ADDIS ABABA UNIVERSITY

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AFRICAN RAILWAY CENTER OF EXCELLENCE

Performance Investigation on AA-LRT Automatic Train Protection System

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A Thesis in Railway Engineering (Traction and Train Control)

By

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Addis Ababa

A Thesis

Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

The undersigned have examined the thesis entitled '**Performance Investigation on AA-LRT Automatic Train Protection System**' presented by **Nahom Assefa**, a candidate for the degree of **Master of Science** and hereby certify that it is worthy of acceptance.

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Chair Person	Signature	Date

Undertaking

I certify that research work titled “Performance Investigation on AA-LRT Automatic Train Protection System” is my own work. The work has not been presented elsewhere for assessment. Where material has been used from other sources it has been properly acknowledged / referred.

Nahom Assefa

Abstract

Railway signalling system consists of the system, the device and means by which trains are operated safely and efficiently. Signalling enables the movement of trains to be controlled in such a way that the existing tracks are utilized to the maximum while maintaining the safety of passenger, rolling stock and the staffs. As part of signalling automatic train control system, the Automatic Train Protection (ATP) is applied to assure the safety of train movement by preventing collisions and derailments.

In this paper a feared event model (ATP not available) of the Addis Ababa Light Rail Transit (AA-LRT) signal Automatic Train Protection system (which is an intermittent type) is developed from system composition and configuration using a Fault tree. The in-depth analyses of the Reliability, Availability, Maintainability and Safety (RAMS) of the AA-LRT signal intermittent-Automatic Train Protection (iATP) system is performed using the signalling system detailed design data and maintenance data. The signal iATP system is composed of different subsystems in series like the Line-side Electronic Unit (LEU), Beacon (B), Trackside Radio Equipment (TRE), Carborne Controller (CC), Driver Machine Interface (DMI), Beacon Antenna (BA), Onboard Antenna (OA) and Odometer (OM).

Mathematical model of the signal iATP subsystems have been developed using Markov process. The selected study methodologies which are quantitative and analytical data analysis methods are evaluated and graph is plotted for different time intervals. Hence the reliability and maintainability of every subsystems are evaluated with graph to investigate their performance at different time intervals.

The analysis from this thesis shows that the reliability of the LEU, Beacon (B), TRE, CC, DMI, BA, OA and OM are 0.9753, 0.9975, 0.9048, 0.9512, 0.9875, 0.9631, 0.9559 and 0.9875 respectively after 2500 hours of operation, the reliability of the entire signal iATP system after 2500 hours of operation is 75.16 % and the maintainability of the LEU, Beacon (B), TRE, CC, DMI, BA, OA and OM after one hour are 0.9092, 0.8997, 0.8646, 0.9257, 0.9391, 0.8891, 0.8775 and 0.8891 respectively according to the design and maintenance data.

Keywords: intermittent-Automatic Train Protection, Reliability, Availability, Maintainability, Safety, Fault tree, Markov process.

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At last, I would like to pay my respects and love to my parents, all other family members and friends for their encouragement and persistent support throughout my thesis work.

Contents

List of Figures

List of Tables

List of Abbreviations

Abbreviation	Meaning
AA-LRT	Addis Ababa Light Rail Transit
AGAN	As Good As New
AP	Access Point
ATC	Automatic Train Control
ATP	Automatic Train Protection
ATS	Automatic Train Supervision
B	Beacon
BA	Beacon Antenna
CBI	Computer Based Interlocking
CC	Carborne Controller
CI	Computer Interlocking
CPM	Central Processing Module
CPU	Central Processing Unit
DCS	Data Communication System
DMI	Driver Machine Interface
DT	Down Time
EB	Emergency Brake
EW	East-West
FMEA	Failure Modes and Effects Analysis
FMECA	Failure Modes, Effects and Criticality Analysis
FTA	Fault Tree Analysis
iATP	intermittent-Automatic Train Protection
LEU	Line-side Electronic Unit
LRT	Light Rail Transit
MA	Markov Analysis
MSS	Maintenance Support System
MTBF	Mean Time Between Failure
MTIB	Moving Train Initialization Beacon
MTTR	Mean Time To Repair
NRM	Non-Restrictive Mode
NS	North-South

Abbreviation	Meaning
OA	Onboard Antenna
OCC	Operation Control Center
OM	Odometer
PSR	Permanent Speed Restriction
RAMS	Reliability, Availability, Maintainability and Safety
RBD	Reliability Block Diagram
RM	Restricted Mode
RMF	Restricted Mode Forward
RMR	Restricted Mode Reverse
RRT	Relative Restoration Time
RT	Restoration Time
SER	Signal Equipment Room
SIL	Safety Integrity Level
SoS	System of Systems
TBF	Time Between Failures
TFF	Time to First Failure
THR	Tolerable Hazard Rate
TMS	Train Management System
TRE	Trackside Radio Equipment
TTM	Time To Maintain
TTR	Time To Restore
UT	Up Time
VIOM	Vital Input Output Module
WO	Work Order
WT	Waiting Time

1. Introduction

1.1 Background

The Railway signalling is the basic safety system controlling the movements of trains. It is the safety critical part of the train control function of the railway. Once instructed by a signaler or an automatic system, it is responsible for setting up non-conflicting and safe routes for trains, for defining (safe) limits of movement and for transmitting instructions or commands to train drivers. There are two principal parts to a train protection system, train detection (knowing where the train is) and movement authority (telling the train how far it can go). The train protection system uses these two parts to safeguard a train's operation.

During the many years of use of railway signalling, drivers' failures to respond to commands transmitted by signal aspects of any type can and have led to a number of accidents, some causing very large numbers of fatalities. In response to the continuing need to reduce risks created by train drivers failing to respond to signal instructions, various forms of driver warning devices and signal command enforcement systems have been developed. These have become known as Train Protection Systems. Those systems that continuously monitor actual train speed and enforce adherence to a commanded speed pattern are referred to as Automatic Train Protection (ATP) systems [5].

The Automatic Train Protection systems are based on the desire to reduce or eliminate the possibility of driver error resulting in a train movement related accident by failing to obey a visually displayed line-side or in-cab signal instruction.

In general, an advantage of Automatic Train Protection system as part of Automatic Train Control (ATC) is that it increases the safety of operation, the train speed and separation between the trains are controlled automatically rather than being human controlled.

This thesis is about performance investigation on AA-LRT Automatic Train Protection system in which the Addis Ababa Light Rail Transit (AA-LRT) signalling system incorporates Automatic Train Protection features. The project work focuses mainly on studying and analysing the

Reliability, Availability, Maintainability and Safety (RAMS) of the ATP system of AA-LRT and its subsystems by calculating their failure rate and repair rate to estimate their RAMS.

1.2 Problem Description

The aim is analysing the performance of AA-LRT signal Automatic Train Protection system (which is an intermittent type) Reliability, Availability, Maintainability and Safety. The RAMS of a railway system is influenced in three ways: by sources of failure introduced internally within the system at any phase of the system (system conditions), by external sources of failure on the system during operation (operating conditions) and by external sources of failure on the system during maintenance activities (maintenance conditions) [1]. These sources of failure can interact, and can affect greatly the operating performance of the railway systems, explaining the large discrepancies observed between intrinsic and effective reliability of existing systems.

The functionality of a railway signalling system is based on the principle of "fail safe"; this means the railway section where a failure is located will not be fully operative, until the failure is repaired, to ensure safety. Since a failure of the signalling system still allows operation of the railway, albeit limited, it is not sufficient to study its effect on the railway operation in terms of reliability and safety by considering only the failures and delays [2].

Furthermore, with a failed signalling ATP system, a driver will operate in a degraded mode, with safety assured by other mitigation measures, such as low speed restrictions. The possibility of operating in a degraded mode reduces the economic and operational effects of a failure of the signalling systems, but makes it more difficult to evaluate the railway operation, since a failure will not necessarily be visible when considering the delays or cancelations, even though safety has been compromised.

Different approaches can be used to evaluate the Reliability, Availability, Maintainability and Safety of railway signalling systems. As stated by Restel [2], the classification into the subsets of availability and failure is not sufficient to model the Reliability, Availability, Maintainability and Safety of the railway signalling system like ATP. There is a need for evaluating the safety and

availability of the railway operation, and to quantify the probability of the ATP signalling system not to supervise the railway traffic.

Therefore, this thesis fulfils the above need, by presenting a framework to evaluate the Reliability, Availability, Maintainability and Safety of AA-LRT operation, focusing on the effects of ATP signalling subsystem (See Figure 1.1). It also can motive to establish a safe, reliable and efficient train operation of AA-LRT by analysing and evaluating the RAMS of the signal intermittent-Automatic Train Protection (iATP) system. The developed methodology for Reliability, Availability, Maintainability and Safety evaluation of the AA-LRT operation for signal iATP system is presented.

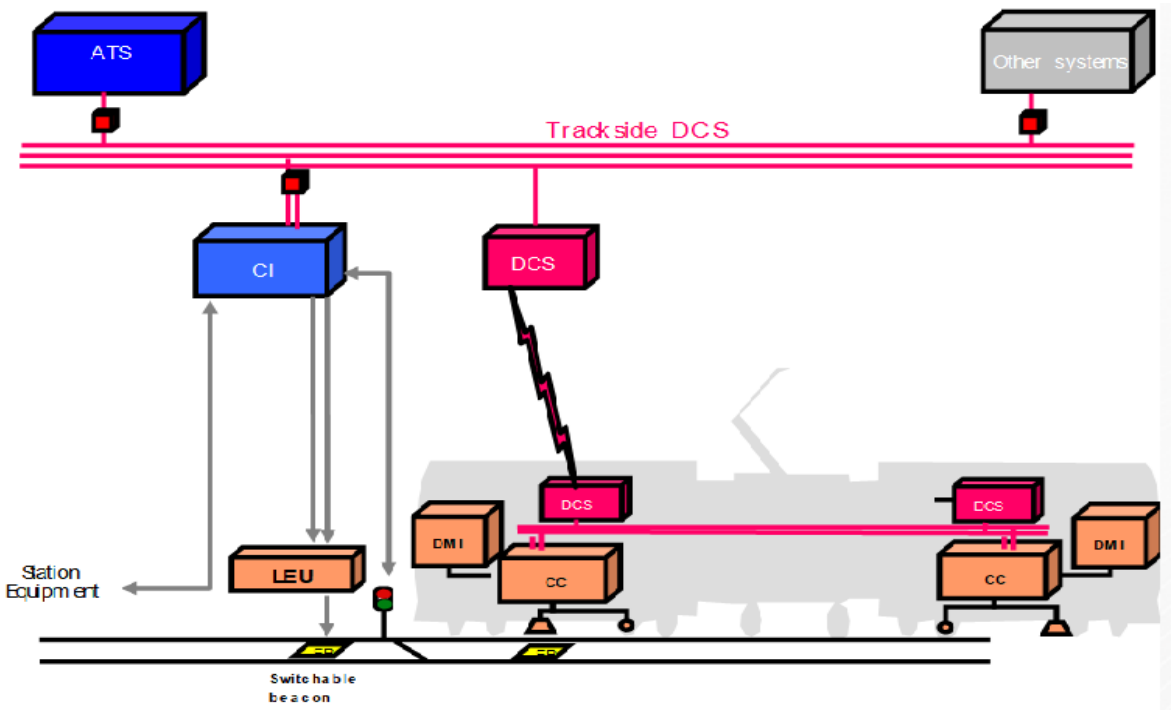

Figure 1.1: Scope of AA-LRT signal iATP system [15].

(The Signal iATP system scope is represented by orange boxes (beacons in yellow color); DCS in pink color, the other signal subsystems are in blue color and the external systems in grey color)

1.3 Objective

1.3.1 General Objective

The main goal of this study is to perform an in-depth analysis on the Reliability, Availability, Maintainability and Safety of the AA-LRT Automatic Train Protection system; and increasing the effectiveness of the Automatic Train Protection signalling system, reducing maintenance and sparing cost and develop the monitoring tools required by modern safety management.

1.3.2 Specific Objective

Specifically, it is aimed:

- To estimate reliability and maintainability pattern of the signalling automatic train protection subsystems at different time intervals.
- Increasing the effectiveness of the AA-LRT automatic train protection system.
- Proposing various approaches to improve the maintenance performance of the AA-LRT automatic train protection system.
- Identify and evaluate the principal technical challenges related to signalling automatic train protection system.
- And make recommendations pertaining to the selection of effective automatic train protection systems.

1.4 Methods and Materials

1.4.1 Methodology

The methods employed to achieve the objectives of the thesis include:

- **Literature Reviewing:** This includes reading books, articles, forums and simulation tools related to the system.
- **Data Collection and Analysis:** Collection of data includes primary data (design data, maintenance record and from field observation) and secondary data (from books, stake holders' inputs and other documented file) sources. The data analysis techniques are qualitative, quantitative and analytical data analysis methods.
- **System Modelling:** Model the current AA-LRT signalling Automatic Train Protection system by fault tree to evaluate the occurrence probability of the feared event; and Markov process to evaluate failure rate and repair rate at different time interval.
- **Simulation:** Using the model presenting the data analysis graphically, by charts, and tabular formation by Matlab simulation software.
- **Performance Evaluation, Comparison and Interpretation of the Results:** This involves evaluating the performance of the AA-LRT signalling ATP system by mainly focusing on assessing the RAMS aspects of the system and interpreting the results obtained.

1.4.2 Materials

Software tools are used to effectively model and simulate the system (realize the thesis objective). That is, the collected data and information are processed and combined for the analyses with Microsoft Excel and Matlab /Simulink used for data processing, model development and verification.

1.5 Literature Review

Railway system is a system engineering that plays a crucial role in transportation and research works has been done in the field from many years. The railway signalling system can be considered as a system of systems (SoS) [3], and the interoperability between the different systems needs to be assured for safe, reliable and efficient operation. There have been some frameworks done in availability and safety of the railway signalling systems in previous research. The article by B. Friman & T. Andreiouk [4] is about describing an automated system testing framework for a SIL 4 safety critical train protection system.

In Daniel Woodland [5], the study shows main line and metro railway models demonstrate a good case for the implementation of ATP in a continuous in-cab form and for the adoption of moving block rather than fixed block train separations, at least in the area of in-line station platforms for capacity enhancement. Also Amparo M. et al., [6] provides a framework to evaluate the safety and availability of the railway operation, and quantifying the probability of the signalling system not to supervise the railway traffic by Markov model. Furthermore, the complex architecture of electronics and the interdependency between the components and systems of railway signalling make it difficult to identify and analyse uncertain behaviours [7]. The effects that different improvements of signalling system can have on the safety and availability of the railway operation are also presented in [8].

Various authors have evaluated the availability and/or safety of railway signalling systems: Markov Chains [9], Monte Carlo Simulation [10] and Stochastic Petri Nets [13-14] are suitable approaches for stochastic modelling to evaluate the RAMS of a railway signalling system. RAMS problems are normally concerned with systems that are discrete in space, i.e., they can exist in one of a number of discrete and identifiable states and are continuous in time; i.e., they exist continuously in one of the system states until a transition takes them discretely to another state, in which they then exist continuously until another transition occurs [11]. In INFRALERT consortium [16], RAMS data collection and failure rate analysis at component level for linear infrastructure efficiency improvement which uses optimized predictive maintenance techniques was presented. Also Alemu Jima [12] performs an investigation on the AA-LRT signal level crossing system where the system modeled and identified using the Markov approach.

1.6 Scope of the Study

The scope of this research was to perform an exploratory analysis which will provide visibility to the best areas to consider improving the reliability, availability, maintainability and safety of the railway signalling ATP system of AA-LRT. The case study of the AA-LRT railway signalling ATP system operation performance within NS10 Signal Equipment Room (SER) control zone is analysed. That is the study area for ATP operational performance in main line includes from Adey Ababa Station (NS9) to Temenja Yazh Station (NS13).

1.7 Thesis Outline

The thesis is organized as follows:

- Chapter 1 deals with the overview of railway transportation and the importance of Automatic Train Protection system. The AA-LRT signal ATP feature is provided and objectives of present work is discussed. Many research works have been done to improve the performance of signalling systems to make it more safe, reliable and efficient. Thus, different literature survey is also done.

- Chapter 2 presents AA-LRT Automatic Train Protection System overview. The different signal iATP subsystems are described. The functions and importance of every subsystem is discussed. Performance through reliability, maintainability, availability and other terms are defined which is used in this paper.

- Chapter 3 deals with different qualitative and quantitative reliability and safety analysis techniques with comparisons. Also the different railway operational states were explained.

- Chapter 4 deals with the identification of the model that describes the RAMS of AA-LRT signal iATP system.

- Chapter 5 presents results and discussions on the quantities of availability (i.e. reliability and maintainability) of AA-LRT signal iATP system and the safety impacts on operation.

- Chapter 6 presents conclusions and recommendations of the thesis work.

2. AA-LRT Signal Automatic Train Protection System

2.1 AA-LRT Overview

The LRT Project in Addis Ababa, the capital of Ethiopia, consists of the East-West Line and the North-South Line. The line is mostly based on ground line. Elevated line and underground line are adopted in some sections. The total length of the planned line in phase 1 and phase 2 is approximately 75km. This AA-LRT project is implemented in the scope of the Phase I Project of these two lines and the total length of line is approximately 31km; wherein, the length of shared track section is approximately 2.662km, from Meskel square to Lideta. The full length of main line of the East-West Line is approximately 16.998km and the full length of main line of the North-South Line is 16.689km.

