Reliability, Availability and Maintainability Analysis of Addis Ababa Light Rail Transit Signaling System

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This is to certify that the thesis prepared by Alemu Ayana, entitled: *Reliability, Availability and Maintainability Analysis of Addis Ababa Light Rail Transit Signaling System* and submitted in partial fulfilment of the requirements for the Degree of Master of Sciences (Electrical and Computer Engineering) complies with the regulations of the university and meets the accepted standards with respect to originality and quality.

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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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This thesis has been submitted for examination with my approval as a university advisor.

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Abstract

The railway network is a complex and distributed system with several technologies working together to fulfil the demands on capacity, speed and mobility to transport goods and passengers. The railway transportation system in Addis Ababa, the capital of Ethiopia plays a vital role in sustaining social and economic activities of a country by providing a safe, reliable, environmentally friendly and cost efficient means of transportation for the people. Following the safe, economical and practical principles, the design of Addis Ababa Light Rail Transit (AA-LRT) chooses a reasonable communication and signal system.

Quality of transportation system critically depend on the reliability of signaling systems. Despite their numerous advantages, considerable train delays, cancellation, high maintenance cost and passenger dissatisfaction are the main disadvantages of signaling systems failures.

Reliability, Availability, and Maintainability (RAM) analysis is a practical technique that uses failure and repair dataset obtained over a reasonable time for dealing with proper signaling system operation, maintenance scheduling, cost control, and improving the availability and performance of signaling systems. This research study and analyse RAM of AA-LRT signaling system with a historical database of failures and repairs of signaling systems was collected in the whole line of AA-LRT over a period of six months operation.

After data analysis, it was revealed that the Axle counter subsystem has the highest failure frequency with relatively low availability and the switch has the lowest failure frequency with highest availability.

A failure Mode and Effect analysis (FMEA) result shows that the switch is most critical subsystem to cause risk. Similarly, estimating the availability of failed signaling subsystems and equipments indicated that all subsystems have an acceptable availability level of above 96%.

Keywords: AA-LRT, Signalling system, Axle Counter, Reliability, Availability, Maintainability, RAM, Failure Mode and Effect Analysis (FMEA) and Risk Priority Number (RPN).

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List of Abbreviations

Abbreviations	Descriptions
AC	Axle Counter
ATP	Automatic Train Protection
ATS	Automatic Train Supervision
CASCO	CASCO SIGNAL LTD.
CBI	Computer Based Interlocking
CC	Carbone Controller
CDF	Cumulative Distribution Function
CNOF	Cumulative Number of Failure
CTBF	Cumulative Time Between Failure
CTTR	Cumulative Time To Failure
DCS	Data Communication System
DMI	Driving Monitor Interface
EN	Europe Standard
FMEA	Failure Mode Effect Analysis
FMECA	Failure Mode Effect and Criticality Analysis
FTA	Fault Tree Analysis
HMI	Human Machine Interface
IATP	Intermittent Automatic Train Protection
IEC	International Electrotechnical Commission
IID	Independent and Identically Distributed
ISO	International Standards Organization
K-S	Kolmogorov-Smirnov
LCD	Liquid Crystal Display
LED	Light Emitting Diode
LEU	Line Encoder Unit
MMS	Maintenance Monitoring System
MSS	Maintenance Support System
MTBF	Mean Time Between Failure
MTTF	Mean Time To Failure
MTTR	Mean Time To Repair
OCC	Open Control Center

PD	Probability Density
PDF	Probability Density Function
PSU	Power Supply Unit
PSS	Power Supply System
RAM	Reliability, Availability and Maintainability
RAMS	Reliability, Availability, Maintainability and Safety
RBD	Reliability Block Diagram
RPN	Risk Priority Number
SDM	Diagnostics and Maintenance Subsystem
SIG	Signaling
SIL	Safety Integrity Level
TBF	Time Between Failures
TRE	Trackside Radio Equipment
TTR	Time To Repair
UPS	Uninterruptible Power Supply

List of Symbols

Symbols	Descriptions
α	Shape/Slope Parameter
β	Scale Parameter
γ	Location Parameter
μ	Mean of the Natural Logarithm
σ	Standard Deviation
$\lambda(t)$	Failure Rate
$\mu(t)$	Restoration Rate

1. INTRODUCTION

1.1 Background

All over the world Railway transportation is increasingly used, as this mode of transport is more energy efficient, higher traffic capacity and environmentally friendly than road transportation [1].

The railway transportation system in Addis Ababa, the capital of Ethiopia plays a vital role in sustaining social and economic activities of a country by providing a safe, reliable, environmentally friendly and cost efficient means of transportation for the people. Following the safe, economical and practical principles, and the characteristics of Light Rail Transit in Addis Ababa, AA-LRT design chooses a reasonable communication and signal system [2]. Signaling system equipments are mainly set along the track, on board trains and on Open Control Center (OCC) to ensure [3]:

- ✓ Management of the line；
- ✓ Traffic supervision and control；
- ✓ Carborne train control；
- ✓ Trackside control；
- ✓ Management of data communication among its components;
- ✓ Signalling system components maintenance.

The purpose of signaling system is mainly to control and regulate the movements of trains safely and efficiently. It also used to direct railway traffic and to pass information to the driver. In controlling train movements, signal systems are used for a number of purposes [4], [5].

- ✓ To regulate the movement of the trains so that they run safely at maximum permissible speeds.
- ✓ To maintain a safe distance between trains that are running on the same line in the same direction.
- ✓ To ensure the safety of two or more trains that have to cross or approach each other
- ✓ To provide facilities of the safe and efficient shunting.
- ✓ To regulate the arrival and departure of trains from the station yard.
- ✓ To guide the trains to run at restricted speeds during the maintenance and repair of tracks.
- ✓ To ensure the safety of the train when it comes in contact with the road traffic at level crossings.

Since Signaling systems are located along the infrastructure and part on the rolling stock and its functionality based on the principle of fail-safe; this implies that the railway section where a failure occurs will be not fully operative until the failure is repaired.

Reliability, Availability and Maintainability (RAM) analysis is performed to decrease the number of failures of the equipments and to predict availability of a system in the future, and to make amendments which will increase the performance of the system.

