim has got the appropriate answer. Hence, now it is the right time to interpret the output of the research to the intended area. This has been done by applying the model to the Addis Ababa LRT as shown in the next section.

5.2 Application of the model to the case of Addis Ababa LRT

In this section, the developed model has been applied to the Addis Ababa LRT project. In this case, the data used were considering only the Addis Ababa LRT project of the Initial Phase.

The model developed in chapter 4 depends on the interacting determinants among the factors affecting the timetable. And the values of the interacting determinants among the factors are given by the researchers and experts in light of their experience, knowledge and the relative data of the timetable.

Accordingly, based on the timetable factors of Addis Ababa summarized under section 4.2, experts were made to mark the values of the interacting determinants as shown in Annex - A.

Determination of the stability index P_i:

A. For the interior interacting determinants (Refer Table 12)

Now, from equation (1) we have

$$P_i = \frac{\sum_{k=1}^{N} f_{ki} + \sum_{j=1}^{N} f_{ij}}{2\sum_{k=1}^{N}(\sum_{j=1}^{N} f_{kj})}$$

Where, in the case of the interior factors affecting timetable stability N runs from 1 to 6, that means the three variables i, j and k can have values 1, 2, 3, 4, 5 and 6.

Then, for i= 1, P_i equals P_1 and is given by

$$P_1 = \frac{\sum_{k=1}^{N} f_{k1} + \sum_{j=1}^{N} f_{1j}}{2\sum_{k=1}^{N}(\sum_{j=1}^{N} f_{kj})}$$

And introducing the values of j from 1 to 6 to the denominator in the parenthesis, we have

$$P_1 = \frac{\sum_{k=1}^{N} f_{k1} + \sum_{j=1}^{N} f_{1j}}{2\sum_{k=1}^{N}(f_{k1} + f_{k2} + f_{k3} + f_{k4} + f_{k5} + f_{k5} + f_{k6})}$$

Now, substituting the corresponding values of the interacting determinants from Table 12 and solving the equation, we have

$$P_1 = 0.226$$

Conducting similar manipulation, we have

$$P_2 = 0.242\ ,\ P_3 = 0.387,\ P_4 = 0.403\ P_5 = 0.387 \text{ and } P_6 = 0.355$$

And using equation (2), the information entropy of the interior interacting determinants will be obtained as follows

$$S_{interior} = -\,c\sum Pi\ln Pi \text{ where } c = 1/\ln(N)$$

And for $N = 6$ the value of c will be equal to $c = 1/\ln(6) = 0.558$

Then, substituting the values of Pi and c, we have

$$S_{interior} = 1.198 = 1.20$$

Now, this value of information entropy should be normalized to timetable stability index using equation (3). That is,

$$G_{interior} = \begin{cases} 0 & S_{interior} \leq M \\ \frac{S - M}{L - M} & M < S_{interior} < L \\ 1 & S_{interior} \geq L \end{cases} \cdots\cdots\cdots\cdots\cdots (5)$$

Where M is the lower bound of S and L the upper bound of S. And the corresponding set value of M is 0.9 and also the set value of L is 1. Then equation (5) holds true for $S_{interior} \geq L$ that means $S_{interior} > 1$. Hence, the corresponding normalized interior timetable stability index, $G_{interior} = 1$.

B. For the exterior interacting determinants (Refer Table 13)

Again in this case, we conduct the following similar manipulation as in part A. Since there are only five exterior factors, N can take values 1, 2, 3, 4, and 5 only. Hence, conducting similar manipulation as in the interior case, the values of P_i for the exterior case are:

$P_1 = 0.458$, $P_2 = 0.492$, $P_3 = 0.220$, $P_4 = 0.407$ and $P_5 = 0.424$

And using equation (2), the information entropy of the interior interacting determinants will be obtained as follows