The East-West Line Phase I Project starts from the south side of gate of Tor Hailoch Hospital in the west. It runs through the Mexico Square, the Mesekel Square and the Megenagna and finally runs to the Ayat. The major roads which the line passes include: Chad St., Ras Mekonen St., Jomo Kenyatta St., Haile Gebre Silasie St., Equatorial Guinea St. and etc. The length of roadbed section in the East-west Line is approximately 12.891km, the length of elevated section is approximately 3.91km (including the 2.662km shared track section) and the full length of underground section is 0.197km. Totally 22 stations are set; wherein, 6 elevated stations (including 5 shared track stations) and 2 semi-underground stations are included and the rest stations are ground stations. The maximum distance between stations is 1.26km, the minimum distance between stations is 0.435km and the mean distance between stations is 0.798km [17].

The North-South Line Phase I Project starts from the east side of St. George Church in the north. After it is laid in a section along the north side of Merkato Market, it turns to the south. After it runs through the west side of this market to the Chad St. and connects the track of the East-west Line, it is laid to the east. It runs to the west side of Mesekel Square and turns to the south. It goes through the Meshalokia Bridge and the China-Ethiopia Friendship Bridge from lower side and finally it runs to the Kality. The major roads which the line passes include: Fitawrari Gebeyebu St., Gyorgis St., Central Afican Republic St., Dej. Mekonin Demisaw St., Dej. Bekele Weya St.,

Chad St., Ras Mekonen St., Ras Biru St., Sierra Leone St., Beyene Aba Sebsib St. and Debre Zeit Rd. The length of roadbed section in the North-South Line is approximately 10.057km, the length of elevated section is approximately 5.977km (including the 2.662km shared track section) and the full length of underground section is approximately 0.655km. Totally 22 stations are set; wherein, 8 elevated stations (including 5 shared track stations) and 1 underground station are included and the rest stations are ground stations.

The maximum distance between stations is 1.972km, the minimum distance between stations is 0.435km and the mean distance between stations is 0.773km. The system operates with a traction power of 750 V DC /Direct Current/ and planned to accommodate 41 operating trains, 21 trains for the East-West (EW) Line and 20 trains for the North-South (NS) Line. The trains being provided with the automatic train protection device, communication device, broadcast facility and emergency lighting device [18].

The Operation control center and maintenance center of this project is located inside the Kality Depot for the East-West Line and the North-South Line share the same Operation Control Center (OCC). In order to provide the position information of the train, AA-LRT uses Axle counter which doesn't provide the exact position of the train but the section occupancy or vacancy information with the help of the sensors installed on the track [21]. The AA-LRT commercial operation is started on September 20, 2015 and it is supervised by the signalling system with fixed block principle. The signalling system which has to be safe, reliable, practical and economical, and having engineering application experience [18].

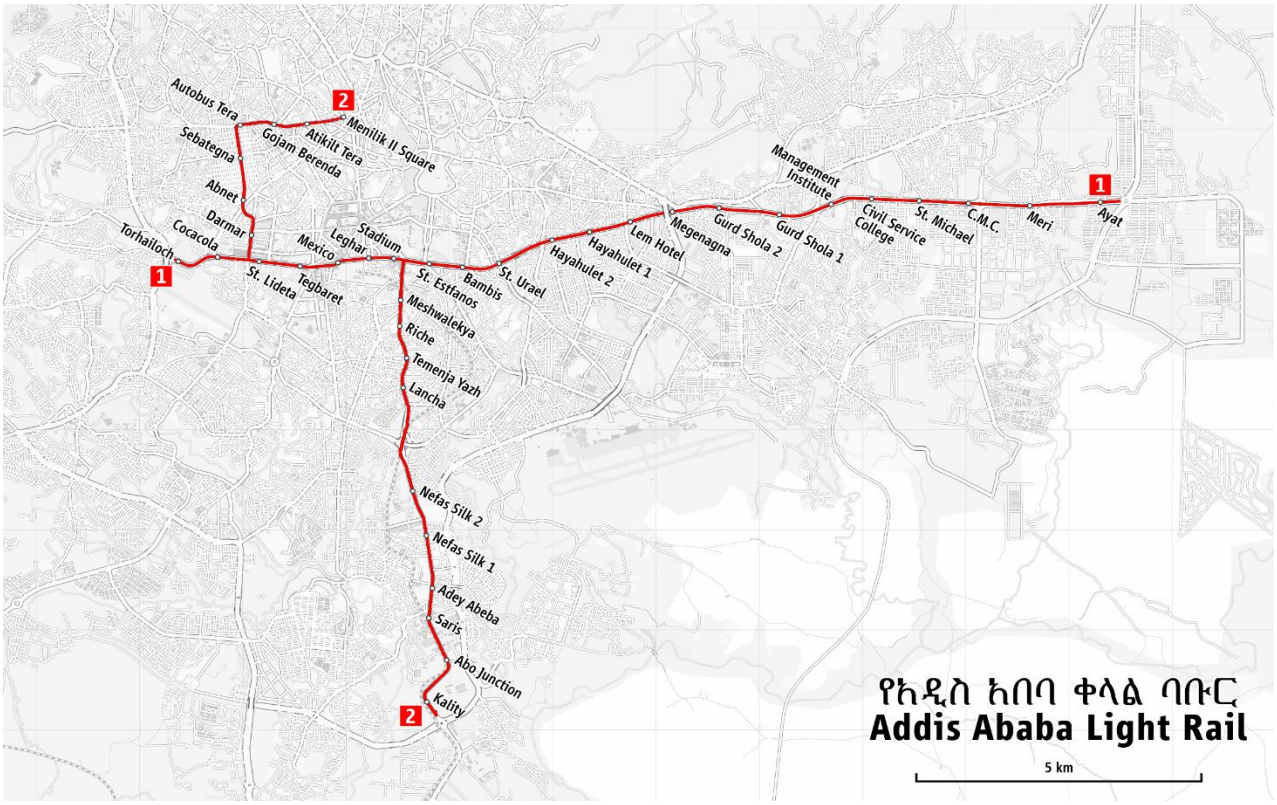

Figure 2.1: Track Layout Diagram of AA-LRT East-West Line (1)/North-South Line (2) Phase I [27].

Generally; the AALRT Signalling System includes the following subsystems: ATS, iATP, CBI, DCS, MSS, Level Crossing System and Power Supply System.

ATS is the Automatic Train Supervision system which provides super visionary functions to the staff concerned. It has redundant DGRAY and LGRAY networks.

iATP is an intermittent-Automatic Train Protection System which provides safety functionality when trains are driven in mainline for operation results in speed restriction and protecting functions to the rolling stock, the staff and the passengers. It has on-board equipment's and wayside equipment's.

CBI is the Computer Based Interlocking System which performs the logical relations /interlocking logic/ between the routes, signals and point machines so as for the safe, reliable and efficient

railway operation. The interlocking system is also termed as the brain of the signalling system having redundant RED and BLUE networks.

DCS is the Data Communication System which provides the communication channel for the signalling subsystems to interchange information. That is, the signalling system devices of AA-LRT communicate through the DCS / Data Communication System/.

MSS is the Maintenance Support System which provides playbacks, alarms, equipment status and logs to the maintenance staff so that it helps to solve system problems in time.

Level Crossing System is a system that indicates the road users i.e. cars or pedestrians that the train arrives and the right of way has to be given to the train. It has barriers to close the road for protection of accidents from happening.

Power Supply System is an intelligent power supply panel which is provided for the AA-LRT signalling subsystems functionality that continuously monitors and distribute power to the subsystems.

Railway transportation of people and cargo has many advantages compared with other modes of land/air transportation. Among these advantages: better control on schedule and travel time, lower exposure to risk factors such as heavy traffic and road accidents, more comfortable seating, contribution to environment and economy. Another advantage of electrified railway system is that the needed energy is delivered to the train when needed, unlike the other modes of transportation (land, air, sea) where the source of energy must be carried by the vehicle for the duration of the journey.

Recently, Ethiopia is constructing railways throughout the country for freight and public transport. Among these projects Addis Ababa Light Rail Transit start its work before $3\frac{1}{2}$ years. The project has built with more than 450 million USD budget and constructed by the Chinese contractor China Railway Engineering Corporation - CREC and a Swedish consultant - SWEROAD [21].

2.2 Automatic Train Protection System

2.2.1 Composition of AA-LRT signal iATP system

The Automatic Train Protection system of AA-LRT is an intermittent-Automatic Train Protection (iATP) type**.** That is, unlike continues throughout the line it uses intermittent transmission where some part of the area uses the access point (AP) located on the Track Side Radio Equipment (TRE) to transmit data to the trains wirelessly through onboard antenna where as in some other places uses beacons for data transmission necessary for protection functions such as speed limits, slope, information of track ahead and status of wayside equipment's like signals opening/closing and point machine position /normal or reverse/ through beacon antenna [15]. The AA-LRT signal iATP system includes the following equipment: (as observed in Figure 1.1 in Chapter 1)

- CC- Carborne Controller
- DMI- Driver Machine Interface
- LEU- Line-side Electronic Unit
- Beacon
- Beacon Antenna
- Coded odometer
- TRE- Trackside Radio Equipment (Trackside Data Communication System /DCS/)
- Onboard Antenna (onboard DCS)

i) Trackside iATP Equipment:

The LEU, TRE and beacons are trackside iATP equipment, in which the LEU located in main station SER, the TRE are located along the track side and the beacons are located between the track gauge lines.

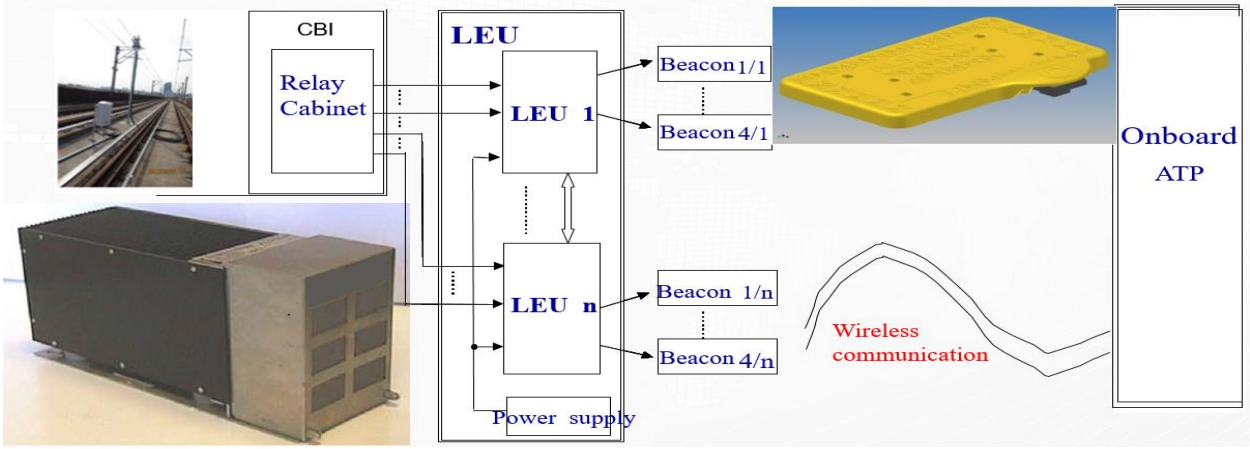

Figure 2.2: Trackside iATP Equipment [15].

Line-side Electronic Unit (LEU)

The LEU subsystem allows acquisition of trackside variable information from CBI equipment and provides messages to switchable beacon (active beacon) installed at signal proximity. The LEU is the safety related track-side equipment interfaced with the lateral signalling and beacon.

Trackside Radio Equipment (TRE)

The TRE is a trackside Data Communication System (DCS) which mainly consists of Radio Modem, Media Converter, Fiber Box and an Access Point (AP) antenna that transmits information wirelessly to the train onboard antenna.

The Trackside Radio Equipment Access Points (AP's) can be found as in RED Network or BLUE Network. But for redundancy mechanism can be found in both RED and BLUE Networks as per the design.

The following figure below shows the TRE components as observed in the Trackside Radio Equipment box.

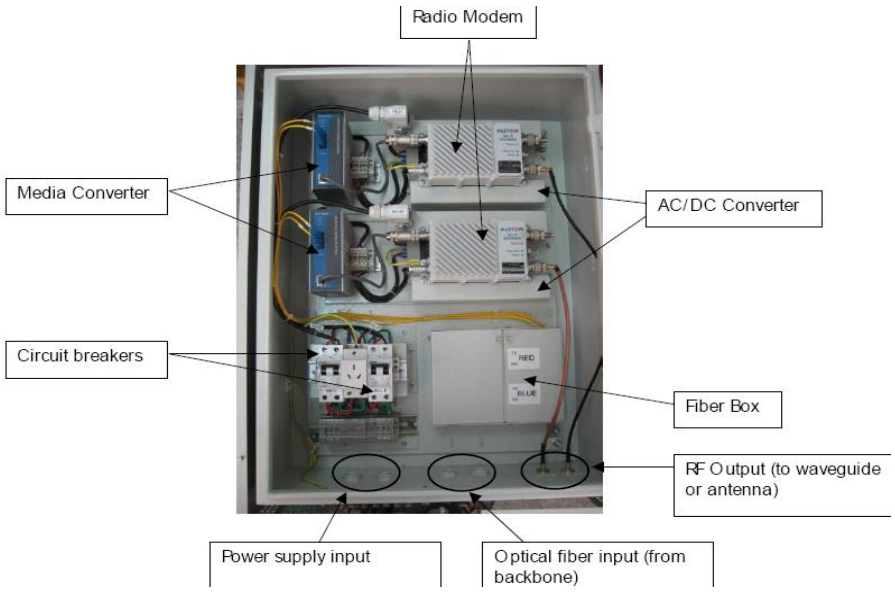

Figure 2.3: The Component of TRE ("Picture taken between NS9 & NS10 track section of TRE/N: AP21009").

Beacon

The Beacon allows the CC to acquire punctually trackside information when train crosses the beacons. Two types of beacons are installed on the track: Active beacon (B) and Passive beacon (RB i.e. Re-localization Beacon). The active beacons transmit variable information such as the state of the track ahead (occupied or not), position of switch and type of signal aspect obtained from the LEU whereas the passive beacons transmit constant information such as slope of the line, location, constant speed information to the train on-board equipment through the beacon antenna.

Two consecutive RB are used for the initialization of the localization of the train. RB could be used for the train to re-localize. As the odometer is mounted on a non-free axle (braked axle), the maximum distance between 2 beacons shall not be over 400m but for redundancy (one missed beacon allowed), and one beacon is installed at least every 200 m. In stations and in the place where a precise stop is needed, RB are installed at specific places in order to perform precise stop.

When the iATP functionality is implemented, B (Beacon) which is linked with LEU subsystem provides the CC with track singularities status: i.e. signals status and point machines status.

ii) Onboard iATP Equipment:

Onboard iATP equipment includes: Carborne Controller (CC), Driver Machine Interface (DMI), Beacon Antenna, coded Odometer and Onboard Antenna (onboard DCS). All of them are connected to a redundant signalling network as shown in the figure below.

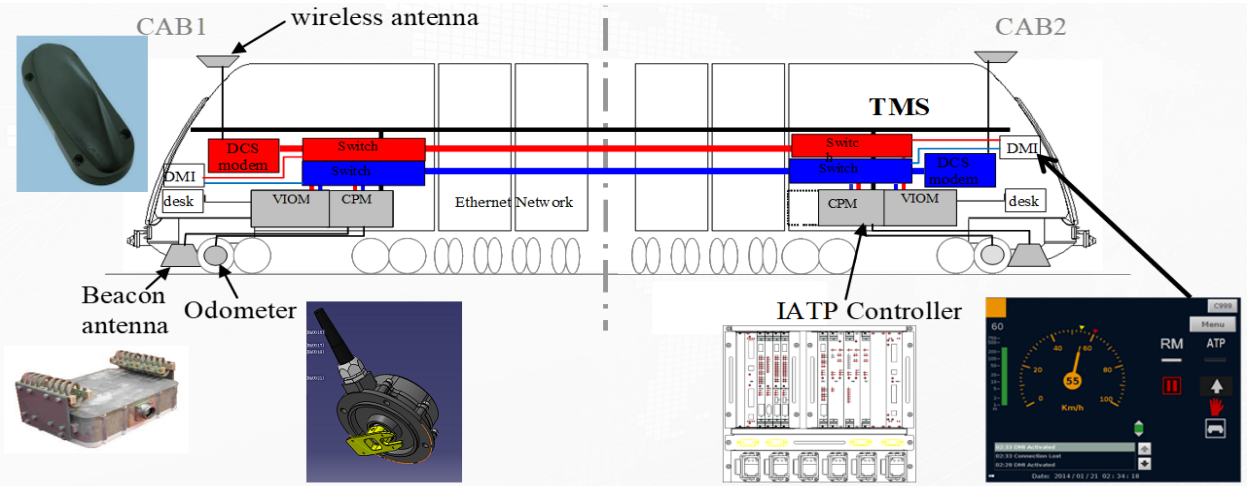

Figure 2.4: Onboard iATP Equipment [15].

Carborne Controller (CC)

The Carborne Controller (CC) is the central processor of the signal iATP On-board equipment in which it gathers information from beacon antenna, odometer, onboard DCS and transmits information to be displayed to the train driver through DMI. The CC rack consists of Central Processing Module (CPM) and Vital Input Output Module (VIOM).

Odometer

The odometer provides safe sensor of the train displacement and acquires speed [28]. It has an optical sensor which is installed on an axle of a wheel; and hence it provides zero velocity information to CC.