RAM analysis has been used in railway systems to provide safe transportation since no errors can be tolerated in railway systems and errors can sometimes result in fatal accidents. To achieve safe transportation on railways there have to be a need for efficient and reliable signaling system. Along with the safety requirements are the RAM requirements whose goal is to ensure the system has a required level of dependability. This means that it must be reliable, have minimum delays and cancellations and minimum incidents. Maintenance must, to the greatest extent possible, be performed during the scheduled possession times [6]**.**

Failures in AA-LRT signaling system adversely affect system reliability so that to realise safe and dependable railway systems with regards to all factors that affect reliability, availability and maintainability, need to be identified and managed. Equipments which have lower reliability and availability may be replaced or upgraded in order to increase the performance of the equipment and availability of the signaling system. Thus, this thesis study and analyse the reliability, availability and maintainability of a signaling system with available failure report and repair data.

1.2 Problem Statement

Quality of transportation system is determined by the speed and safety of conveyance of passengers and goods to the destination. Both of these parameters depend critically on the reliability of signaling systems. Failure of these systems have a large impact on train running, passenger comfort and safety (in the worst case, to derailments and collisions) [7].

Due to high reliability and safety requirements, good maintenance strategies for railway signaling systems are also very important. Traffic Accidents record in AA-LRT since September,2015 to September, 2016 shows signaling equipment failures has an economic impact, costs over 657,546ETB. Thus, Dealing with the RAM of a signaling system is very important to improve overall system availability, quality, minimize and prevent system failure and reduce maintenance cost.

From unstructured interviews and observational data in Addis Ababa, the customer needs to demand more, better and faster deliveries of transportation services timely and safely at relatively lower cost. Failure reports from October, 2016 to November, 2016 and January, 2017 to April, 2017 shows that, the average punctuality rate is about 86.06% and around 216.56 hrs delay due to failures in the AA-LRT. From statistical data, 40% of the total failures are signaling system failures and the most frequently failed subsystem. In addition to train delay and cancellation problem, trains clear the passengers even though they don’t arrive their Destinations. Thus, the customer has to rely on the AA-LRT transportation services; AA-LRT must as far as possible try to fulfill the customers’ needs and demands.

Generally, From weekly failure data and maintenance reports, signaling system in AA-LRT is the critical issue since the faults and failures have economic consequences (high maintenance costs, etc.), that can affect operation (delays, cancellations, speed restrictions, etc.), and have safety consequences (injuries, death, etc.) in transportation system. The RAM of a signaling system provides data on failure rates of the system, possible failure modes, maintenance operations, etc.

Considering this problem, RAM analysis should be done for the signalling system of AA-LRT based on the failure and repair data of signaling equipments. It will be done through identification of the problem causes, and by determining parameters and suggest remedial measures using Failure Mode and Effect Analysis (FMEA), and Time Between Failure (TBF) and Time To Failure (TTR) data for improvements, design updates and overall mission success.

1.3 Objectives

1.3.1 General Objectives

The main objective of this research is to analyse and estimate reliability, availability and maintainability of different AA-LRT signalling subsystems and components.

1.3.2 Specific Objectives

In order to achieve the main objective of this research the following tasks will be performed:

- ✓ Evaluate the failure frequency and distribution functions
- ✓ Identify most critical subsystems and their problem causes.
- ✓ Calculate the RAM parameters from the failure and repair data.
- ✓ Suggest remedial measures to improve its RAM.

1.4 Scope

The thesis focuses on the RAM of the existing AA-LRT (phase I) signalling systems during real-life operation using historical failure and repair data. The thesis is limited to the signalling system hardware components located mainly on wayside (such as switches, axle counters, etc.), ATP and ATS (i.e. the thesis will not consider CBI and DCS failures).

- ✓ FMEA is limited to current failures related to signaling system of AA-LRT.
- ✓ Calculation of RAM parameters will be limited to the available failure and repair data.
- ✓ The thesis will recommend on areas that needs improvements with corrective actions.

Furthermore, the thesis will mainly focus on areas and components that need more attention and improvements and it is assumed that components fail independently of other components.

1.5 Contributions

The thesis has developed approaches, methodologies and tools to analyse and evaluate the RAM of AA-LRT signalling systems based on failure and repair data. The thesis contributes on the following areas:

- ✓ Formal initial analysis to/ for estimate actual RAM of AA-LRT signaling system.
- ✓ Good understanding of the role of RAM analysis plays in ensuring safety operation and used for further studies.
- ✓ A base line for performance and quality analysis of AA-LRT.
- ✓ Suggest the remedial measures for the improvement of the system.

1.6 Methodology

The study approach is based on both quantitative and qualitative methods to obtain the most critical failures modes, causes and to evaluate the RAM of AA-LRT signaling system. The information was gathered from literature study, unstructured interviews and depot visitation, daily failure data and maintenance records, discussions and consultation with signaling and communication engineers from AA-LRT.

This research focuses on failure and maintenance of AA-LRT signaling system. Thus, the primary objective is to assess failures from the root cause to the remedial measures and finally evaluate the RAM. To reach the identified goals and analyse reliability, availability, and maintainability (RAM) of the AA-LRT signaling systems mainly three steps was employed such as Data collection, Data Evaluation and Data Analysis. The flowchart for the research work shown in Figure 1.1.