$S_{exterior} = - c\sum Pi \ln Pi$ where $c = 1/\ln(N)$

And for $N = 5$ the value of c will be equal to $c = 1/\ln(5) = 0.622$

Then substituting the values of Pi and c, we have

$$S_{exterior} = 1.1$$

Now, this value of information entropy should be normalized to timetable stability index using equation (3). That is,

$$G_{interior} = \begin{cases} 0 & S_{exterior} \le M \\ \frac{S - M}{L - M} & M < S_{exterior} < L \\ 1 & S_{exterior} \ge L \end{cases} \cdots\cdots\cdots\cdots\cdots (5)$$

Where, M is the lower bound of S and L the upper bound of S. And the corresponding set value of M is 0.9 and also the set value of L is 1. Then equation (5) holds true for $S_{exterior} \ge L$ that means $S_{exterior} > 1$. Hence, the corresponding normalized interior timetable stability index, $G_{exterior} = 1$

Since the timetable stability is affected by the interior factors and the exterior factors, then, the timetable stability value W is given by the product of the interior timetable stability value and exterior timetable stability value.

That is,

$$W = G_{interior} \times G_{exterior} = 1 \times 1$$

$$W = 1$$

Hence, the timetable stability value is 1. Based on this value, the following suggestion has been given.

Discussion on the computed stability value of LRT

The value of the timetable stability obtained above is the maximum possible one. This shows that the timetable to be designed based on the identified timetable data of LRT, will be stable. In this sense, we are certain that the network will not encounter schedule failure as far as the conditions are kept the same. That is the operation of the 37 trains in the network of Addis Ababa LRT with the cycle time of 3minutes at the shared rail sections and 6minutes at other sections with the passengers load forecasted, the intended service can be delivered at very efficient level. Hence, unless in the future the transportation demand exceeds the forecasted level and the trains & infrastructure status decline, keeping track of this stability level is possible for LRT. So, professionals may proceed to set the timetable for Addis Ababa LRT operation having the above timetable data.

However, disturbances due to unforeseen events may happen to the timetable of Addis Ababa LRT. In such situation, there should be a monitory technique to reduce delay and propagation of the disturbances to recover the original status of the LRT timetable. For this purpose the following monitoring technique can be used.

Timetable monitory technique

The extent of recoverability of timetable in the case of disturbance depends on the amount of total buffer times added, the performance of each train, the speed limit along the routes, etc. Based on the data of Addis Ababa LRT, the amount of recoverable time can be estimated in this way. Hence, in order to keep the timetable stabile, for the Addis Ababa LRT, the following monitoring technique can be employed.

a) Distribution of recovery times

Trains are usually driven with a speed below the line speed for safety reasons. In the case of occurrence of any disturbance leading to train delay, the train timetable can be recovered by driving the train faster than the scheduled speed before delay. The train may be required to be driven to the line speed for such recovery purpose. In this manner the train may reduce the amount of delay and maintain the stability of the timetable.

b) Distribution of buffer times

Another way we can use to monitor small train timetable disturbance is by careful distribution of buffer times. In this case, some parts of the buffer times are allocated for train travel time. Hence, the delay time may be recovered and train may arrive at less delayed or even on time to avoid delay propagation. Accordingly, the train timetable will be kept stable.

Contribution of the research work

The finding of the research work is new in its kind and the advance one than any other previously developed methods of evaluating railway timetable stability. It evaluates the stability of railway timetable at a faster rate and in an advance approach. Hence, this makes the research output to be unique and enables it to increase the existing stockpile of knowledge by contributing one more method of evaluating railway timetable stability.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