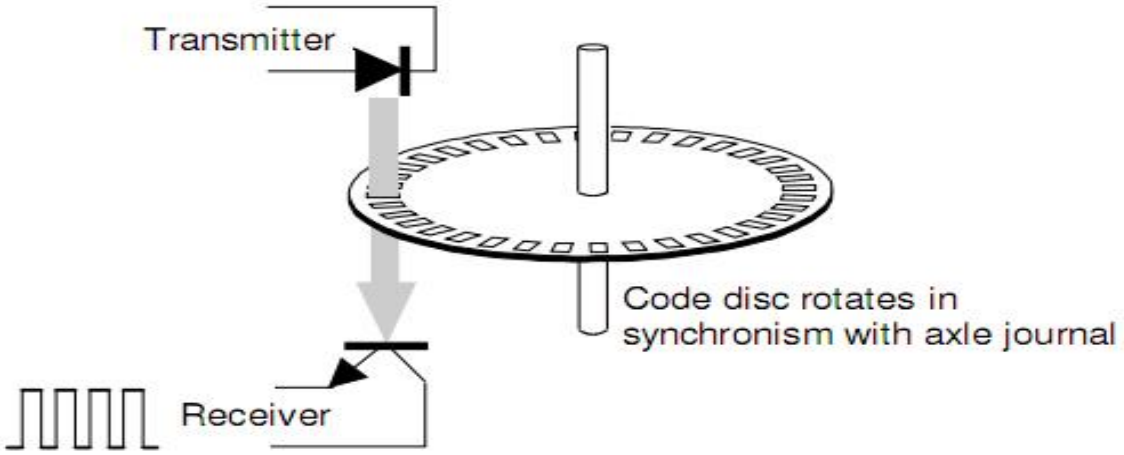

Figure 2.5: Coded Odometer [15].

Beacon antenna

Beacon antenna is track to train spot transmission device. It is installed under the car and one antenna by CPM of the CC. Beacon antenna performs air-gap transmission between the beacons and the safe processor unit; and it is powered from the CPM of CC.

Driver Machine Interface (DMI)

DMI is a Driver Machine Interface device. DMI offers a friendly user interface and represents a modern driving supervision method allowing improving the driving ergonomics and the overall traffic management. It is equipped in each cab and communication is done by means redundant system. The DMI, in its compact version, is composed with a screen and a CPU (Central Processing Unit) screwed together [28]. The screen part is 10.4".

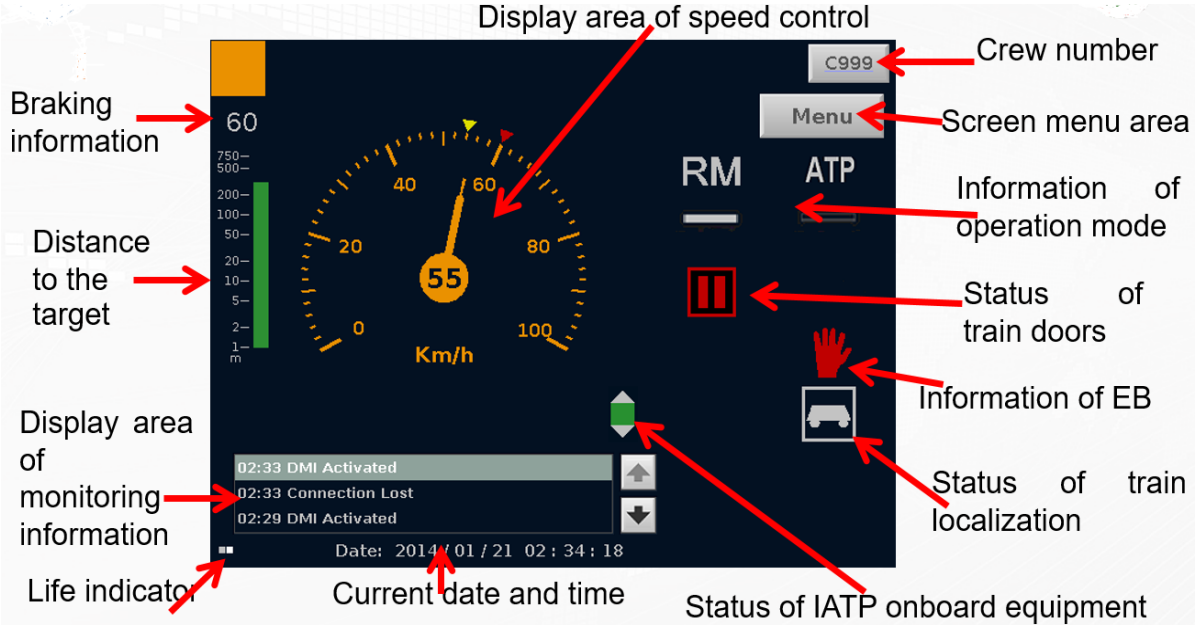

Figure 2.6: Screen Layout of DMI [15].

The functional descriptions on DMI include: iATP Braking information, Target distance and speed information, iATP status, Restricted Mode (RM) selection status, RM availability status, ATP mode availability status, Train door state, Emergency information, Localization information, Life indicator, Current date and time, Text message, Menu button and Crew number button.

Onboard antenna

Onboard antenna (wireless antenna) is an onboard DCS whereas the train communicates information with the TRE.

2.2.2 Functions of Signal iATP system

The signal iATP is a crucial signalling system together with other subsystems that ensures the AA-LRT operation safety and reliability. That is the iATP system protects the passengers, the rolling stock and the staff from a severe accident due to abnormalities and the so-called of over speeding. The following include the functions provided by iATP [15].

Update track description:

The objective of this function is to calculate the track description and status according to inputs given by the CBI.

Train can get trackside information by two ways:

- One is when train pass the switchable beacon, iATP can get trackside information through LEU by beacon antenna.
- Another is when train enter the radio area with the spacing signal in normal direction with iATP protection, (this area will consider safe braking distance and time for radio establishment) iATP can get trackside information through CBI by radio.

Determine cab kinematics:

The objective of this function is to compute safety kinematics information. That is to measure train movement with automatic calibration by MTIB /Moving Train Initialization Beacon/, compute speeds and acceleration, determine the information of complete train stop i.e. only if during odometer detecting speed, zero speed information will be compared with other cab and if this two information were same iATP will consider filter stop but if this two information were not same iATP will consider mechanical issue (axle damage or axle locked), and also train movement was detected by odometer and the minimum measurement distance was about 3 cm.

Locate train on track:

The objective of this function is to localize the train. Train localization is initialized by two successive beacons (train was not in switch area)； it is maintained by measuring the train movement and is realigned by beacons. The maximum location uncertainty is 65m, once this uncertainty is exceeded, CC will de-localize.

Monitor train speed:

This function ensures that the train speed does not exceed the most restrictive limits. The output of this function consists in triggering EB (Emergency Brake) if speed exceeds: the maximum speed defined for each mode (RM, iATP); in RMR (Restricted Mode Reverse) mode: EB will be triggered if the reverse speed is over than 5km/h; in RMF (Restricted Mode Forward) mode: EB will be triggered if the forward speed is over than 10km/h; provides PSR (Permanent Speed Restriction) and the speed restriction for passing the level crossing.

Monitor train spacing:

This function checks that for a restrictive stopping point: that the target point has not been crossed; for divergent point: that the point will not have to be trailed and does not change position at the head of the train; the train rollback has to be shorter than 1m distance and the train does not reverse more than 5m.

Emergency brake application:

If one of the following cases happened, CC will trigger emergency brake (EB):

- Onboard and trackside equipment was in major failure and could not perform safety function normally (for any driving mode), emergency brake would be triggered and alarm as well,
- The train speed is exceeded emergency triggering curve (RM, iATP mode), for example, the continuous communication with trackside and onboard was broken, the authorized end will back to signal. If the train speed was above the emergency curve, emergency brake would be triggered,
- During train movement if the driving mode change to no available one or cab active information lost,
- The constant of current track state (signal or points) was not available (ATP driving mode),

- Train location lost,
- Train unexpected movement,
- Train door close lock status lost during train movement, and
- Train overrun the red signal (iATP mode).

Define driving modes:

All the driving modes can be exchanged manually, it also can be exchanged automatically in some case, and the condition must be fulfilled as below:

Table 2.1: Driving Modes Transition [15]

Current Mode	**After Transition**		
	ATP	RMF	RMR
ATP	✓	When the train speed is lower than authorized speed (10km/h), switch the selector to RM position.	After train stop, switch lead lever to reverse position, switch the selector to RM position.
RMF	ATP available is displayed on DMI, switch the selector to ATP position	✓	After train stop, switch the lead lever to reverse position.
RMR	After train stop, switch the lead lever to forward. ATP available is displayed on DMI, switch the selector to ATP position	After train stop, switch the lead lever to forward.	✓

Manage cab activity:

The objective of this function is:

- To determine the active cab; and
- To manage the availability of the iATP equipment in the train.

Turn back mode:

Turn back manually under ATP supervision (iATP Mode)

This mode is used for the driver to control the train with the driving handle. In this mode, the driver drives the train to the turn back line manually, switch off the driver desk and switch on the other driver desk, move to the start platform until correctly stop. The driver presses the door open push button to open the door.

Turn back manually in Restricted Mode (RMF/RMR Mode)

This mode is used for the driver to control the train with the driving handle. In this mode, the driver drives the train to the turn back line manually, switch off the driver desk and switch on the other driver desk, moving to the start platform until correctly stop. The driver presses the door open push button to open the door; in the whole turn back process, on board ATP control the train moving under the settled low speed (10km/h).

Turn back manually in Non-Restrictive Mode (NRM)

In this mode, the driver according to the dispatcher command and the trackside signal, drive the train to the turn back line and stop it, and drive the train to the start line and stop it, press the door open push button to open the train door.

2.3 AA-LRT signalling system: Reliability, Availability, Maintainability and Safety data

This thesis deals with reliability, availability, maintainability and safety modelling and performance analysis of AA-LRT signal iATP system failure and repair data analysis using a Markov model.

Signal: A signal is a mechanical or electrical device erected beside a railway line to pass information relating to the state of the line ahead to train. The driver interprets the signal's indication and acts accordingly. Typically, a signal might inform the driver of the speed at which the train may safely proceed or it may instruct the driver to stop.

Reliability: The ability of a system or component to perform its required functions under stated conditions for a specified period of time. Reliability Engineering is a sub-discipline within Systems Engineering. Reliability is often measured as probability of failure, frequency of failures, or in terms of availability, a probability derived from reliability and maintainability. Maintainability and maintenance are often important parts of reliability engineering. Reliability engineering is closely related to safety engineering, in that they use common methods for their analysis and may require input from each other. Reliability engineering focuses on costs of failure caused by system downtime, cost of spares, repair equipment, personnel and cost of warranty claims. The focus of safety engineering is normally not on cost, but on preserving life and nature, and therefore deals only with particular dangerous system failure modes. Reliability engineering for complex systems requires a different, more elaborate systems approach, than reliability for non-complex systems. Reliability analysis has important links with function analysis, requirements specification, systems design, hardware design, software design, manufacturing, testing, maintenance, transport, storage, spare parts, operations research, human factors, technical documentation, training and more. Effective reliability engineering requires experience, broad engineering skills, and knowledge from many different fields of engineering.

Availability: The degree to which a system, subsystem, or equipment is in a specified operable and committable state at the start of a mission, when the mission is called for at an unknown, i.e., a random time. Simply put, availability is the proportion of time a system is in a functioning

condition. This is often described as a mission capable rate. Mathematically, this is expressed as 1 minus unavailability. The ratio of (a) the total time a functional unit is capable of being used during a given interval to (b) the length of the interval. The simplest representation for availability is as a ratio of the expected value of the uptime of a system to the aggregate of the expected values of up and down time, or [20]

$$A = \frac{E[up\ time]}{E[up\ \ tme]+E[down\ time]} \tag{2.1}$$

If we define the status function X(t) as: -

$$X(t) = \begin{cases} 1, & system\ function\ at\ time\ t \\ 0, & otherwise \end{cases} \tag{2.2}$$

Therefore, the availability A(t) at time t > 0 is represented by: -

$$A(t) = Pr\ [\ X(t) = 1] = E[X(t)] \tag{2.3}$$

Average availability must be defined on an interval of the real line.

If we consider an arbitrary constant C > 0, then average availability is represented as: -

$$A_c = \frac{1}{c}\int_0^c A(t)\ dt \tag{2.4}$$

Limiting (or steady-state) availability is represented by: -

$$A = \lim_{t\to\infty} A\ (t) \tag{2.5}$$

Limiting average availability is also defined on an interval (0, C) as: -

$$A_\infty = \lim_{c\to\infty} A_c = \lim_{c\to\infty}\ \frac{1}{c}\int_0^c A(t)\ dt, \qquad c > 0 \tag{2.6}$$

Maintainability: It is the ease with which a product can be maintained in order to: isolate defects or their cause correct defects or their cause, meet new requirements make future maintenance easier, or cope with a changed environment. In some cases, maintainability involves a system of continuous improvement - learning from the past in order to improve the ability to maintain

systems, or improve reliability of systems based on maintenance experience. In telecommunication and several other engineering fields, the term maintainability has the following meanings: A characteristic of design and installation, expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time, when the maintenance is performed in accordance with prescribed procedures and resources. The ease with which maintenance of a functional unit can be performed in accordance with prescribed requirements.
Safety: is the freedom from an unacceptable risk of harm. That is, it is concerned with the non-existence of an unacceptable damage risk.

Most of the discussion henceforth concerns the determination of Reliability, because the rest of RAMS parameters, Availability, Maintainability and Safety are derived from it.

Below are quantitative data taken from the signalling system design [21].

1) Reliability

   ATS system: MTBF$\geq 2.0\times10^5$ h;

   ATP system: MTBF$\geq 2.0\times10^5$h;

   CBI system: MTBF$\geq 2.0\times10^5$h;

   Single outdoor balise (beacon): MTBF$\geq 10^6$h;

   Onboard DMI: MTBF$\geq 2.0\times10^5$h;

   Mean correct counts of axle counter is $\geq 1\times10^9$ axles;

   Axle counter: MTBF$\geq 1.75\times10^5$h

2) Availability

   The availability degree of computer system of individual subsystems shall be ≥99.998%;

   The availability degree of whole signaling system shall be ≥99.99%.

3) Maintainability:

   Onboard equipment: MTTR≤ 30 minutes;

   OCC equipment: MTTR≤ 30 minutes;

   Station equipment: MTTR≤30 minutes;

   Electronic and electrical equipment (except switch machine) of trackside equipment: MTTR≤30 minutes;

   Level crossing signalling equipment: MTTR≤30 minutes

4) Safety

   The safety integrity level SIL of safety-related equipment in the signalling system reaches the level 4:

The Tolerable Hazard Rate of each function per hour (THR (h^{-1})) is 10^{-9}/h≤ THR<10^{-8}/h; that is the probability of dangerous failure per hour.

Notice:

From the above discussion of the AA-LRT signal iATP system track-side and on-board iATP system main units include: Line-side Electronic Unit (LEU), Trackside Radio Equipment (TRE), Beacon, Car-borne Controller (CC), Odometer, Beacon antenna, Driver Machine Interface (DMI) and Onboard antenna (onboard DCS). These track-side and on-board units of signal iATP sub systems are highly affecting the overall performance of the AA-LRT signal intermittent-Automatic Train Protection system. Hence, in this thesis these eight subsystems of the signal iATP system are considered to analyses the overall performance of AA-LRT Automatic Train Protection system.

3. Reliability Concepts and Analysis Techniques

3.1 Reliability Concepts

Reliability is defined in IEC 61508 (IEC2001) as follows: The probability that an item can perform a required function under given conditions for a given time interval. The phrase required function means that a component here referred to as an item works in conformance with its specifications under the precondition that it has done so on entering service and that no maintenance has since been necessary. This results in the requirement of failure-free working of the component during a specified time period. Reliability prediction can be defined in its simplest form as estimation of the probability of successful system performance or operation. [25].

Reliability and Availability refer to the ability of a system to operate correctly, and they depend on several factors such as failure modes, the ratio of these failures over time or cumulated tons of loads, and their effects on the whole system. Reliability functions can by estimated using non-parametric or parametric analyses, having both methods their advantages and disadvantages:

- Non-parametric analyses do not require any specific distributional assumptions about the shape of the reliability function, so errors coming from selecting a potentially incorrect distribution are avoided.
- Parametric models on the other hand make assumptions about the distribution function, but when a good fit to data is obtained, they tend to give more precise estimates of the quantities of interest, because these estimates are based on fewer parameters.

Maintainability of a system is related with duration and effort required by corrective actions, and it depends on the duration of those actions, time used in failure detection, identification and location, and time used to restore the system to its normal operation. Maintainability of a part in a system is the probability of completing system maintenance, whether by replacing or by repairing that part, in time t_1, where that part fails or has to be replaced preventively [26].

Safety refers to the functional safety within the system and protection against hazardous consequences caused by technical failure and unintended human mistakes. Safety-critical system

is a system whose failure may have a severe consequence. Many safety-critical systems nowadays are designed on the basis of Electrical, Electronic, or Programmable Electronic (E/E/PE) technology. These systems are named by the term E/E/PE safety-related system in the standard IEC 61508. Safety-critical systems have wide application areas. They can be used in process industry, machinery industry, and nuclear industry. In railways, an automatic train control signalling system is a safety-critical system. Hence a safety function is implemented to protect against a specific undesired event that can cause harm [16].

Since the Availability, Maintainability and Safety parameters of the RAMS can be derived from the Reliability of the system, here after the section focuses on Reliability analysis in depth.

3.2 Reliability Analysis Techniques

Since technology has allowed us to create complex and safety critical systems, a challenge inherent to these systems is the problem of analyzing and predicting how reliable they are. In the advancement of technology and the modification and improvement of these complex and safety critical systems, one goal has always been to make them safer and more reliable. Both qualitative and quantitative methods have been developed to analyze complex and safety critical systems, and there are constantly more being researched in the academic community. The techniques developed have their advantages and disadvantages.