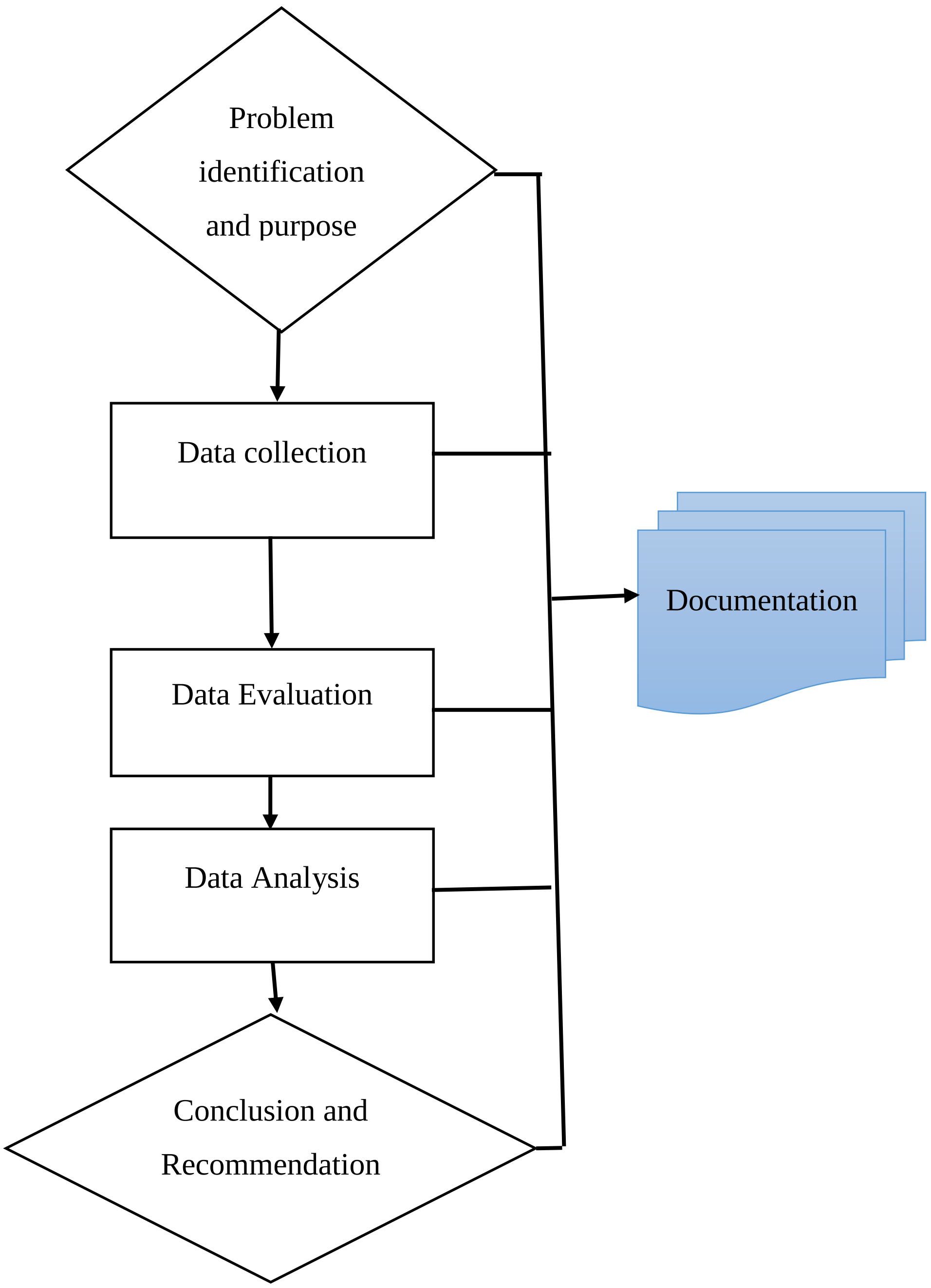


Figure 1.1 Flowchart for Research Methodology

1.6.1 Data Collection

Data collection is the process of identifying and acquiring data to support the analysis at the subsystem, component, product and system levels. The data that is relevant for analysing the RAM of the AA-LRT signaling system can be collected are architectural, operational and maintenance data. It can be through literature reviews, observation and interviews and documentations and standards.

1.6.2 Data Evaluation

Data Evaluation describes the approach needed for evaluation of the collected data in order to select appropriate probability and statistical analysis techniques. The main assumption of the data is that the collected data are independent and identically distributed (IID). This assumption needs verification by appropriate statistical tests such as the trend and serial correlation test.

A. IID Assumption

The assumption that the data sets are IID implies that probability distributions can be used to model the subsystems. The assumption that the data sets are independent means that one failure is not dependent on the previous one, which implies that the parameters of the chosen distribution do not change with time. The assumption that the data sets are identical means that the different data points follow the same distribution.

The trend test can verify the independent assumption, either analytically or graphically. While the serial correlation test can verify the identical assumption, either analytically or graphically.

B. Trend Test

In the trend test, the cumulative TBF/TTR is plotted against the cumulative failure number/repair number. If a line drawn through the data points either resembles a concave upwards or concave downwards trend in the data, the system is respectively an improving or deteriorating system. However, if the line drawn through the data points is approximately a straight line, then the data is free from trend, which implies that the data set is identically distributed.

C. Serial correlation Test

In the serial correlation test, the $(i-1)^{th}$ TBF/TTR is plotted against the i^{th} TBF/TTR. If the data points are randomly scattered without any clear pattern it implies a data set free from serial correlation, which again implies that the data points in the data set are independent of each other.

1.6.3 Data Analysis

Data analysis involves converting the collected data into common measures to perform statistical analyses. It describes the approach needed for evaluation of the collected data in order to select appropriate RAM analysis techniques. In this research, data analysis will be mainly in two ways.

1. Failure analysis using Failure Modes and Effects Analysis (FMEA).

An FMEA is an analysis that reveals system failure modes, their causes, and the effects of the failure mode occurrence on the system operation. It provides a basis for identifying potential system failures and unacceptable failure effects and corrective actions to prevent them.

2. RAM analysis through Goodness of fit using TBF and TTR data's.

In RAM analysis of any equipment or system, providing an appropriate field database of failures and maintenance data is important for getting reliable and accurate results. TBF and TTR data analysis is used to model the failure and repair processes of the different subsystems by fitting a probability distribution that best represent the failure data and repair data, and estimating parameters to fit the distributions to the different data sets.

1.7 Structure of Thesis

The thesis contains five chapters.

Chapter 1: Presents the background and topic of this thesis. It also presents the general and specific objectives along with problem statement, contributions and scope of the thesis. Furthermore, the methodologies used for achieving the research objectives are also presented.

Chapter 2: Presents the literature for the thesis topic. Specifically, it introduces RAM; what it is, important parameters to calculate. Finally, the literatures related to the topic (related works) are presented.

Chapter 3: Presents brief descriptions of AA-LRT signaling system, subsystems and components included in the system. .

Chapter 4: Presents a methodology for RAM analysis, specifically FMEA, and TBF and TTR data analysis.