The method proposed in this research takes into account both the interior factors and the exterior factors affecting the train timetable stability. The interior factors affecting railway timetable stability are the total time supplement for running in the sections, the total time supplements for dwelling on the stations, the timetable periodic time, the buffer times between train paths, the heterogeneity of the planned train traffic, the capacity load of the sections and the capacity load of the stations. And the exterior factors affecting railway timetable stability are the grade of the railway lines, the blocking system type, the station interlocking type, the leading locomotive traction performance and the average mileage of the sections. The interacting relations between these factors have been analyzed for both the interior and exterior factors separately. Values of interacting determinants among the factors are the superficial elements to affect the evaluating results, which are given by the researchers and experts. Researchers and experts marked the values in light of their experience, knowledge and the relative data of the timetable. And these values are analyzed using the concept of information entropy method for railway timetable stability analysis. In this method, the effects of factors affecting the stability of railway timetable can be introduced and their effect can be observed easily. Accordingly, the model developed taking into account all the above factors can evaluate the train timetable stability effectively and can provide decision supporting information in timetable design process. Also, the method proposed has the potential to evaluate the stability of a railway network as a whole rather than only considering the effect of a single train’s section or station. Furthermore, the proposed method can be applied to both the periodic and non periodic railway timetable. Accordingly, this method is applicable to the train timetable in the city (usually periodic timetable) and intercity (may be non-periodic timetable). This makes the method to be applicable to any train network all over Ethiopia. All these contribute the developed method to be the more advance and advantageous one.

6.2 RECOMMENDATIONS

The method of railway timetable stability evaluation approach presented in this paper is very helpful in providing necessary information required during timetable design process or evaluating the stability of an existing railway timetable. Also the method is capable of realizing the probable situations of railway operation into a more quantified and feasible status. In its kind, the research output is advance type that can enhance the existing potential of timetable stability analysis and maximize efficiency of railway operation. Since, the method proposed has the potential to evaluate the stability of a railway network as a whole rather than only considering the effect of a single train's section or station and can be applied to both the periodic and non periodic railway timetable; and it takes into account both the interior and the exterior factors, hence its application will have higher benefit without outlaying higher effort and longer time as its application is so easier. This has been shown with the application of the method to the case of Addis Ababa LRT Project considering the initial phase. In that the method is applicable to any one of the railway network in Ethiopia or elsewhere in the world. Therefore, the Ethiopian Railway Corporation should put the proposed method into practice for the currently ongoing construction of the railway networks in Ethiopia, to have the benefits of the proposed method.

Further research is directed toward more advancing the method in applying the information entropy theory concept for timetable stability evaluation by including more affecting factors and restrictions to obtain a more practical timetable with high quality.

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Annex - A

Interacting Determinants matrix

Table 11 and Table 12 below were made to be filled by experts using the weighting values described as below for the Addis Ababa LRT timetable.

Weighing values:

- If one factor **does not** interact on the other one give value = 0
- If one factor interact on the other one **very weakly** give value = 1
- If one factor interact on the other one **weakly** give value = 2
- If one factor interact on the other one **moderately** give value = 3
- If one factor interact on the other one **strongly** give value = 4
- If one factor interact on the other one **very strongly** give value = 5

The Interior Factors	The capacity load of the sections	The capacity load of the stations	The total time supplements for running in the sections	The total time supplements for dwelling on the stations	The timetable periodic time	The buffer time between train paths
The capacity load of the sections	-	3	1	3	0	0
The capacity load of the stations	4	-	1	3	0	0
The total time supplements for running in the sections	0	0	-	2	5	4
The total time supplements for dwelling on the stations	1	2	1	-	4	4
The timetable periodic time	1	1	5	3	-	2
The buffer time between train paths	1	1	5	2	3	-

Table 11: Interacting determinants matrix of the interior factors

The Exterior Factors	The grade of the railway lines	The automatic blocking system	The station computer interlocking	The leading locomotive performance	The average mileage of the sections
The grade of the railway	-	5	1	5	4
The automatic blocking	2	-	5	1	4
The station computer	1	2	-	1	1
The leading locomotive	5	5	1	-	1
The average mileage of	4	5	1	5	-

Table 12: Interacting determinants matrix of the exterior factors

Declaration

I, the undersigned, declare that this study entitled: "*Railway Timetable Stability Analysis: Case of Addis Ababa LRT*" is my original work and has not been presented for a degree in any other university, and that all sources of materials used for the study have been duly acknowledged.

Declared by:

Name: Asfaw Workineh

Signature ______________________________________

Date____

This is to certify that the above declaration made by the candidate is correct to the best of my knowledge.

___________________________ ______________________

Dr. Gulelat Gatew Date

(Advisor)