Qualitative reliability analysis methods have always been used to help identify all possible failures that could occur within a system, and the general risks associated with each of those failures. The most widely used qualitative method is failure modes and effects analysis (FMEA), sometimes also known as failure modes, effects and criticality analysis (FMECA). The purpose of FMEA is to review a system in terms of its subsystems, assemblies, and so on, down to the component level, in order to identify all of the causes and modes of failure and the effects of these failures. FMEA can be completed either on an existing system or during the design phase, and its application at different phases fulfills various objectives [22].

There are several methods of quantitative reliability analysis techniques, with various theories behind them. The three that are most widely used are fault tree analysis (FTA), reliability block

diagrams (RBD), and Markov analysis (MA). As will be discussed, all three of these methods are best for different situations, and all have their own advantage and disadvantage. Quantitative analysis aims to use knowledge of how a system works, often gained from previously completed qualitative assessments, and apply information about failure rates, probabilities, characteristics, and so on to this knowledge in order to gain more knowledge of subsystems or the system as a whole. The information concerning failure rates, distributions, or probabilities can be gained in a variety of ways, but the most accurate is always through test data. However, when this data is not available, or sufficient data does not exist, a variety of theories can be applied to hypothesize and predict the failure characteristics of a component or subsystem [22]. Some details of the most widely used quantitative reliability analysis methods are presented below.

3.2.1 Fault Tree Analysis

The FTA concept was developed in 1962 by Bell Telephone Laboratories for the U.S. Force for use with the Minuteman system. A fault tree is a logic diagram that shows potential events that might affect system performance, and the relationship between them and the reasons for these events. Failure of one or more components of the system is not the only possible causes however. The reasons also include environmental conditions, human errors, and other factors. A fault tree helps to illustrate the state of a system, otherwise denoted as the top event, in terms of the states of the system‘s components, otherwise denoted as basic events. A top event can be connected to lower events through gates. The two gates that form the building blocks for the other (more complicated, less used) gates are the “OR” gate and the “AND” gate. The “OR” gate symbolizes that the output event will occur if any of the input events occur. The “AND” gate means that the output event will occur only if all of the input events occur [24].

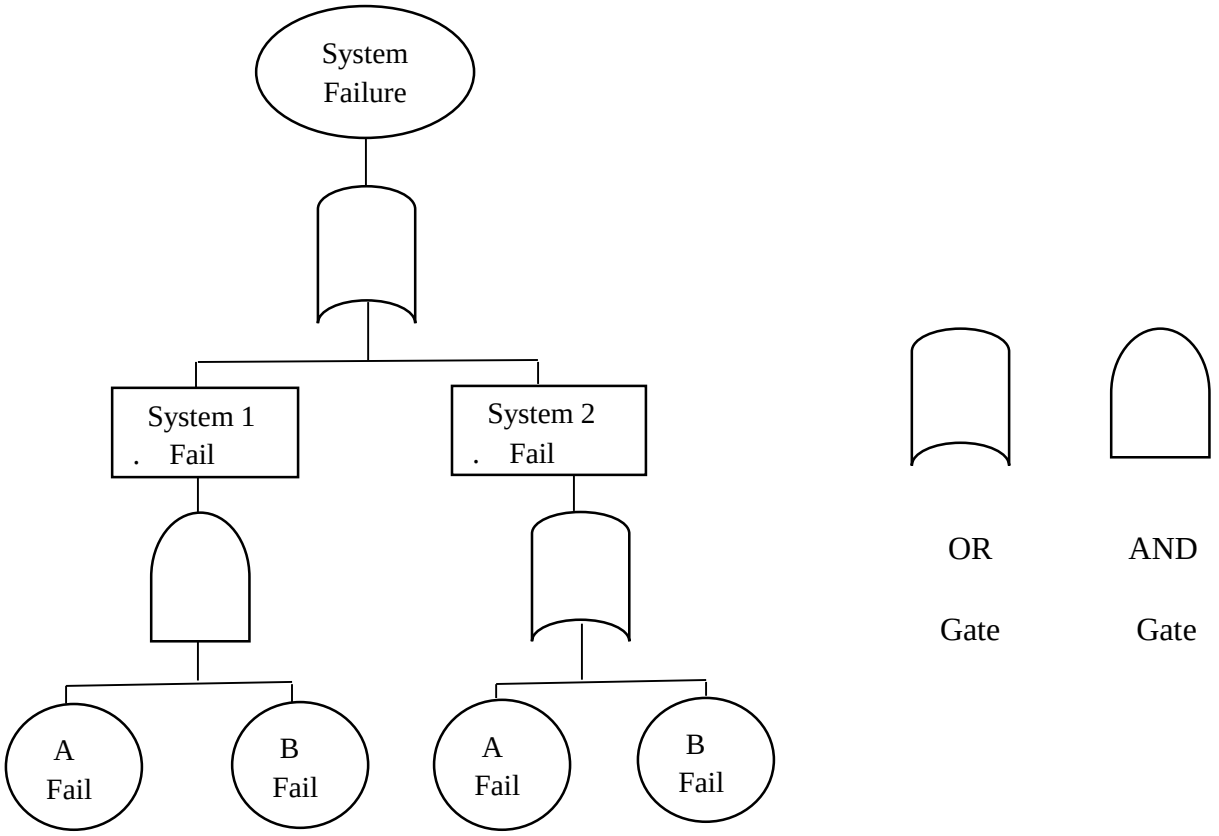

Figure 3.1: Sample Fault Tree Analysis (FTA)

These are the only two gates that were originally used when fault trees were developed, but since then many more types of gates have been created to fit specific needs (such as Inhibit gates, Priority AND gates, Exclusive OR gates, and k-out of- n gates).

3.2.2 Reliability Block Diagram

The reliability of a system can be predicted by looking at the reliabilities of the components that make up the entire system. In order to do this, a configuration must be predetermined that accurately represents the logic behind the reliability of the system. This action is similar to determining what types of gates to use in a fault tree. However, in the case of RBDs, a top-down approach is used as well, so at the end of this composition the sum of the components must accurately represent the whole system. The two basic structures employed in RBD that coincide

with the two gates mostly used in FTA are the series and parallel configurations. A sample RBD can be seen in Figure below. A set of blocks in series is the equivalent of a set of events connected by an "OR" gate, while a set of blocks in parallel is the RBD equivalent of a set of events all under the same "AND" gate. Similarly, just as in FTA, blocks can be connected through sets of series and parallel connections in order to accurately represent a system. In addition, there are many other types of connections (such as the k-out-of-n, or the bridge structure) that can be used to form the block diagrams for more complex systems [22].

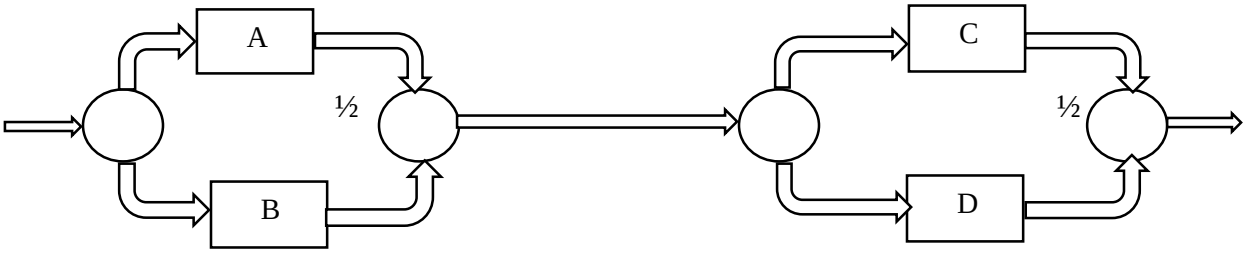

Figure 3.2: Sample Reliability Block Diagram (RBD)

From the above RBD A and B are connected in parallel one out of two systems and again C and D are connected in parallel one out of two systems. Again A, B and C, D are connected in series.

3.2.3 Markov Analysis

The Markov analysis is different from the others described previously in that it is a dynamic, state-space analysis. This means that the state of the system is what is modelled, and not the probability of specific events occurring. Each system state represents a set of local states, meaning that a state can represent when all of the components are functioning, when one specific component has failed, when another has failed, when two have failed, and so on until every possible global state is represented.

In addition, there are transitions that exist between many of these states, depending on the nature of the system, and each is given a failure rate that is assumed to be constant. For instance, Figure 3.3 below shows a system of two identical components (A and B), both of which can be functioning or failed at any time, independent of what state each other is currently in, with a failure rate of

each component of λ and repair rate of μ. This means that there can be four possible global states: both are working, A is working and B is failed, B is working and A is failed, and both have failed.

As can be seen there is then a failure rate associated with each transition between states. Since this is a repairable system there can also be transitions from failed states back to working states with given constant rates as well. (There is no transition directly from the state where both are working to the state where both have failed because it is theoretically impossible for two independent components to fail simultaneously.) [24]

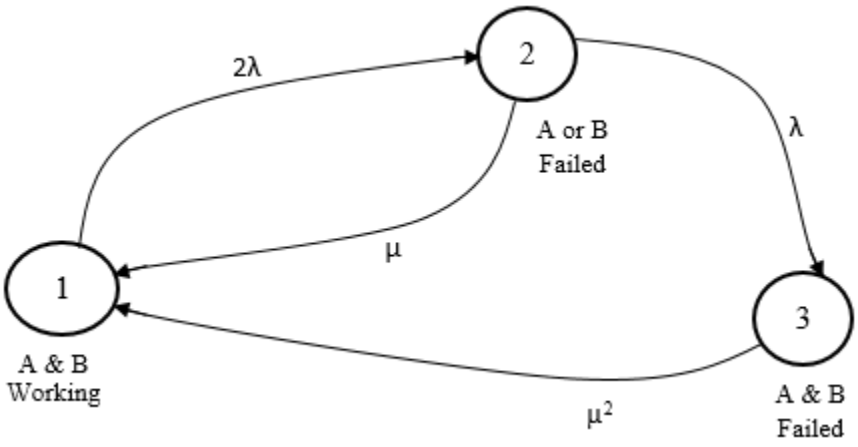

Figure 3.3: Sample Markov Chain

The qualities inherent to MA give it many distinct advantages and disadvantages. The major advantage comes from it being a dynamic analysis. This allows MA to be representative of the system at any given time using just one model. It also gives an illustration of the state of every component or subsystem at any given time in the analysis.

However, since MA is a state-space analysis as opposed to an event-based analysis (like FTA or RBD) the models can get incredibly large very quickly. This is because when developing a MA model, every single possible state must be considered, which makes the model as well as the analysis very complicated. When modelling a very complex system, this can get completely out of hand very quickly, which is one of the large reasons that MA is not commonly used for very complex systems.

The main disadvantage of Markov methods is as the size of the system increases the explosion of the number of state and limited to the use of constant failure rates for the transitions. The resulting diagram for large systems are generally extremely large and complicated, difficult to construct and computationally extensive [22].

3.3 Reliability Analysis Techniques Comparison

Table 3.1 shows a comparison of the different widely used approaches to reliability analysis, and a summary of some of the important characteristics of the methods are presented.

Table 3.1: Characteristics Comparison of Reliability Analysis Methods [22]

Characteristic	**FTA**	**RBD**	**MA**
Static	✓	✓	
Dynamic			✓
Logic-based	✓	✓	
State-space			✓
Top-down	✓	✓	✓
Variable distributions	✓	✓	
Can be used for dependent event			✓
ICE standard	**61025**	**61078**	**61165**

3.4 Railway System Operational State Description

The railway operation can be considered to be in one of three possible states depending on whether operation is possible and whether the signal Automatic Train Protection (ATP) system is operative:

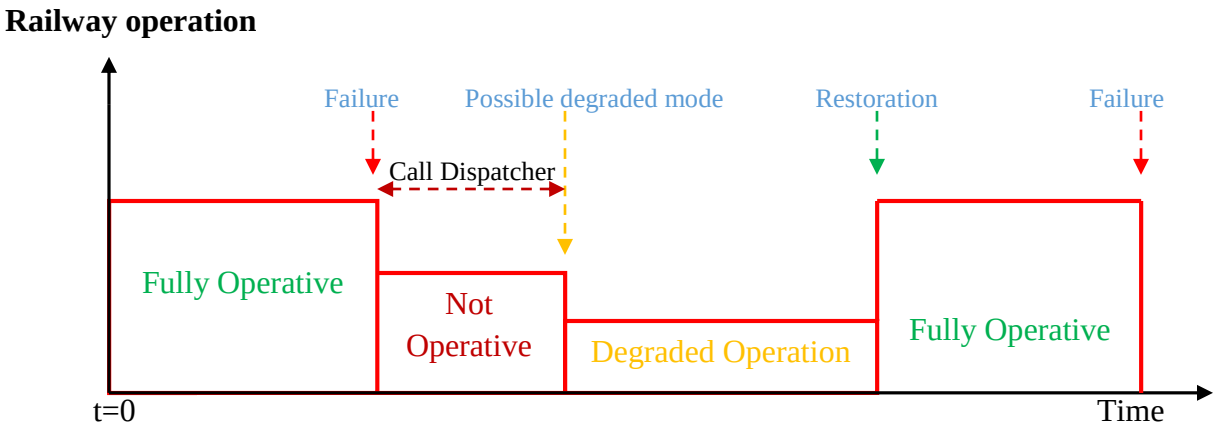

Figure 3.4: Railway operation at different corresponding time

Operative state: In this state, operation is possible and the signal iATP system is fully operative.

Faulty state: This is the operational state from when a failure occurs and the operation is stopped until the dispatcher allows continued operation in a degraded mode (i.e. till ordered to use NRM to drive the train and driver responsible for supervision and protection)

Degraded state: In this state, railway operation is possible in a degraded mode [22] (i.e. drive the train with NRM according to the civil speed posted along the railway track and driver responsible for supervision and protection), but the signal iATP system is not operative due to a failure in one or more of its signalling subsystems.

For the signal iATP system, three possible states (times) can be considered:

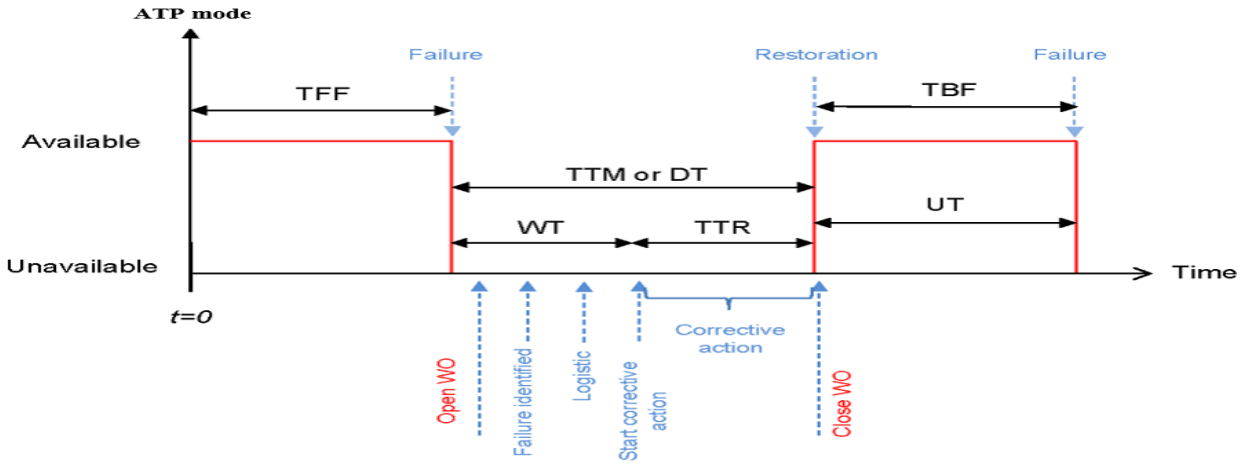

Figure 3.5: Failure Episode and Definition of Times [16].

Available state or **Up Time (UT)**: the system is fully operative.

Not available state during waiting or **Waiting Time (WT)**: the time between when a failure occurs until the corrective action is started. During the waiting time, the WO (work order) is opened, the failure is identified, maintenance personnel are informed, the spare parts and tools needed are gathered and the personnel go where the failure is located.

Not available state during Restoration or **Restoration Time (RT)**: corrective actions (repair or replacement) are performed and the WO is closed.

From Figure 3.5 the following important parameters are defined as well: [16]

- TFF: Time to First Failure, when the item fails for the first time.
- TBF: Time Between Failures, which excludes the down time.
- TTM or DT: Time To Maintain or Down Time, during which the system is not available for operation.

  TTM = t(finish corrective action) – t(failure identification) (3.1)
- UT: Up Time or available state, during which the system is in full operation.

- WT: Waiting Time, in which the WO has been opened and the system is waiting for a corrective action to be taken.
- TTR: Time To Restore, in which the failure has been already identified and the corrective action is taking place.

  TTR = t(finish corrective action) – t(start corrective action) (3.2)

The Relative Restoration Time (RRT) is a ratio defined as, [22]

RRT (%) = TTR/TTM (3.3)

and it gives an idea of the efficiency of the corrective actions.

4. RAMS Modelling of AA-LRT Signal iATP System

4.1 Modelling Description

Obtaining a numeric indicator is desirable to realize how effective the AA-LRT signal iATP system is, taking into account other measures which are keys to its performance. When considering Automatic Train Protection, the important factors are Reliability, Availability, Maintainability and Safety (RAMS) and also inspection policy to evaluate its performance.