Chapter 5: Presents Results and Discussions such as failure analysis and RAM analysis.

Chapter 6: Presents Conclusions and Recommendations of the thesis work.

2. THEORETICAL BACKGROUND AND LITURATURE STUDIES

2.1 Introduction to RAM

Analysing and establishing RAM will help to ensure that the system or the service will be free from RAM-related problems that could prevent the accomplishment of safety, environment, performance, schedule, and economic goals. RAM to acquire quality products (systems) that satisfy user needs with measurable improvements to mission capability and operational support in a timely manner, and at a fair and reasonable price [8].

2.2 RAM Defined

2.2.1.1 Reliability (R)

Reliability (R) is defined in [9] as the probability that an item can perform a required function under given conditions for a given time interval (t1, t2) [7].

It is also defined as the probability that a specified item will perform a specified function within a defined environment, for a specified length of time. In other words; reliability is a measure of the product’s ability to avoid failure. A reliability deficiency will eventually result in an impaired or lost performance, compromised safety, and the need for such restorative actions as diagnosis, repair, spare replenishment, and maintenance. High-reliability products will operate longer, allowing resources to be focused on improving performance.

2.2.2 Maintainability (M)

Maintainability (M) is defined as in [10] the probability that a given active maintenance action, for an item under given conditions of use, can be carried out within a stated time interval when maintenance is performed under stated conditions and using stated procedures and resources [7].

Maintainability refers to the measures taken during the development, design, and installation of a manufactured product that reduce required maintenance, man hours, tools, logistic cost, skill levels, and facilities, and ensure that the product meets the requirements for its intended use [8].

2.2.3 Availability (A)

Availability (A), according to [10], it is defined as the ability of the product to be in a state to perform a required function under functions at a given instant of time, over a given time interval, assuming that the required external source of help are provided. This means that the system (product) will fulfill the required tasks (functions) under the defined framework conditions [7].

2.3 Why RAM

Engineering systems, components and devices are not perfect. The reliability of engineering systems has become an important issue during the design process because of the increasing dependence of our daily lives and schedules on the satisfactory functioning of these systems. Thus, reliability is important to minimise and prevent failures in order to maximize system performance and efficiently use of resources.

Maintainability is important due to high operating and support costs of systems and equipment. Thus, applying maintainability engineering principles to systems and equipment are used to reduce projected maintenance cost and time through design modifications directed at maintenance simplifications, to use maintainability data for estimating equipment availability or unavailability, and to determine labor hours and other related resources required to perform the projected maintenance [11].

Thus, Achieving specified levels of RAM for a system is important to increase system readiness (the state of preparedness of systems to meet a mission) and availability, to reduce maintenance personal requirement and life-cycle cost, system safety and mission success.

2.4 RAM(S) in Railway

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 lifecycle (system conditions), by sources of failure imposed on the system during operation (operating conditions) and by sources of failure imposed on the system during maintenance activities (maintenance conditions) [10]. These sources of failure can interact. Improving the factors influencing the RAMS will improve the dependability.

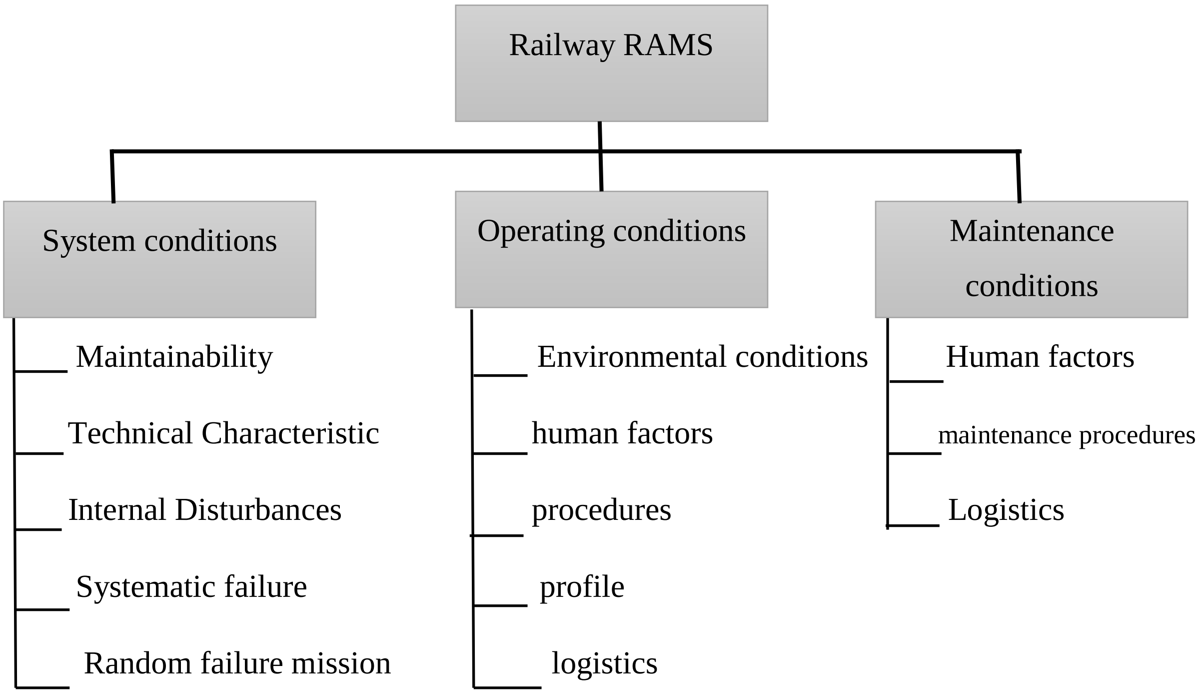


Figure 2.1 Factors Influencing Railway RAMS [10].

2.5 RAM Parameters

RAM of the system can be defined as qualitative and quantitative indexes related to the system, subsystem and components can be relied and available upon to function as specified. RAM is used as an available tool to understand how the whole system functions, to predict the imperfections and showing the influence on the quality and performance of the system.