RAMS modelling can simulate the configuration, operation, failure, repair, maintenance and safety of signal iATP system equipment. The inputs to RAMS modelling will include the physical components and maintenance schedules in a system and the outputs can determine how effective the system can be over the plant life. RAMS studies will generate sufficient data to base decisions for possible system changes that may increase system efficiency and hence project profits. RAMS modelling assesses a production systems capabilities, whether it be in operation or still in design phase. The application of relatively inexpensive but powerful RAMS forecasting tools can provide a number of benefits to the signal iATP system of AA-LRT. These benefits include: [19]

- Reducing maintenance and sparing costs while maintaining and increasing production levels;
- Optimizing capital investment for reducing the cost of production;
- Alignment of maintenance resources based on the criticality of equipment to production revenue;
- Detecting failures in the early part of equipment design;
- Optimizing maintenance schedules;
- Adequately allocating the spare parts inventory; and
- Increasing the effectiveness of the signal iATP system.

The modelling of signal iATP system comprises its track-side and on-board subsystems. That is:

- CC- Carborne Controller
- DMI- Driver Machine Interface

- LEU- Line-side Electronic Unit
- Beacon
- Beacon Antenna
- Coded odometer
- TRE- Trackside Radio Equipment (Trackside Data Communication System /DCS/)
- Onboard Antenna (onboard DCS)

4.2 AA-LRT Signal iATP Fault Tree Model

From the description of the AA-LRT signal Automatic Train Protection system in the previous sections, we were able to model the Feared Event (Signal iATP system not to supervise the railway traffic i.e. ATP not available) by a Fault Tree.

Since the signal iATP system consists of Carborne Controller (CC), Driver Machine Interface (DMI), Line-side Electronic Unit (LEU), Beacon, Beacon Antenna, Odometer, Trackside Radio Equipment (TRE) and Onboard Antenna which are the measure parts and hence it's considered these eight subsystems of the signal iATP system to analyze their performance in this thesis.

The following fault tree model in Figure 4.1 was developed taking no consideration to subsystems with redundant communication network and analytically their performances were evaluated using Markov analysis. This would create a visual understanding of AA-LRT signal iATP system.

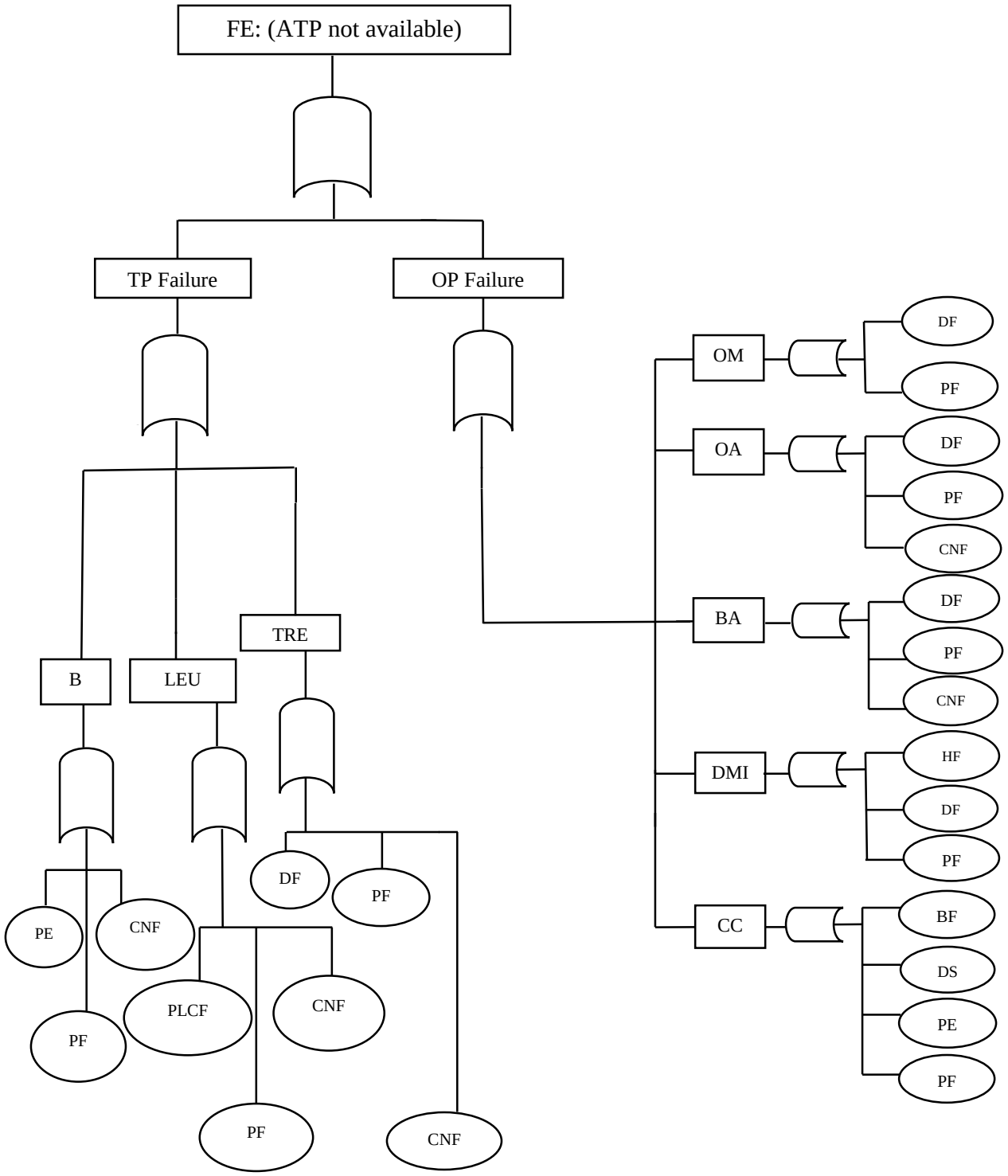

Figure 4.1: Fault Tree Diagram of AA-LRT Signal iATP System

Table 4.1: Symbols of Intermediate Events

Symbols	**Intermediate Events**
FE	Feared Event
TP	Trackside Part
OP	Onboard Part
B	Beacon
LEU	Line-side Electronic Unit
TRE	Trackside Radio Equipment
OM	Odometer
OA	Onboard Antenna
BA	Beacon Antenna
DMI	Driver Machine Interface
CC	Carborne Controller

The basic events which produce the feared event are given in the table 4.2 below:

Table 4.2: Basic Events

Symbol	**Basic Event**
HF	Human Failure
PF	Power Failure
PE	Program Error
PLCF	Programmable Logic Controller Failure
CNF	Communication Network Failure
DF	Device Failure
BF	Board Failure
DS	Device Saturation

In Figure 4.1 a graphical presentation of the logical relationship between these basic events can be presented. The successive levels in the fault tree depict how the propagation of lower-level events causes the top event to occur. This method is easy to understand computational advantage and hundreds of components can be easily solved. However, this method lacks the ability to handle various dependences, such as the failure dependencies, redundancy in repairable system, and shared repair, which are of essential importance for system level reliability analysis; and also this method cannot accurately model dynamic system behavior. In these cases, Markov chain method has to be important and the method is used in this thesis for the analysis of the performance of the AA-LRT signal iATP system.

4.3 Markov Analysis Model

System modelling using Markov analysis is widely used in safety and reliability engineering [23]. The reliability behavior of a system is modeled by Markov chains as a state transition net of sequence which consists of a set of descript states that the system can be in, and defines the speed at which transitions between those states takes place [19]. Thus, Markov models consists of representations of possible chains of events that is transition, within systems, which in the case of reliability and availability analysis corresponds to sequences of failures and repair.

A Markov model (chain) describes a stochastic process within a number of states in which the probability of occurrence of future states in conditional only upon the current state; past state are inconsequential (the "memory-less property").

A state of Markov chain, represented by a circle or oval (Figure 4.2), corresponds to global system state. A change of system states is always stochastic, using the exponential distribution, which is the only one satisfying the memory-less property. It is represented by arc attributed with the parameter λ of the exponential distribution rate [1/time unit], used usually for modeling of failure processes, μ is used for repair actions. The rate corresponds usually to the reciprocal value of mean time to failure MTTF or to repair MTTR assuming that its value is constant during whole system life time. An n-state Markov model leads to system of n-coupled differential equations. Let P(t) be a vector that gives the probability of being in each state at time t. The system of differential equation that describes a Markov model is given by: [22]

$$\frac{d\,P(t)}{dt} = A.\,P(t) \qquad (4.1)$$

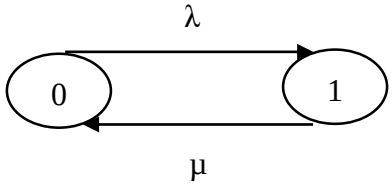

Figure 4.2: Graphical Elements of Markov Modelling in a Chain

The transition matrix A is easily constructed when Markov model is presented in terms of flow in and flow out. The element a_{ij} is equal to transition rate from i to j state, and its symmetric element a_{ji} is equal to transition rate from j to i state. The diagonal entries are obtained by summing all

transition rate from state i to another state and negating it. Hence the sum of all transition rate in the same rows are zero. The solution of the differential equation can be written as:

$$P(t) = P_0 e^{At} \tag{4.2}$$

Where $P_0 = P(t = 0)$ represents the initial state probabilities P(0). It can be used for system state probability evaluation at the time t (transient analysis) or in the steady state $t \rightarrow \infty$ (stationary analysis).

A Markov model divides the system configuration into a number of states. Each of these states is connected to all other states by transition rates. It then utilizes transition matrixes and state transition diagrams to represent the various system states and the possible transitions between these states. These state diagrams are more visual in nature than mathematical representations thus they are much easier to interpret. These advantages, however, must always be traded-off against the explosion in complexity and resulting increase in computation time as the number of states increase.

Therefore, Markov analysis can be a powerful RAMS analysis tool. It allows the analyst to model complex, dynamic, highly distributed, fault tolerant systems that would otherwise be very difficult or impossible to model with classical techniques. Markov techniques decrease the analyst's task by reducing the problem from one of mathematical computation to that of state modelling. Model reduction techniques also exist which can yield relatively simple models with insignificant impact on model accuracy. In many situations it is also possible to use a combination of Markov analysis and more conventional approaches, e.g., reliability block diagrams, fault trees, etc. in such a way that the resulting individual dynamic portion are relatively small and easy to control.

Markov model is a random process characterized as memory-less. The next state depends only on the current state and not on the sequence of events that preceded it. Markov model is a better technique that has constant failure rate and repair rate. Modern probability theory studies chance processes for which the knowledge of previous outcomes influences predictions for future experiments. In principle, when a sequence of chance experiments, all of the past outcomes could

influence the predictions for the next experiment. In Markov chain type of chance, the outcome of a given experiment can affect the outcome of the next experiment. The system state changes with time and the state X and time t are two random variables. Each of these variables can be either continuous or discrete. Various degradations on signal iATP system can be viewed as different Markov states and further degradation can be treated as the outcome of the present state. In this paper the signal iATP system treated as a discrete state continuous time system with two possible outcomes, namely, S1: Good condition and S2: System completely fails. Partial degradation failures and partially working were not considered.

The calculation of the reliability of the signal iATP system is complicated since the system has elements or subsystems exhibiting dependent failures and involving repair and standby operations. As discussed in chapter three Markov model is a better technique that has much appeal and works well when failure hazards and repair hazards are constant than other reliability analysis techniques. This paper presents a Markov model of the signal iATP system by means of the different states and transitions between these states.

The assumptions are as follows:

- The time between failure (TBF) and time to repair (TTR) data are exponentially distributed. So there are no simultaneous failures of subsystems and the probability of more than one failure or repair in a time interval is zero.

- The repaired units are as good as new (AGAN) one repair or replacement is carried out only in case of failure.

- The failure rates and repair rates for all subsystems of the system are constant over time and statistically independent.

- Standby system, partial degradation failures and partially working were not considered in this paper.

The methodology of Markov process of reliability modelling of AA-LRT signal iATP system is shown below.

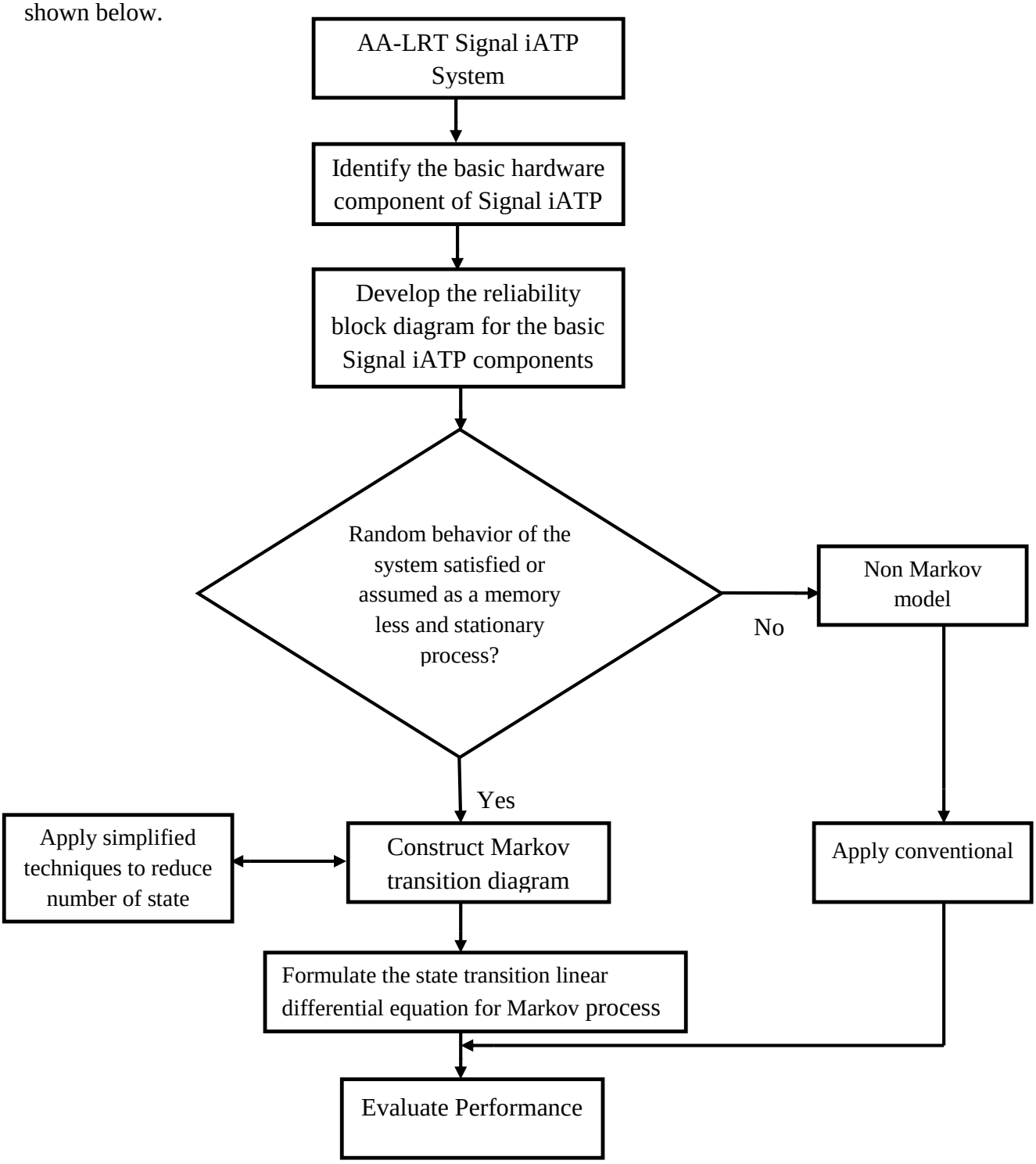

Figure 4.3: Framework for Reliability Modelling by Markov Process

4.3.1 Description of AA-LRT signal iATP Model

The Schematic description of AA-LRT signal iATP system model is presented in Figure 4.4 in this paper eight main subsystems of the automatic train protection were selected to estimate their reliability, availability, maintainability and safety. These were used for the analysis of the overall performance and reliability of the signal intermittent-Automatic Train Protection system. These eight subsystems include the Carborne Controller (CC), Driver Machine Interface (DMI), Line-side Electronic Unit (LEU), Beacon, Beacon Antenna, Odometer, Trackside Radio Equipment (TRE) and Onboard Antenna.

In the figure below the LEU is connected with the double two out of two (2*2oo2) CBI (Computer Based Interlocking) system where as it gets way-side information (status of signals, point machine, …) and transmit it to the beacon (active beacon) in a wired communication; then the beacon antenna takes this data to onboard signalling equipment (Carborne Controller (CC) for processing) from the beacon when the train runs over the top wirelessly. The TRE also gets the way-side information from the 2*2oo2 CBI through the trackside DCS (Data Communication System) and transmits it to the onboard antenna in a wireless communication; whereas the onboard antenna forwards the data to onboard signalling equipment (CC for processing) through the onboard DCS. The odometer provides safe sensor of the train displacement and zero velocity information to CC. The CC rack consists of Central Processing Module (CPM) and Vital Input Output Module (VIOM). The CC transmits necessary information (speed limit, target distance to stop, …) to be displayed to the train driver on DMI (Driver Machine Interface) as cab signalling form in ATP mode of operation.

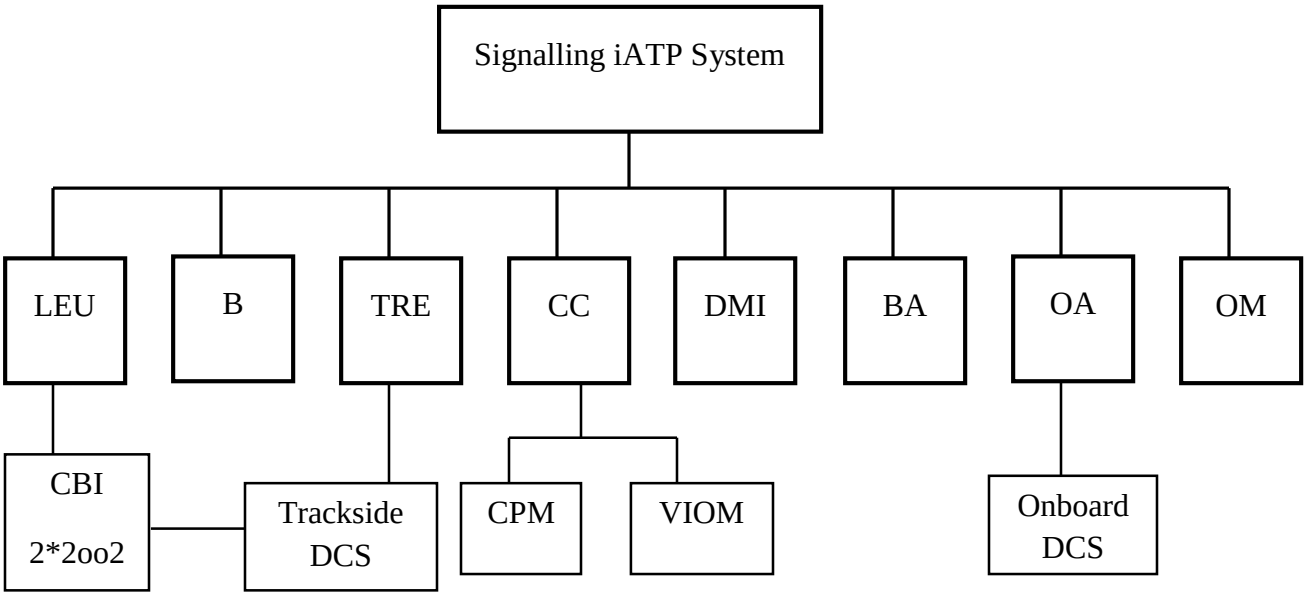

Figure 4.4: Schematic presentation of AA-LRT signal iATP Subsystem

Therefore, the simplified reliability block diagram of AA-LRT signal iATP system was presented in Figure 4.5 using only eight main iATP subsystems were selected for this thesis. The subsystems redundant network (the partial failure (redundancy loss) of communication network) and human factors were not used in this paper.

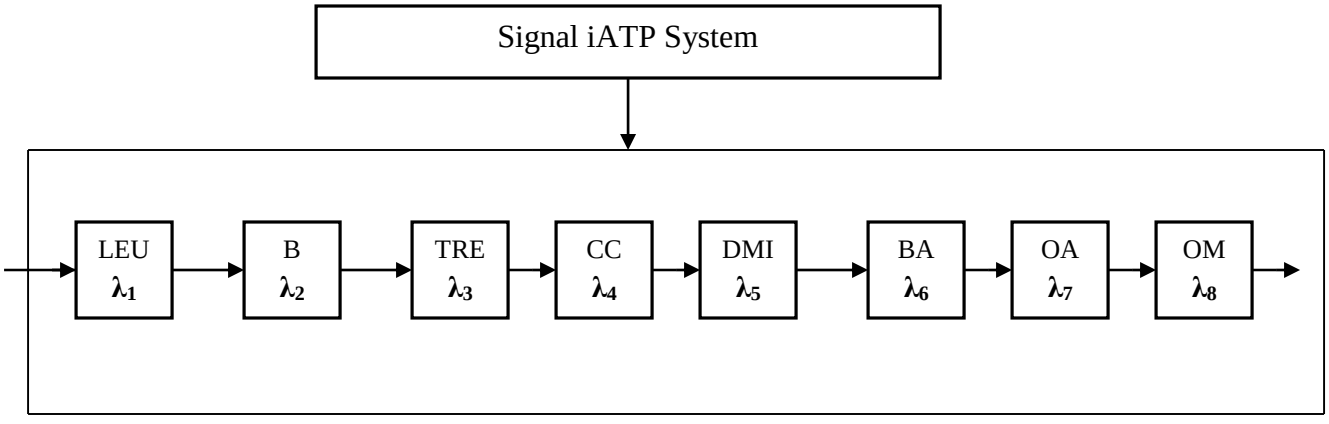

Figure 4.5: Simplified AA-LRT Reliability Block Diagram of Signal iATP System

4.3.2 State Transition and Mathematical Analysis of Markov Model

The transition probabilities P_{ij} of a homogeneous Markov process form an n × n matrix, called a transition matrix which is: [29]

$$[P_{ij}] = \begin{pmatrix} P_{11} & P_{12} & \cdots & P_{1j} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2j} & \cdots & P_{2n} \\ \cdot & \cdot & \cdots & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot & \cdots & \cdot \\ P_{i1} & P_{i2} & \cdots & P_{ij} & \cdots & P_{in} \\ \cdot & \cdot & \cdots & \cdot & \cdots & \cdot \\ \cdot & \cdot & \cdots & \cdot & \cdots & \cdot \\ P_{n1} & P_{n2} & \cdots & P_{nj} & \cdots & P_{nn} \end{pmatrix} \quad (4.3)$$

and the reliability R(t) of the different subsystems become:

$$R(t) = \prod R_i = R_1 . R_2 . R_3 . R_4 . R_5 . R_6 . R_7 . R_8 \text{ (for eight subsystems of signal iATP system)} \quad (4.4)$$

where: R_1- (the reliability of the LEU), R_2- (Reliability of the Beacon), R_3- (Reliability of TRE), R_4- (Reliability of the CC), R_5- (Reliability of the DMI), R_6 – Reliability of Beacon Antenna, R_7 - Reliability of the Onboard Antenna, and R_8 – Reliability of the Odometer.

Therefore, $R(t) = e^{-\lambda_1 t} . e^{-\lambda_2 t} . e^{-\lambda_3 t} . e^{-\lambda_4 t} . e^{-\lambda_5 t} . e^{-\lambda_6 t} . e^{-\lambda_7 t} . e^{-\lambda_8 t}$ (4.5)

Where:

λ_1 – the failure rate of the LEU

λ_2 – the failure rate of the Beacon (B)

λ_3 - the failure rate of the TRE

λ_4 - the failure rate of the CC

λ_5 - the failure rate of the DMI

λ_6 - the failure rate of the BA

λ_7 - the failure rate of the OA

λ_8 - the failure rate of the OM

$$R(t) = e^{-\sum \lambda_i t} \quad (4.6)$$

$$= e^{-Ft} \quad \text{where } (F=\sum \lambda_i \; ; \; i = 1,2.3,4,5,6,7,8)$$

From the transition diagram presented in Figure 4.6 there are two discrete state of the transition, state 0: all signal iATP subsystems working normally and state 1: only the Line-side Electronic Unit (LEU) is down, whereas the rest of subsystems are up; state 2: only the Beacon (B) down; state 3: only Trackside Radio Equipment (TRE) is down; state 4: only Carborne Controller (CC) is down; state 5: only the Driver Machine Interface (DMI) is down, state 6: only the Beacon Antenna (BA) is down, state 7: only the Onboard Antenna (OA) is down and state 8: only the Odometer (OM) is down within a continues time interval. The Markov equations and the steady state availability of the signal iATP system is found as follows: [30]

$$PS = \frac{1}{1+\sum \frac{\lambda_i}{\mu_i}} = \frac{1}{1+D} \quad \text{where } D = \sum \frac{\lambda_i}{\mu_i} \quad (4.7)$$

and PS is Probability of State.

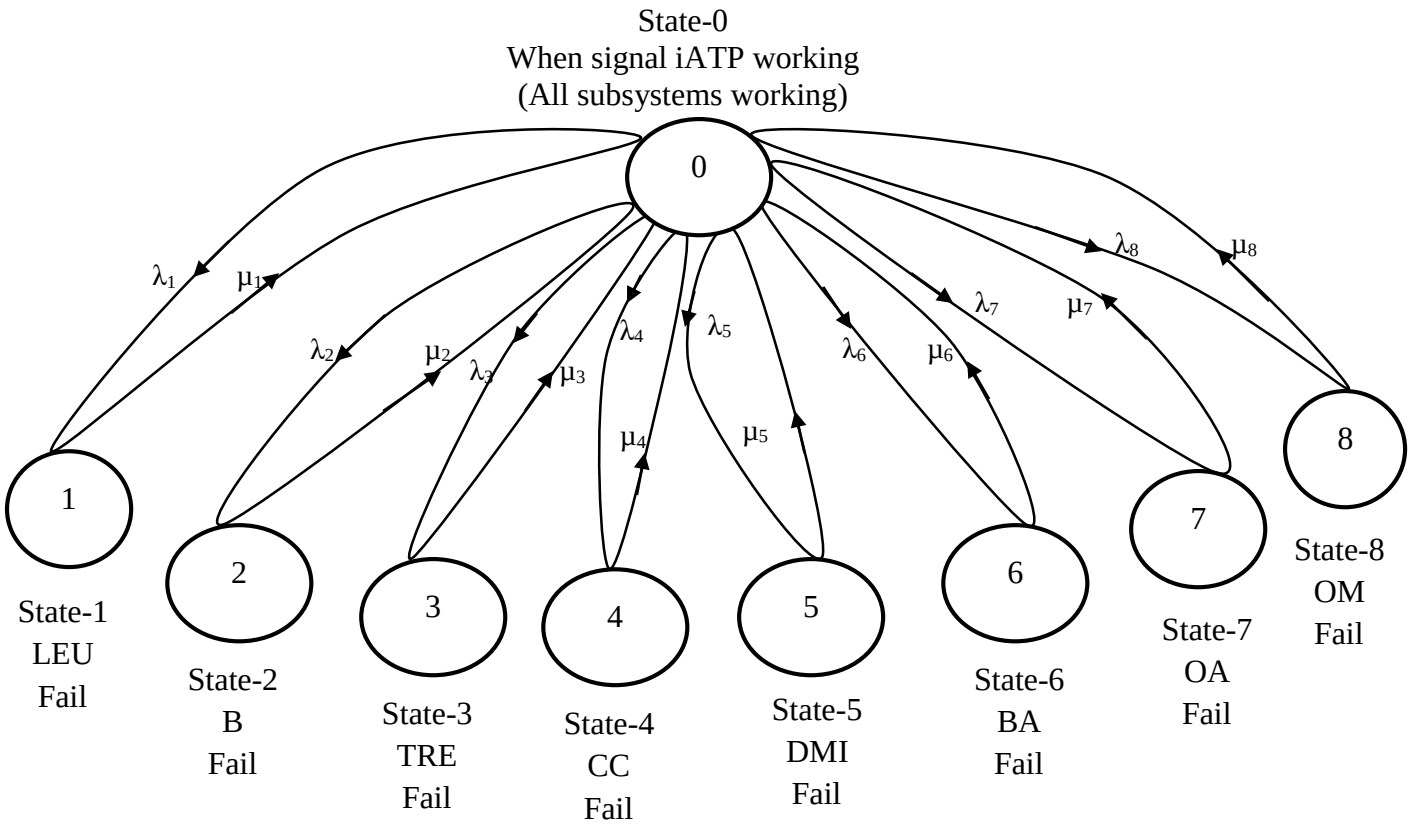

Figure 4.6: Transition Diagram for Signal iATP System and Subsystems

The probability that the system is in the operating state after a time interval *dt* (i.e.at time *t+dt*) is given by: [11]

PS0 *(t+dt)* = [Probability of being in operating state at time *t*] and [Probability of not failing states between *t* and *t+dt*] + [Probability of being failed states at time *t*] and [Probability of being repaired states between *t* and *t+dt*]

Probabilities of failure between *t* and *t+dt* are $\lambda_i dt$ and probabilities of not failing between *t* and *t+dt* are $(1-\lambda_i dt)$. Similarly the probabilities of repair are $\mu_i dt$.

Using the addition and multiplication rule for probabilities gives:

$PS0\ (t+dt) = PS0\ (t)\ (1- [\lambda_1 dt + \lambda_2 dt + \lambda_3 dt + \lambda_4 dt + \lambda_5 dt + \lambda_6 dt + \lambda_7 dt + \lambda_8 dt]) + [\mu_1 dt\ PS1(t) + \mu_2 dt\ PS2(t) + \mu_3 dt\ PS3(t) + \mu_4 dt\ PS4(t) + \mu_5 dt\ PS5(t) + \mu_6 dt\ PS6(t) + \mu_7 dt\ PS7(t) + \mu_8 dt\ PS8(t)]$

Where:

μ_1 – the repair rate of the LEU

μ_2 – the repair rate of the Beacon (B)

μ_3 - the repair rate of the TRE

μ_4 - the repair rate of the CC

μ_5 - the repair rate of the DMI

μ_6 - the repair rate of the BA

μ_7 - the repair rate of the OA

μ_8 - the repair rate of the OM

$PS0\ (t+dt) = PS0\ (t) - [\lambda_1 dt\ PS0\ (t) + \lambda_2 dt\ PS0\ (t) + \lambda_3 dt\ PS0\ (t) + \lambda_4 dt\ PS0\ (t) + \lambda_5 dt\ PS0\ (t) + \lambda_6 dt\ PS0\ (t) + \lambda_7 dt\ PS0\ (t) + \lambda_8 dt\ PS0\ (t)] + [\mu_1 dt\ PS1(t) + \mu_2 dt\ PS2(t) + \mu_3 dt\ PS3(t) + \mu_4 dt\ PS4(t) + \mu_5 dt\ PS5(t) + \mu_6 dt\ PS6(t) + \mu_7 dt\ PS7(t) + \mu_8 dt\ PS8(t)]$

$PS0\ (t+dt) - PS0\ (t) = (-\lambda_1 dt - \lambda_2 dt - \lambda_3 dt - \lambda_4 dt - \lambda_5 dt - \lambda_6 dt - \lambda_7 dt - \lambda_8 dt)\ PS0\ (t) + \mu_1 dt\ PS1(t) + \mu_2 dt\ PS2(t) + \mu_3 dt\ PS3(t) + \mu_4 dt\ PS4(t) + \mu_5 dt\ PS5(t) + \mu_6 dt\ PS6(t) + \mu_7 dt\ PS7(t) + \mu_8 dt\ PS8(t)$

(Rearranging results in :)

$$\frac{PS0\ (t+dt) - PS0\ (t)}{dt} = (-\lambda_1 - \lambda_2 - \lambda_3 - \lambda_4 - \lambda_5 - \lambda_6 - \lambda_7 - \lambda_8)\ PS0\ (t) + \mu_1\ PS1(t) + \mu_2\ PS2(t) + \mu_3\ PS3(t) + \mu_4\ PS4(t) + \mu_5\ PS5(t) + \mu_6\ PS6(t) + \mu_7\ PS7(t) + \mu_8\ PS8(t)$$

$dt \rightarrow 0$

$$or \frac{d\,PS0\,(t)}{dt} = -\,PS0\,(t)\,(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7 + \lambda_8) + \mu_1\,PS1(t) + \mu_2\,PS2(t) + \mu_3\,PS3(t) + \mu_4\,PS4(t) + \mu_5\,PS5(t) + \mu_6\,PS6(t) + \mu_7\,PS7(t) + \mu_8\,PS8(t)$$

$$= \sum \mu i\,PSi(t) - PS0(t) \sum \lambda i \qquad (4.8)$$

Similarly for other states become:

$$\frac{d\,PS1\,(t)}{dt} = \lambda_1\,PS0(t) - \mu_1\,PS1(t)$$

$$\frac{d\,PS2\,(t)}{dt} = \lambda_2\,PS0(t) - \mu_2\,PS2(t)$$

$$\frac{d\,PS3\,(t)}{dt} = \lambda_3\,PS0(t) - \mu_3\,PS3(t)$$

$$\frac{d\,PS4\,(t)}{dt} = \lambda_4\,PS0(t) - \mu_4\,PS4(t)$$

$$\frac{d\,PS5\,(t)}{dt} = \lambda_5\,PS0(t) - \mu_5\,PS5(t)$$

$$\frac{d\,PS6\,(t)}{dt} = \lambda_6\,PS0(t) - \mu_6\,PS6(t)$$

$$\frac{d\,PS7\,(t)}{dt} = \lambda_7\,PS0(t) - \mu_7\,PS7(t)$$

$$\frac{d\,PS8\,(t)}{dt} = \lambda_8\,PS0(t) - \mu_8\,PS8(t) \qquad (4.9)$$

The transition matrix expression for the transition rates looks like:

$$\begin{bmatrix} \frac{d\,PS0(t)}{d(t)} \\ \frac{d\,PS1(t)}{d(t)} \\ \frac{d\,PS2(t)}{d(t)} \\ \frac{d\,PS3(t)}{d(t)} \\ \frac{d\,PS4(t)}{d(t)} \\ \frac{d\,PS5(t)}{d(t)} \\ \frac{d\,PS6(t)}{d(t)} \\ \frac{d\,PS7(t)}{d(t)} \\ \frac{d\,PS8(t)}{d(t)} \end{bmatrix} = \begin{pmatrix} -(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\lambda_6+\lambda_7+\lambda_8) & \mu_1 & \mu_2 & \mu_3 & \mu_4 & \mu_5 & \mu_6 & \mu_7 & \mu_8 \\ \lambda_1 & -\mu_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \lambda_2 & 0 & -\mu_2 & 0 & 0 & 0 & 0 & 0 & 0 \\ \lambda_3 & 0 & 0 & -\mu_3 & 0 & 0 & 0 & 0 & 0 \\ \lambda_4 & 0 & 0 & 0 & -\mu_4 & 0 & 0 & 0 & 0 \\ \lambda_5 & 0 & 0 & 0 & 0 & -\mu_5 & 0 & 0 & 0 \\ \lambda_6 & 0 & 0 & 0 & 0 & 0 & -\mu_6 & 0 & 0 \\ \lambda_7 & 0 & 0 & 0 & 0 & 0 & 0 & -\mu_7 & 0 \\ \lambda_8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\mu_8 \end{pmatrix} \begin{bmatrix} PS0(t) \\ PS1(t) \\ PS2(t) \\ PS3(t) \\ PS4(t) \\ PS5(t) \\ PS6(t) \\ PS7(t) \\ PS8(t) \end{bmatrix}$$