2.5.1 Reliability Parameters

Reliability concerns the probability of a device to have failure in a specific time period. Reliability can be specified as the mean number of failures in a given time which can be also described as failure rate or can be expressed as the mean time between failures MTBF for repairable items, or as the mean time to failure MTTF for non-repairable items. Repairable items are repaired and returned to use again after repair. The basic reliability parameters in are Failure rate (λ), Mean Time Between Failure (MTBF), Mean Time To Failure (MTTF).

For complex systems the reliability requirement is normally specified in terms of the Mean Time Between Failures (MTBF) or as a failure rate (λ).

i. Failure rate (λ)

Failure Rate (λ) is the probability of occurrence of a failure at a specific component age, defined in terms of failures per time, load cycle, or cumulative load [7].

It is the probability of failure per unit time of items in operation; sometimes estimated as a ratio of number of failures to the accumulated operating time for the items. Failure rate is usually time dependent, and thus the rate changes over time versus the expected life cycle of a system. In the special case when the likelihood of failure remains constant with respect to time, failure rate is simply the inverse of the Mean Time Between Failure (MTBF). It is computed as a simple ratio of the number of failures, f, during a specified test interval T;

$$\lambda(t) = \frac{\text{failures}}{\text{time unit}} = \frac{f}{T} = \frac{1}{\text{MTBF}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Failure rate is the frequency with which an engineered system or component fails, expressed for example in failure per hour.

ii. Mean Time Between Failure (MTBF)

MTBF is a basic measure of reliability for repairable items and described as the time passed before a component, assembly, or system fails, under the condition of a constant failure rate. MTBF is the time or load span between two failures and calculated as the inverse of the failure rate, λ, for constant failure rate systems. The higher the MTBF number is, the less maintenance actions are needed in the same time span and the higher the reliability of the product [7].

During the operating period, when failure rate is fairly constant, MTBF is reciprocal of the constant failure rate to the number of failures.

$$\text{MTBF} = \frac{\text{Total operating time}}{\text{number of failures}} = \frac{1}{\lambda} = \frac{T}{f} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(2)}$$

Further reliability parameters are MTTF (Mean Time To Failure), MTBM (Mean time between Maintenance for preventive maintenance), MTFF (Mean Time to First Failure) and train delaying failures.

iii. Mean time to failure (MTTF)

The probable time to failure for a non-repairable system is described as Mean time to failure. MTTF is an estimate of the average, or mean time until components first failure or disruption in the operation of the product, process, procedure, or design occurs. MTTF assumes that the product cannot resume any of its normal operations as it cannot be repaired.

MTTF for all the products which are identical in their design and operate under identical conditions is assumed to be same. If we have life-tests data on the population of N items with failure times t_1, t_2,……..t_n then the MTTF can be mathematically expressed as:

$$\mathrm{MTTF} = \frac{\text{Total time}}{\text{number of units under test}} = \frac{1}{n}\sum_{i=1}^{n} ti \quad \text{……………………. (3)}$$

iv. Reliability

The constant failure rate model for continuously operating systems leads to an exponential distribution. Probability density functions for a constant failure rate (PDF);

$$f(t) = \lambda e^{-\lambda t} \quad \text{……………………………………….…………. (4)}$$

Similarly, cumulative distribution function (CDF) becomes

$$F(t) = 1 - e^{-\lambda t} \quad \text{………………………………………………. (5)}$$

And reliability may be written as:

$$R(t) = e^{-\lambda t} \quad \text{…………………………….………………...….. (6)}$$

2.5.2 Maintainability Parameters

The basic Maintainability parameters in are Maintenance (Restoration) Rate (μ), Mean Time To Repair (MTTR), Mean Time Between Maintenance (MTBM), Mean Time Between Repair (MTBR), Mean Down time (MDT).

i. (Restoration) Rate (μ)

The restoration rate (μ) can be calculated as adapted from [10]:

$$\text{Restoration rate, } \mu\,(t) = \frac{1}{\mathrm{MTTR}}\text{ ; when constant……………….…...… (7)}$$

$$\text{Operational Restoration rate } (\mu_O)\text{; } \mu_O\,(t) = \frac{1}{\mathrm{MTTM}}\text{ ; when constant …. (8)}$$

ii. Mean Time To Repair (MTTR)

MTTR is the average of down time that includes time to troubleshoot and fault- isolate a failure, remove and replace or repair faulty items, and perform functional check-out to verify restoration to operational status. It is useful when calculating costs associated with loss of income due to outage of the system, and with maintenance operations [7].

The sum of corrective maintenance times divided by the total number of repairs within an item. That indicates the average time to fully repair a failed system – it includes detection of failure(s) removal and replacement of the failed components and final check.

MTTR can be calculated as adapted from [10]:

$$\text{MTTR} = \frac{\text{Total TTRs}}{\text{No.of failures}} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(9)}$$

iii. Mean time between maintenance (MTBM)

MTBM is the average time between all system maintenance actions. Maintenance actions may be for both preventive purpose and repair.

iv. Mean Time Between Repair (MTBR)

The average time between corrective maintenance actions, which require removal or replacement of subsystems.

2.5.3 Availability Parameters

Reliability and maintainability determine the availability of systems and equipment. Formulas for availability calculation of railway systems are given in the norm [10]. According to this norm, the following generally indicate the availability formula:

$$A = \frac{\text{MUT}}{\text{MUT+MDT}}\text{; with } 0 \le A \le 1 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(10)}$$

Where, MUT= Mean Up Time,

MDT= Mean Down Time.

Depending on the definitions of MUT and MDT, it is possible to have different types of availability using the same formula:

i. Inherent (Intrinsic) Availability, A_i

$$Ai = \frac{\text{MTBF}}{\text{MTBF+MTTR}}\text{;} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(11)}$$

Where, MUT = MTBF (Mean Time between Failures).

MDT=MTTR (Mean Time to Restore).

ii. Achieved (technical availability), A_a

$$Aa = \frac{\text{MTBM}}{\text{MTBM+MTTMa}}\text{;} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(11)}$$

Where, MUT=MTBM (Mean Time between Maintenance)

MDT=MTTMa (Mean Time to Maintain)

iii. Operational (logistic) Availability, A_o

$$Ao = \frac{\text{MTBM}}{\text{MTBM+MTTMo}} \; ; \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

Where, MUT=MTBM (Mean Time between Maintenance)

MDT=MTTMo (Mean Time to Maintain) for preventive and corrective Maintenance

Reliability and maintainability are both probability values which lead to failure rates and maintenance rates respectively, related to the defined time period. An important requirement of the railway system is the high availability. In particular, from the requirements of high reliability, two requirements result regarding reliability and maintainability are low failure rates and high maintenance rates [7].