Equating first order derivative to zero for a steady state these equations will take the following form for the signal iATP subsystems only,

$P_0\,(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \lambda_7 + \lambda_8) = \mu_1 P_1 + \mu_2 P_2 + \mu_3 P_3 + \mu_4 P_4 + \mu_5 P_5 + \mu_6 P_6 + \mu_7 P_7 + \mu_8 P_8$

[i.e. taking PSi(t) = Pi(t) where i = 0, 1, 2, 3, 4, 5, 6, 7, 8]

$P_1\mu_1 = P_0\lambda_1$ so $P_1 = \frac{\lambda 1}{\mu 1} P_0$

$P_2\mu_2 = P_0\lambda_2$

$P_3\mu_3 = P_0\lambda_3$

$P_4\mu_4 = P_0\lambda_4$

$P_5\mu_5 = P_0\lambda_5$

$P_6\mu_6 = P_0\lambda_6$

$P_7\mu_7 = P_0\lambda_7$

$P_8\mu_8 = P_0\lambda_8$ (4.10)

$P_0 + P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8 = 1$ (4.11)

Substituting the values of P_0, P_1, P_2, P_3, P_4, P_5, P_6, P_7 and P_8 in equation (4.11) the steady state at $t\rightarrow\infty$ availability of signal iATP system is found as:

$A_s = P_0 = \frac{1}{1+\sum\frac{\lambda i}{\mu i}} = \frac{1}{1+D}$ where $D = \sum\frac{\lambda i}{\mu i}$ (4.12)

Unavailability of the signal iATP system is found as:

$UA_s = P_1 + P_2 + P_3 + P_4 + P_5 + P_6 + P_7 + P_8$ (4.13)

Where:

$P_1 = \frac{\lambda_1}{\mu_1}\left[\frac{1}{1+D}\right]$

$P_2 = \frac{\lambda_2}{\mu_2}\left[\frac{1}{1+D}\right]$

$P_3 = \frac{\lambda_3}{\mu_3}\left[\frac{1}{1+D}\right]$

$P_4 = \frac{\lambda_4}{\mu_4}\left[\frac{1}{1+D}\right]$

$P_5 = \frac{\lambda_5}{\mu_5}\left[\frac{1}{1+D}\right]$

$P_6 = \frac{\lambda_6}{\mu_6}\left[\frac{1}{1+D}\right]$

$P_7 = \frac{\lambda_7}{\mu_7}\left[\frac{1}{1+D}\right]$

$P_8 = \frac{\lambda_8}{\mu_8}\left[\frac{1}{1+D}\right]$ (4.14)

The Reliability of the signal iATP different subsystems is:

$R_1(t) = e^{-\lambda_1 t}$, $R_2(t) = e^{-\lambda_2 t}$, $R_3(t) = e^{-\lambda_3 t}$, $R_4(t) = e^{-\lambda_4 t}$, $R_5(t) = e^{-\lambda_5 t}$, $R_6(t) = e^{-\lambda_6 t}$, $R_7(t) = e^{-\lambda_7 t}$, $R_8(t) = e^{-\lambda_8 t}$

Where R_1, R_2, R_3, R_4, R_5, R_6, R_7 and R_8 are reliability of the LEU, Beacon (B), TRE, CC, DMI, BA, OA and OM respectively. As these subsystems are connected in series, so the reliability of the signal iATP system will be the product of the individual subsystem reliabilities.

$R(t) = \prod R_i = R_1 R_2 R_3 R_4 R_5 R_6 R_7 R_8 = e^{-\lambda_1 t}. e^{-\lambda_2 t}. e^{-\lambda_3 t}. e^{-\lambda_4 t}. e^{-\lambda_5 t}. e^{-\lambda_6 t}. e^{-\lambda_7 t}. e^{-\lambda_8 t}$

$= e^{-\sum \lambda_i t} = e^{-Ft}$ [where $F = \sum \lambda_i$, $(i = 1, 2, 3, 4, 5, 6, 7, 8)$].

The Maintainability of the signal iATP different subsystems is:

$M_1(t) = 1 - e^{-\mu_1 t}$ where μ is the repair rate.

$M_2(t) = 1 - e^{-\mu_2 t}$

$M_3(t) = 1 - e^{-\mu_3 t}$

$M_4(t) = 1 - e^{-\mu_4 t}$

$M_5(t) = 1 - e^{-\mu_5 t}$

$M_6(t) = 1 - e^{-\mu_6 t}$

$M_7(t) = 1 - e^{-\mu_7 t}$

$M_8(t) = 1 - e^{-\mu_8 t}$ (4.15)

Mean Time To Failure (MTTF) = $\frac{1}{\sum \lambda_i} = \frac{1}{F}$

For Steady State Availability (A) = $\frac{MTTF}{MTTF+MTTR} = \frac{\mu}{\mu+\lambda}$

Thus Mean Time To Repair (MTTR) = MTTF × D , where D = $\sum \frac{\lambda_i}{\mu_i}$

System Repair Rate (μs) = $\frac{1}{MTTR} = \frac{1}{MTTF} \times \frac{1}{D}$

Maintainability Ms (t) = $1 - e^{-(\mu st)}$

Since R (t) = e^{-Ft}

Therefore, t = $\frac{\ln R\ (t)}{F}$.

Safety of the signal iATP system reaches SIL4; [21] and the Probability of dangerous Failure per Hour (PFH) ranges in between 10^{-8} and 10^{-9}. The probability of signal iATP system not to supervise the railway traffic becomes: [6]

$P_{degraded} = 1 - P_{operative} - P_{faulty}$

Where: $P_{operative} = \prod_{i=1}^{8} P_{operative}\ iATP\ system\ component\ (i)$

$P_{faulty} = 1 - \prod_{i=1}^{8}(1 - P_{faulty}\ iATP\ system\ component\ (i))$

and, iATP system component 1 is LEU, component 2 is Beacon (B), component 3 is TRE, component 4 is CC, component 5 is DMI, component 6 is BA, component 7 is OA and component 8 is OM.

5. Results and Discussions

The failure and repair rate data of the subsystems of the signal intermittent- Automatic Train Protection (iATP) System for this study were obtained from Signalling System detailed Design of AALRT Part I Technical Specification [21], Maintenance data records related to signal iATP system over the NS10 SER control zone (as seen in 'Appendix A' and 'Appendix B'), interview and site assessment. With the help of these data reliability and maintainability of the eight main subsystems and the entire signal iATP system versus time at different intervals were calculated and estimated using Markov process. The signalling system detailed design data was used for some of the subsystems with no maintenance records such as LEU, Beacon (B), BA and OM for failure and repair rates whereas maintenance data used for the TRE, CC, DMI and OA for repair rates in the analysis. The graphs for reliability and maintainability versus time at different intervals were also plotted to estimate reliability and maintainability of the eight main subsystems and the entire signal iATP system. The failure and repair rate is shown in table 5.1 below.

Table 5.1: Failure rate and Repair rate of the different signal iATP subsystems

No.	**Components**	**Failure Rate (λ)** [/Hour]	**Repair Rate (μ)** [/Hour]
1	Line-side Electronic Unit (LEU)	0.0000100	2.4
2	Beacon (B)	0.0000010	2.3
3	Trackside Radio Equipment (TRE)	0.0000400	2.0
4	Carborne Controller (CC)	0.0000200	2.6
5	Driver Machine Interface (DMI)	0.0000050	2.8
6	Beacon Antenna (BA)	0.0000150	2.2
7	Onboard Antenna (OA)	0.0000180	2.1
8	Odometer (OM)	0.0000050	2.2

From the above failure rate and repair rate of the different signal iATP system components that is the LEU, Beacon (B), TRE, CC, DMI, BA, OA and OM; the reliability at different time interval is calculated as shown in the table 5.2.

Table 5.2: Reliability of signal iATP system and subsystems for different time interval

Time (H)	LEU	B	TRE	CC	DMI	BA	OA	OM	iATP
0	1	1	1	1	1	1	1	1	1
100	0.9990	0.9999	0.9960	0.9980	0.9995	0.9985	0.9982	0.9995	0.9886
200	0.9980	0.9998	0.9920	0.9960	0.9990	0.9970	0.9964	0.9990	0.9774
300	0.9970	0.9997	0.9880	0.9940	0.9985	0.9955	0.9946	0.9985	0.9663
400	0.9960	0.9996	0.9841	0.9920	0.9980	0.9940	0.9928	0.9980	0.9554
500	0.9950	0.9995	0.9801	0.9900	0.9975	0.9925	0.9910	0.9975	0.9445

From Tables 5.1 and 5.2 reliability of the different signal iATP subsystems is calculated and Reliability versus Time (H) graph is plotted as observed in Figure 5.1.

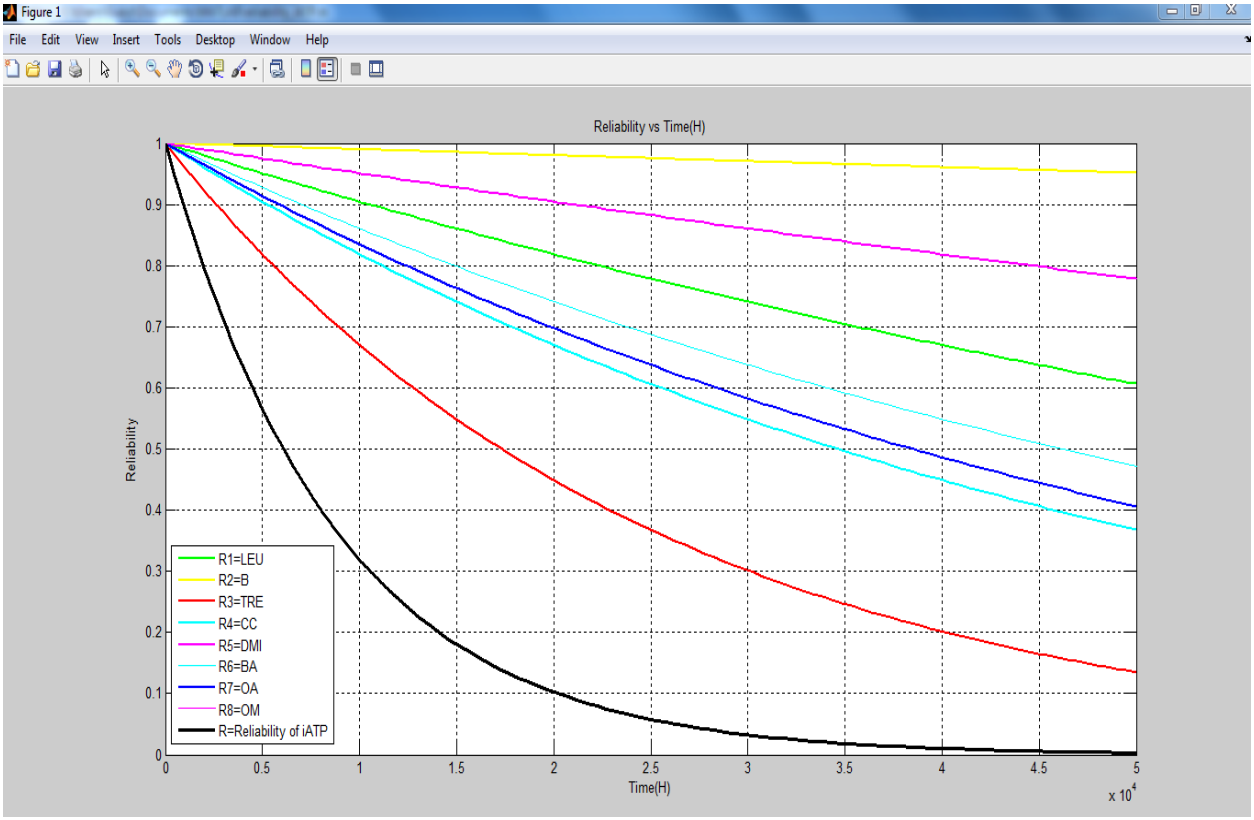

Figure 5.1: Reliability versus time pattern for signal iATP system and subsystems

In figure 5.1 the diagram of reliability of subsystems and the entire signal iATP system were plotted and the following observations were made:

- The reliability of the LEU, Beacon (B), TRE, CC, DMI, BA, OA and OM are 0.9753, 0.9975, 0.9048, 0.9512, 0.9875, 0.9631, 0.9559 and 0.9875 respectively after 2500 hours of operation. After 5000 hours of operation the reliability of the LEU, Beacon (B), TRE, CC, DMI, BA, OA and OM becomes 0.9512, 0.9950, 0.8187, 0.9048, 0.9753, 0.9277, 0.9139 and 0.9753 respectively. So reliability of TRE is the lowest out of the eight subsystems of signal iATP system. Thus it is required more attention to TRE than LEU, Beacon (B), CC, DMI, BA, OA and OM.

- The reliability of the entire signal iATP system after 2500 hours of operation is 75.16 %, in 5000 hours of operation is 56.53 %, in 1×10^4 hours of operation is 31.97 %, in 1.5×10^4 hours of operation is 18.08 %, and in 2×10^4 hours of operation drops down to 10.22 %. As it is observed from the graph the reliability of one single subsystem can affect the entire signal iATP system. That is, the failure of single subsystem affects the entire signal iATP system operation in that particular location or for the specific train.

- As Amparo M. et al [6] reported that for the considered railway corridor in Swedish railway the percentage of probability of a train having all track sections operative based on the state of signalling systems is between 76% and 96% considering the different scenarios, comparatively but only taking into account the signal iATP system of AA-LRT: the reliability after 2500 hours of operation is 75.16% which is lower than the minimum of probability of operation in Swedish railway. Thus the timely preventive maintenance activity works has to be improved at large.

The Maintainability of the different signal iATP system components that is the LEU, Beacon (B), TRE, CC, DMI, BA, OA and OM at different time interval is calculated as shown in the table 5.3.

Table 5.3: Maintainability of signal iATP system and subsystems for different time interval

Time (H)	LEU	B	TRE	CC	DMI	BA	OA	OM	iATP
0	0	0	0	0	0	0	0	0	0
0.5	0.6988	0.6833	0.6321	0.7274	0.7534	0.6671	0.6500	0.6671	0.6671
1	0.9092	0.8997	0.8646	0.9257	0.9391	0.8891	0.8775	0.8891	0.8891
1.5	0.9726	0.9682	0.9502	0.9797	0.9850	0.9631	0.9571	0.9631	0.9631
3	0.9992	0.9989	0.9975	0.9995	0.9997	0.9986	0.9981	0.9986	0.9986
6	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999	0.9999

The Maintainability pattern of the different signal iATP system is shown in the Figure 5.2 below.

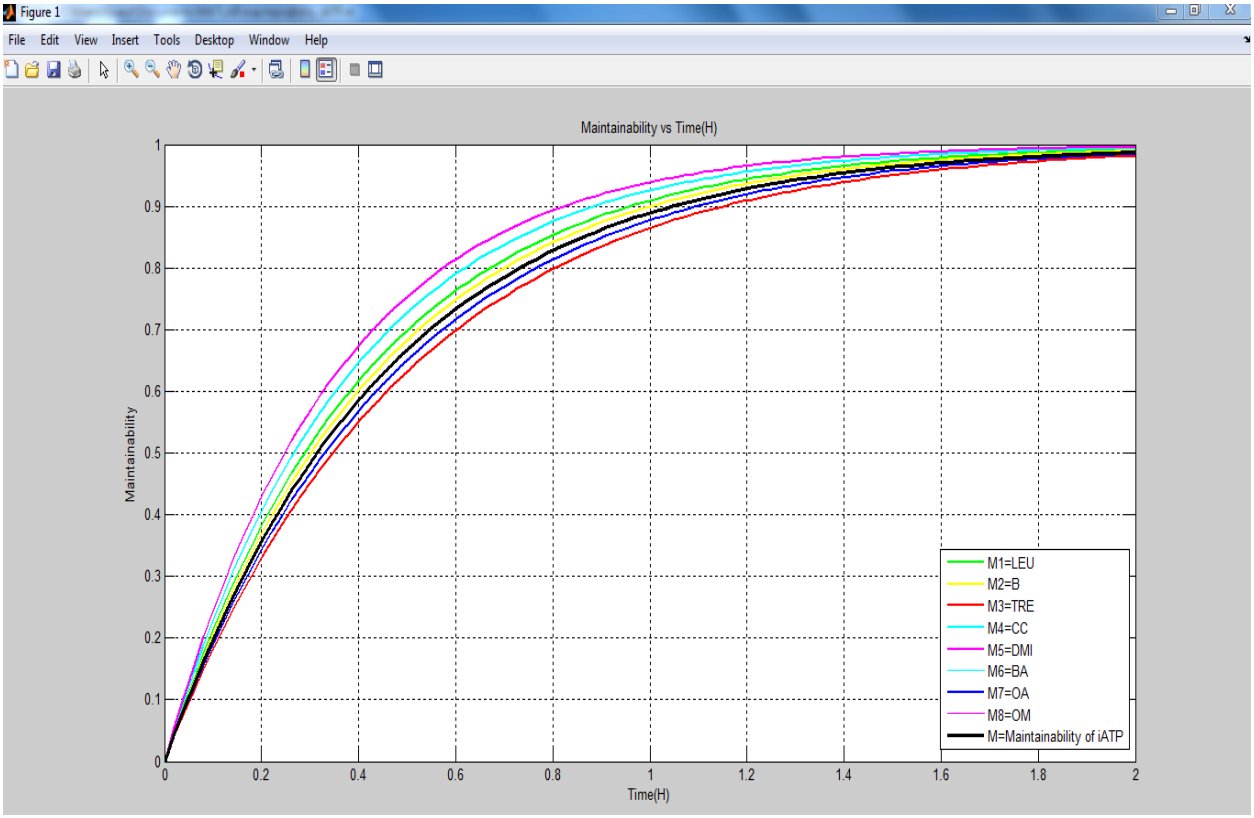

Figure 5.2: Maintainability versus time pattern for signal iATP system and subsystems

From the diagram of figure 5.2 the following observations were noticed for the maintainability of the signal iATP system and subsystems.