2.6 RAM Analysis methods

RAM of a system can be analysed using qualitative and quantitative methods. There are various tools and methods are used for RAM analysis. Some of these are [12]:

i. FMEA / FMECA (Failure Mode and Effects (and Criticality) Analysis),

ii. FTA (Fault Tree Analysis),

iii. CCA (Cause - Consequence Analysis),

vi. RBD (Reliability block diagrams)

2.6.1 Qualitative Methods

i. Failure Modes, Effects, and Criticality Analysis (FMEA/FMECA):

This method is used to identify the potential failure modes of each of the functional blocks of a system and to study the effects these failures might have on the system. FMEA/FMECA is primarily a tool for designers but is frequently used as a basis for more detailed reliability analyses and for maintenance planning.

2.6.2 Quantitative Methods

ii. FTA (Fault Tree Analysis):

The fault tree illustrates all possible combinations of potential failures and events that may cause a specified system failure. Fault tree construction is a deductive approach where one start with the specified system failure and then consider what caused this failure. Failures and events are combined through logic gates in a binary approach. The fault tree may be evaluated quantitatively if one have access to probability estimates for the basic events.

iii. CCA (Cause and Effect Diagrams):

Cause and effect diagrams are frequently used within quality engineering to identify and illustrate possible causes of quality problems. The same approach may also be used in reliability engineering to find the potential causes for system failures. Cause and effect diagrams are qualitative and cannot be used as a basis for quantitative analyses.

iv. RBD (Reliability Block Diagrams):

A reliability block diagram is a success-oriented network illustrating how the functioning of the various functional blocks may secure that the system function is fulfilled. The structure of the reliability block diagram is described mathematically by structure functions.

2.7 Literature Review

Due to the complexity of railway signalling system many countries have developed several standards and recommendations to regulate the system development process (lifecycle) of signalling systems. Standards have been developed for the reliability, availability maintainability and safety (RAMS) of railway systems, with special focus on the signalling, communications and processing systems used by the railway [10], [13], [14]. These standards aim to enable interoperability of the line without affecting the safety of the system. The railway standard [10] is the specification and demonstration of reliability, availability maintainability and safety in the railway applications; it stresses their interaction and defines a process, based on the system lifecycle and tasks within it, for managing RAMS.

2.7.1 Literature Review about Railway Signaling System

Researches were done in railway signaling system by explaining the requirements for setting reliability targets and assessing reliability of the functions and the main safety-critical functions in relation with signaling systems. Fault tree analysis method was adopted for the research but the failure causes and the effects on the system were not clearly stated. In this research the reliability for each signaling subsystem and components was not calculated and evaluated from historical failure data [15].

The reliability, availability and maintainability (RAM) of a signaling system was done with failure and repair data by Markov modelling by classifying the system in to different subsystems like track circuit, signal unit and point and point machine. But in this research, the causes of failure, the mode and the effects of the failure subsystems are not clearly stated; and of course remedial measures (corrective actions) to improve the RAM of the system are not also investigated [16].

Failure Analysis was done for railway Switches and Crossings for preventive maintenance using failure mode and effect analysis (FMEA). In the research modes of failure, components most likely to fail and type of failure that more likely to occur in subsystems and components were analysed but their RAM were not investigated [17].

2.7.2 Literature Review about AA-LRT Signaling System

The failure analysis was done by employing model-based failure analysis methods and system fault tree, causes and effects, major failures were investigated. But in the research, remedial measures were not suggested so as to minimize the failure of subsystems and components, and of course the most critical subsystems and areas were not identified [18].

As it is stated, this research will try to address the objectives; from the failure cause to the remedial measure for failure and RAM analysis will be done for the most critical subsystems.

3. AA-LRT SIGNALING SYSTEM

3.1 General Description of AA-LRT

The LRT project at Addis Ababa, the capital of Ethiopia, consists of the East-west line and the South-north 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 is approximately 75km. The existing AA-LRT phase I of these two lines and the total length of line is approximately 31km; wherein, the length of shared track section is approximately 2.662km.

The East-West line phase I project starts from Ayat and ends at Torhailoch. The total length is 17.4km. 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.

The South-North line phase I project starts from Minilik II Square and ends at Kality. The total length is 16.97km. The length of roadbed section in the South-north 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 [2], [3].

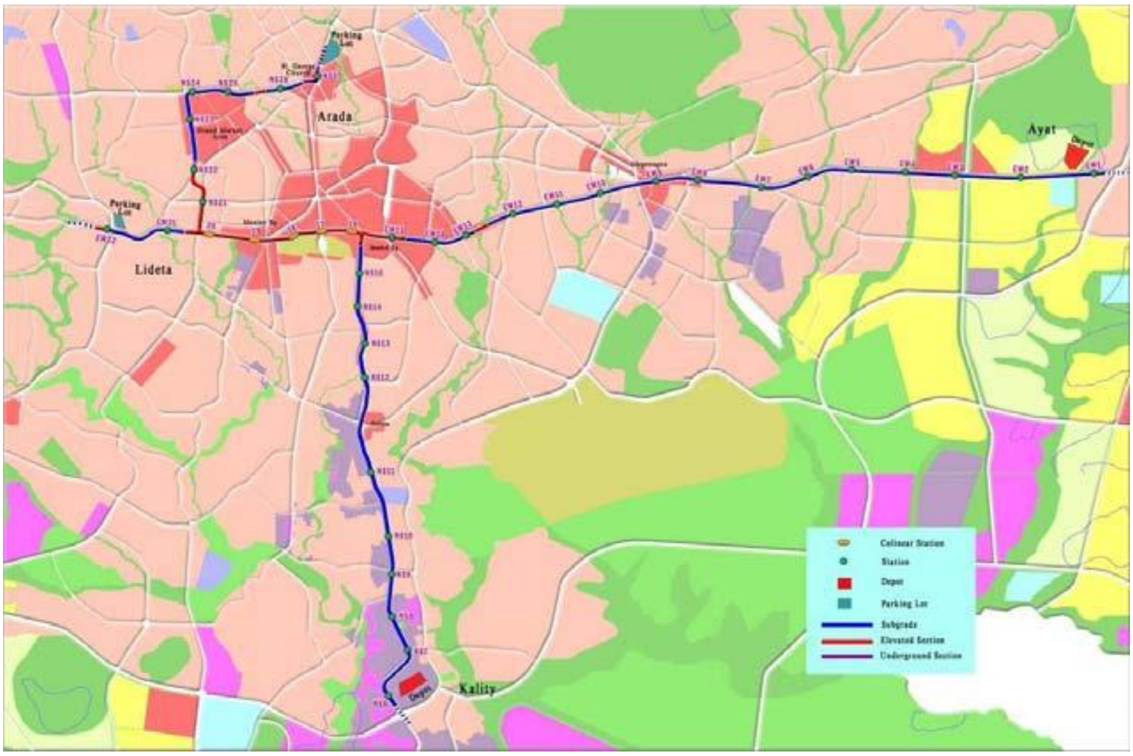


Figure 3.1 Diagram of Line Route of East-West Line/South-North Line Phase I Project [3].

The AA-LRT system can be divided into different subsystems depending on functionality, such as the rolling stock, the track, the power supply, the signalling and communication system, etc. Following the safe, economical and practical principles, and the characteristics of LRT in Addis Ababa, this design chooses a reasonable communication and signal system.

3.2 Signaling System Composition

The signaling system design of the existing AA-LRT project is based on iCMTC system provided by a Chinese organization CASCO [2]. It includes the following subsystems:

- ✓ iTC subsystem(IATP subsystem);
- ✓ iLock subsystem(CBI subsystem);
- ✓ iTC subsystem(ATS subsystem);
- ✓ DCS subsystem;
- ✓ MSS subsystem.

The system structure of signaling system is shown in the following figure:

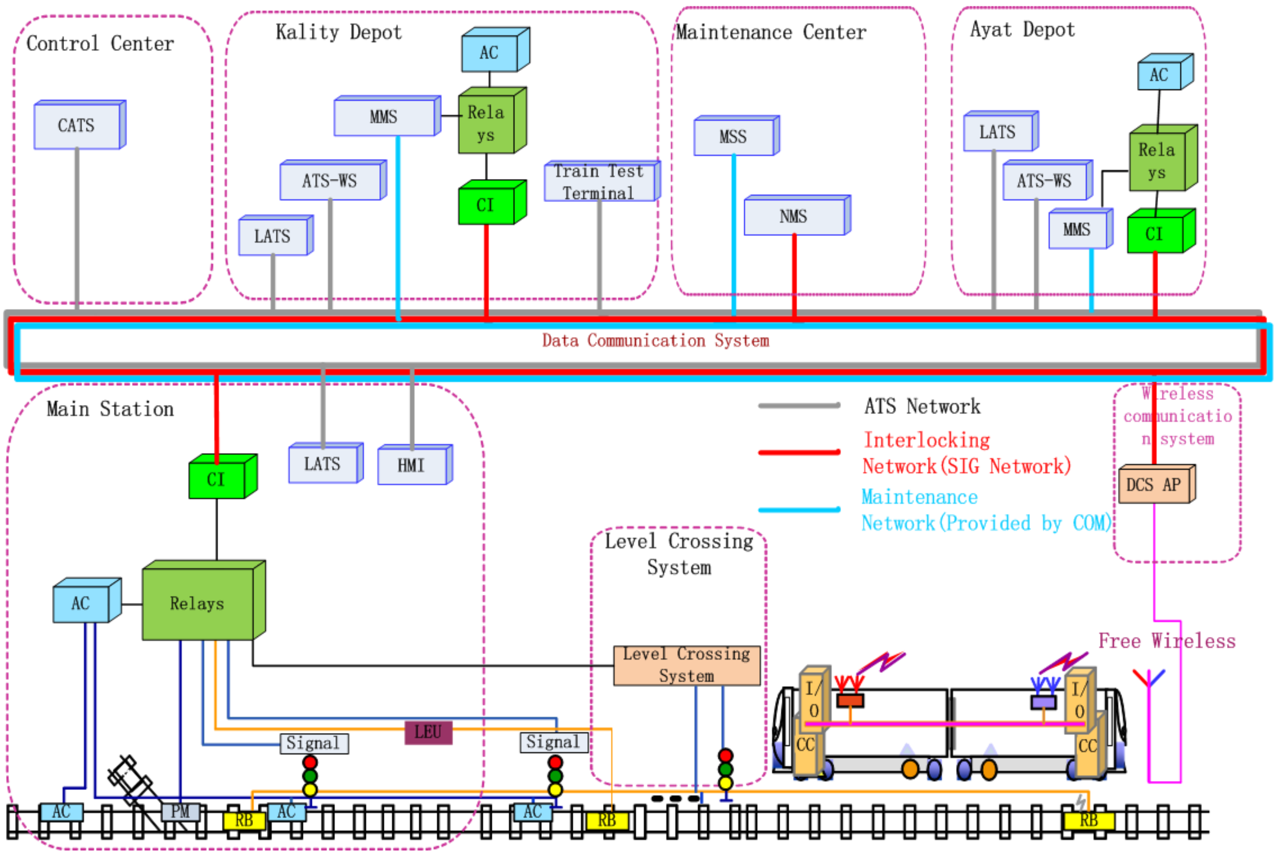


Figure 3.2 AA-LRT Signaling System Structure Sketch Map [19]

3.2.1 IATP Subsystem

The IATP subsystem consists of trackside equipment and onboard equipment. The iCC on-board equipment mounted in each train is able to realize the following ATP functions:

- ✓ Over speed protection;
- ✓ Restrictive signal overrun red light protection;
- ✓ Rollback protection;
- ✓ Spacing protection;
- ✓ Train door monitoring;
- ✓ Driving mode switch as well as the train control in different modes;
- ✓ Assisting drivers in operating trains via DMI.