- The maintainability of the LEU, Beacon (B), TRE, CC, DMI, BA, OA and OM after one hour are 0.9092, 0.8997, 0.8646, 0.9257, 0.9391, 0.8891, 0.8775 and 0.8891 respectively. Maintainability of LEU, Beacon (B), CC, DMI, BA and OM is good but for TRE and OA its lower.
- The Maintainability of the entire signal iATP system after one hour is observed to be 88.91%.
- A failure at all signal iATP subsystems and the entire signal iATP system is repaired within one hour except for the TRE and OA.

For any system to have 100 percent of expected reliability, maintenance interval should be zero. Maintenance time may also be reduced by proper planning and spare parts management for increased availability of the system equipment. From the above analysis it is found that the reliabilities of the subsystems and signal iATP system are in decreasing as time increase. It is also seen that the failure rate and repair rate data taken from initial design data and maintenance data where the reliability of LEU, Beacon (B), TRE, CC, DMI, BA, OA and OM with time is satisfactory.

A better maintenance planning is required to enhance the obtained reliability and maintainability and to improve the RAMS of the equipment for signal iATP system that modelled and quantitatively analysed by Markov process. This investigation provides data for predicting the control needs in maintenance or repair processes and potential design modification to ensure a desirable level of the signal iATP system's reliability, availability and maintainability.

If decreased reliability and maintainability is observed, improving the signalling iATP system maintainability has to be done. Hence, proper resource allocation, a maintenance strategy suitable for the environmental condition as well as technical problems, and design out maintenance activity can only reduce the frequency of equipment failure or repair time and consequently improve the system availability (i.e. reliability and maintainability).

As signal iATP system supervises the railway traffic of the AA-LRT operation, but as observed in the 'Appendix C' the power off data is frequent within NS10 SER that have a control authority for the railway operation from Adey Ababa (NS9) to Temenja Yazh (NS13) stations that results in the probability of being in a state where operation is possible in a degraded mode being greater than the probability of not being operative at all, which reduces delays comparatively from being not operative at all, but requires other risk mitigation measures to ensure safe operation. That is the signal iATP equipment status is in failure due to power off to the signalling system and train can run in NRM mode where the driver operates the train according to the trackside signals in coordination with dispatcher orders.

6. Conclusions and Recommendations

6.1 Conclusions

The analytical probability models for signal iATP system that consists of eight main subsystems in series are developed. The models assume both failure and repair rates to be exponentially distributed. The mathematical model of operation and the probability model of failure for the individual subsystems and entire signal iATP system are presented. These models were applied to investigate the effect of system parameters on system performance in the actual signal iATP system of AA-LRT. The following conclusions can be pointed out:

- The reliability of the LEU, Beacon (B), TRE, CC, DMI, BA, OA and OM are 0.9753, 0.9975, 0.9048, 0.9512, 0.9875, 0.9631, 0.9559 and 0.9875 respectively after 2500 hours of operation and reliability of the LEU, Beacon (B), TRE, CC, DMI, BA, OA and OM becomes 0.9512, 0.9950, 0.8187, 0.9048, 0.9753, 0.9277, 0.9139 and 0.9753 respectively after 5000 hours.
- The maintainability of the LEU, Beacon (B), TRE, CC, DMI, BA, OA and OM after one hour are 0.9092, 0.8997, 0.8646, 0.9257, 0.9391, 0.8891, 0.8775 and 0.8891 respectively.
- The maintenance center signal and communication division of AA-LRT may adopt the appropriate maintenance policy for the signal iATP system, focusing primarily on TRE that displays the lowest reliability and maintainability.
- Combining maintenance improvements to reduce the failure rate and increase the repair rate is more efficient at increasing the performance of the entire signal iATP system of AA-LRT.

It is worth noting in here that stable and reliable power supply has to be provided for NS10 SER to enhance the signal iATP system supervision of the railway traffic safety over the stations from Adey Ababa (NS9) to Temenja Yazh (NS13) and reduce delays that result from degraded mode of operation during power off times.

In addition, the steady state probability models described in equations (4.12), (4.13), and (4.14) can be applied in each subsystems consisting of individual components which fail more or less frequently, leading to failures in the equipment. Hence, it can estimate the demand for subsystems support through spare parts delivery and determine the inventory management at large.

6.2 Recommendations

This thesis work is done on the application of Markov process to analyses the performance of the signal iATP system of AA-LRT and the following recommendations are provided.

- Markov process may also be applicable for other signalling subsystems of AA-LRT such as Automatic Train Supervision (ATS), Computer Based Interlocking (CBI), Data Communication System (DCS) and Maintenance Support System (MSS) and also to different signalling equipment at component levels like Axle Counters, Signal Machines and Switch Machines.
- Since detail design signalling system data used for some subsystems with no failure records and maintenance data used for some other subsystems with maintenance records which brings in good reliable and maintainable results. Hence by considering the actual repair rate and failure rate properly logged data for all signal iATP subsystems the performance of the system can be analysed using Markov processes more accurately.
- Considering the effects of the redundant communication networks, human factors and environmental conditions the analysis can provide more accurate results.
- Modelling proper maintenance and inspection policies can be further use for the cost optimization of the railway signalling automatic train protection system.
- Applying proper resource allocations, having a maintenance strategy suitable for the technical and environmental problems, and with proper design improvements can reduce the frequency of equipment failure or repair time and subsequently improve the signal iATP system availability (i.e. reliability and maintainability).

- Further works can be done on the application of Markov method or different approach to evaluate and compare the performance of the signal iATP system of AA-LRT ensuring the safety of operation on different sections, architectures or design solutions thereby assisting in the decision-making process when improving or updating the automatic train protection system over the entire railway infrastructure.

7. References

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Appendix A

Trackside Signal iATP Equipment Data

Trackside Signal iATP Equipment Data within NS10 SER Control Zone of AA-LRT.

Beacons

No.	Beacons	Type		Location				Direction	
		Active	Passive	Entry of Station	Middle of Station	Exit of Station	Between Stations	Up	Down
1	RB_1086	0	1	0	0	0	1	1	0
2	RB_1085	0	1	0	0	0	1	1	0
3	RB_1084	0	1	1	0	0	0	1	0
4	RB_1080	0	1	0	1	0	0	1	0
5	B20905	1	0	0	0	1	0	1	0
6	RB_1074	0	1	0	0	0	1	1	0
7	RB_1073	0	1	0	0	0	1	1	0
8	RB_1070	0	1	0	0	0	1	1	0
9	RB_1068	0	1	0	0	0	1	1	0
10	RB_1065	0	1	0	0	0	1	1	0
11	RB_1060	0	1	0	0	0	1	1	0
12	B21006	1	0	0	0	0	1	1	0
13	RB_1052	0	1	0	0	0	1	1	0
14	RB_1051	0	1	0	0	0	1	1	0
15	RB_1168	0	1	1	0	0	0	1	0
16	B21008	1	0	1	0	0	0	1	0
17	RB_1045	0	1	0	1	0	0	1	0

18	B21001	1	0	0	0	1	0	1	0
19	RB_1039	0	1	0	0	0	1	1	0
20	RB_1037	0	1	0	0	0	1	1	0
21	RB_1033	0	1	0	0	0	1	1	0
22	RB_1029	0	1	0	0	0	1	1	0
23	RB_1027	0	1	0	0	0	1	1	0
24	RB_1025	0	1	0	0	0	1	1	0
25	RB_1024	0	1	0	0	0	1	1	0
26	RB_1023	0	1	1	0	0	0	1	0
27	RB_1022	0	1	0	1	0	0	1	0
28	B21103	1	0	0	0	1	0	1	0
29	RB_1019	0	1	0	0	0	1	1	0
30	RB_1018	0	1	0	0	0	1	1	0
31	RB_1016	0	1	0	0	0	1	1	0
32	RB_1015	0	1	0	0	0	1	1	0
33	RB_1014	0	1	0	0	0	1	1	0
34	RB_1013	0	1	0	0	0	1	1	0
35	RB_1010	0	1	0	0	0	1	1	0
36	RB_1009	0	1	0	0	0	1	1	0
37	B21202	1	0	0	0	0	1	1	0
38	RB_1007	0	1	0	0	0	1	1	0
39	RB_1006	0	1	0	0	0	1	1	0
40	RB_1005	0	1	0	0	0	1	1	0
41	RB_1004	0	1	0	0	0	1	1	0
42	RB_1003	0	1	1	0	0	0	1	0
43	RB_1002	0	1	0	1	0	0	1	0
44	B21201	1	0	0	0	1	0	1	0
45	RB_999	0	1	0	0	0	1	1	0

46	RB_998	0	1	0	0	0	1	1	0
47	RB_997	0	1	0	0	0	1	1	0
48	RB_996	0	1	0	0	0	1	1	0
49	RB_995	0	1	0	0	0	1	1	0
50	RB_994	0	1	1	0	0	0	1	0
51	RB_993	0	1	0	1	0	0	1	0
52	B21301	1	0	0	0	1	0	1	0
53	RB_990	0	1	0	0	0	1	1	0
54	RB_989	0	1	0	0	0	1	1	0
55	RB_988	0	1	0	0	0	1	1	0
56	RB_843	0	1	1	0	0	0	0	1
57	RB_844	0	1	0	1	0	0	0	1
58	B21302	1	0	0	0	1	0	0	1
60	RB_848	0	1	0	0	0	1	0	1
61	RB_849	0	1	0	0	0	1	0	1
62	RB_850	0	1	0	0	0	1	0	1
63	RB_852	0	1	1	0	0	0	0	1
64	RB_853	0	1	0	1	0	0	0	1
65	B21204	1	0	0	0	0	1	0	1
66	RB_858	0	1	0	0	0	1	0	1
67	RB_860	0	1	0	0	0	1	0	1
68	RB_861	0	1	0	0	0	1	0	1
69	RB_862	0	1	0	0	0	1	0	1
70	RB_863	0	1	0	0	0	1	0	1
71	RB_871	0	1	0	0	0	1	0	1
72	RB_865	0	1	0	0	0	1	0	1
73	RB_866	0	1	0	0	0	1	0	1
74	RB_868	0	1	0	0	0	1	0	1

75	B21101	1	0	0	0	0	1	0	1
76	RB_872	0	1	0	0	0	1	0	1
77	RB_874	0	1	0	0	0	1	0	1
78	RB_875	0	1	0	0	0	1	0	1
79	RB_877	0	1	1	0	0	0	0	1
79	RB_878	0	1	0	1	0	0	0	1
80	B21102	1	0	0	0	1	0	0	1
81	RB_881	0	1	0	0	0	1	0	1
82	RB_882	0	1	0	0	0	1	0	1
83	RB_883	0	1	0	0	0	1	0	1
84	RB_884	0	1	0	0	0	1	0	1
85	RB_886	0	1	0	0	0	1	0	1
86	RB_887	0	1	0	0	0	1	0	1
87	RB_888	0	1	0	0	0	1	0	1
88	RB_889	0	1	1	0	0	0	0	1
89	RB_890	0	1	0	1	0	0	0	1
90	B21010	1	0	0	0	1	0	0	1
91	RB_893	0	1	0	0	0	1	0	1
92	RB_894	0	1	0	0	0	1	0	1
93	RB_895	0	1	0	0	0	1	0	1
94	RB_1169	0	1	0	0	0	1	0	1
95	B21004	1	0	0	0	0	1	0	1
96	RB_898	0	1	0	0	0	1	0	1
97	B21002	1	0	0	0	0	1		1
98	RB_900	0	1	0	0	0	1	0	1
99	RB_901	0	1	0	0	0	1	0	1
100	RB_902	0	1	0	0	0	1	0	1
101	RB_903	0	1	0	0	0	1	0	1

102	RB_904	0	1	0	0	0	1	0	1
103	B20903	1	0	0	0	0	1	0	1
104	RB_906	0	1	0	0	0	1	0	1
105	RB_909	0	1	1	0	0	0	0	1
106	RB_910	0	1	0	1	0	0	0	1
107	B20902	1	0	0	0	1	0	0	1

Key:- 1 ---------- Yes

0 ---------- No

Note: There are five (5) LEU's within NS10 SER Control Zone.

Trackside Radio Equipment (TRE) Access Points

No.	**AP Name**	**Network Type**	**Location between Stations**	**Failed during 18 -21/10/2018**
1	AP21011	RED	NS8-NS9	1
2	AP21008	RED	NS9-NS10	1
3	AP21006	RED	NS10-NS11	1
4	AP21004	RED	NS11-NS12	1
5	AP21002	RED	NS11-NS12	1
6	AP21012	BLUE	NS8-NS9	0
7	AP21010	BLUE	NS9-NS10	0
8	AP21007	BLUE	NS10-NS11	0
9	AP21005	BLUE	NS11-NS12	0
10	AP21003	BLUE	NS11-NS12	0

11	AP21001	BLUE	NS12-NS13	0
12	AP21009	RED	NS9-NS10	1
13	AP21009	BLUE	NS9-NS10	0
14	AP21004a	RED	NS11-NS12	1
15	AP21004a	BLUE	NS11-NS12	0

Key:- 1 ---------- Yes

0 ---------- No

Appendix B

Onboard Signal iATP Equipment Data

Onboard Signal iATP Equipment Failure indication Data of AA-LRT from September to December 2018 / Sample Data /.

Date	**Train Number**	**Failure Frequency**	**Failure Description** (ATP icon display)	**Location**
20/10/2018	208, 218	2	Red	NS10
26/10/2018	220	1	Red	NS10
03/11/2018	220	1	Red	NS10
05/11/2018	207, 209	2	Red	NS10

N.B: ATP icon display ‘Red’ indicates that the Onboard signal iATP equipment in major failure.

Appendix C

Frequency of Power off Data

Frequency of Power off data within NS10 SER Control Zone of AA-LRT that affect the iATP system operation from September to December 2018 / Sample Data /.

Date	Power off Duration	Turnouts Manual Locking Duration	Power off Frequency /day	Power off Duration Status
02/09/2018	17:37 - 19:02	17:50-18:10	1	Operation Time
04/09/2018	06:40- 09:18	06:55-07:16	1	Operation Time
05/09/2018	08:10 - 14:04	08:36-08:59	1	Operation Time
07/09/2018	10:27 – 16:14	10:55-11:18	2	Operation Time & Maintenance Time
	04:06 - 09:31 at 08/09/2018	05:03-05:23		
12/09/2018	18:07 - 18:30	*Power on before locking*	1	Operation Time
18/09/2018	14:56 - 18:31	15:11-15:38	1	Operation Time
19/09/2018	13:44 - 16:46	13:56-14:04	1	Operation Time
21/09/2018	09:15 - 10:16	09:32-09:54	1	Operation Time
25/09/2018	12:14 - 14:54	15:19-15:27	2	Operation Time & Maintenance Time
	07:30 -15:09 at 26/09/2018	08:30-08:56		
05/10/2018	08:20 - 10:10	09:13-09:50	1	Operation Time
13/10/2018	06:45 - 06:50	*Power on before locking*	1	Operation Time
17/10/2018	08:05 - 08:37	*Power on before locking*	1	Operation Time
18/10/2018	12:36 - 13:30	12:59-13:12	2	Operation Time
	15:39 - 16:24	15:52-15:59		
19/10/2018	17:42 - 17:43	*Power on before locking*	1	Operation Time
23/10/2018	07:10 - 08:52	08:10-08:23	1	Operation Time

24/10/2018	13:48 - 15:27	13:31-13:40	1	Operation Time
25/10/2018	22:35 -05:15	23:40-23:50	2	Operation Time & Maintenance Time
	7:07- 10:32	08:37-08:44		
27/10/2018	07:53 - 07:57	*Power on before locking*	1	Operation Time
06/11/2018	09:35 - 11:17	09:48-10:04	1	Operation Time
08/11/2018	12:41 - 12:53	*Power on before locking*	1	Operation Time
14/11/2018	17:38 -20:48	17:54-18:16	1	Operation Time
15/11/2018	19:31 - 23:17	20:17-20:19	1	Operation Time
21/11/2018	11:11 - 13:43	11:56-12:09	1	Operation Time
24/11/2018	22:42 - 05:49	23:00-23:11	1	Operation Time & Maintenance Time
01/12/2018	05:55 - 08:22	07:10-07:34	1	Operation Time
13/12/2018	06:53 - 06:57	*Power on before locking*	1	Operation Time
19/12/2018	09:55 - 14:27	10:02-10:26	1	Operation Time
22/12/2018	21:59 - 07:09	23:00-23:24	1	Operation Time & Maintenance Time
24/12/2018	08:03 - 13:54	08:59-09:11	1	Operation Time
26/12/2018	13:38 - 14:27	14:05-14:15	1	Maintenance Time & Operation Time

Key:- Operation Time: 06:00 – 0:00

Maintenance Time: 0:00 – 06:00

NB: After turnouts manual locking time the dispatcher arranges a degraded mode of operation over the entire NS10 SER control zone sections till power on.