The Onboard iCC system obtains trackside variable information via European beacon and train-ground wireless communication. It obtains train position information via relocalization beacon and realizes intermittent ATP protection controls.

Trackside equipment includes beacon, LEU and trackside radio equipment. Onboard equipments includes Carbone controller, odometer, beacon antenna, DMI, onboard switch and radio equipment.

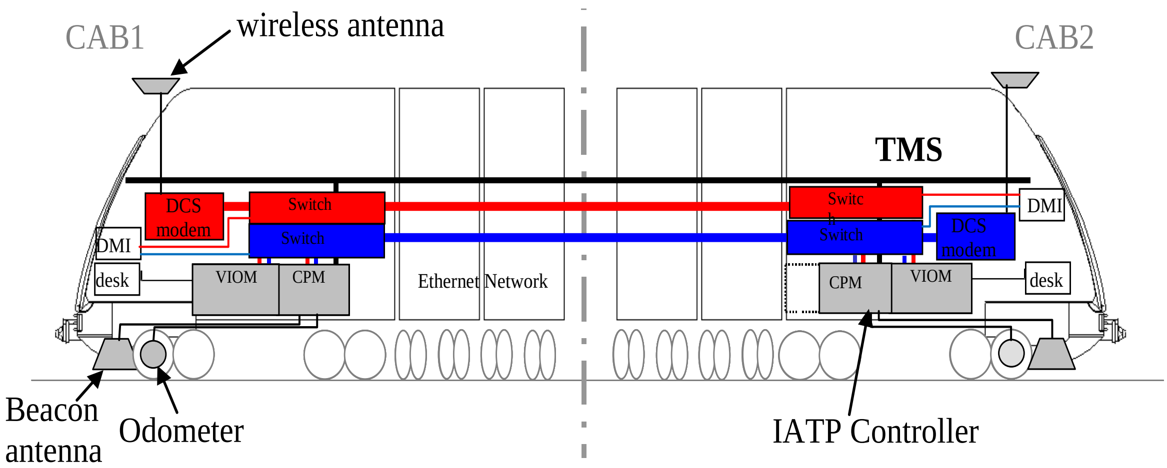


Figure 3.3 The Structure of iCC Onboard System [3]

3.2.1.1 Trackside IATP equipment

I. Beacon

For beacon, it is applied for several functionalities:

- ✓ RB-Relocation Beacon: The Relocation Beacon is used to ensure that the train, running over it and get beacon message. The stored message includes the beacon identification which must be unique for one beacon on the line, which can check and correct train position, the train localization can still be ensured.
- ✓ MTIB-Wheel diameter calibration beacon: it consists of two RB separated by the very precise distance of 21 m. When the train runs over them, the wheel is automatically calculated and calibrated.
- ✓ The switchable beacons: are used provide trackside variants such as signal and switch to CC when train run over it.

II. LEU

LEU acquires trackside equipment status such as signal and switch, and provides to active switchable beacon. Knowing the permissive or restrictive status of signal and position of switch, train can get movement authority when running over the switchable beacon.

3.2.1.2 Trackside radio equipment

Bi-direction trackside radio equipment is set in route signal which have IATP protection function. The area covered by trackside radio equipment is not less than train safety braking distance.

3.2.1.3 On-board equipment

I. Onboard controller CC

On-board equipment of each end includes: one CC, one On-board equipment, two on-board switch, One set driver console, one odometer and one beacon antenna.

The communication between train head/tail and trackside is redundancy structure, which is blue/red redundant network. The CPM and VIOM are also redundant equipment, as figure below:

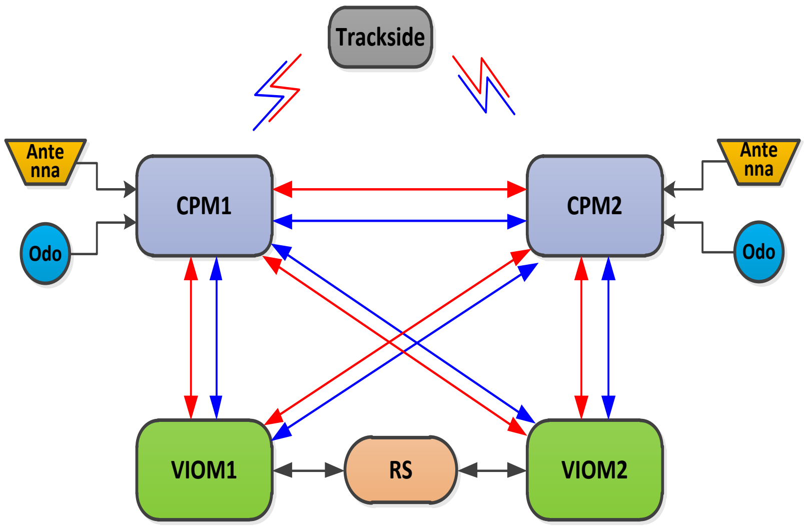


Figure 3.4 : Onboard Controller Structure [2].

3.2.2 CBI Subsystem

The basic interlocking function of CBI ensures the operational safety of train. It is interfaced to the trackside signaling equipment via safe relay to realize the correct interlocking relationship among track sections, points and signals in train routes as well as the route control. At the same time, it is responsible to be interfaced to LEU. In the intermittent ATP mode, trains obtain the relevant information of trackside signals and points via the active beacon corresponding to signal.

3.2.3 ATS Subsystem

The automatic supervise system (ATS) is the core of supervise system. It acquires and processes the information from trackside and equipment centralization stations in real time and provides a human-machine interface. The graphical model illustrations are adopted. It also provides a set of alarm management system for online analysis and post-mortem investigation and establishes history records of relevant events.

One set of central ATS equipment is configured in the operation control center to complete monitoring functions for the signaling system of East-west Line/South-north Line. Each equipment centralization station is equipped with 1 set of station ATS which is connected to the central ATS equipment via redundant ATS network. If any failure occurs to the central ATS, local operation functions can be executed via the local operator workstation or the station level automatic route control can be realized via the station ATS.

3.2.4 DCS subsystem

The DCS wired network is the transmission platform of the whole signaling system. The ATS network is used for connecting the ATS equipments located in operation control center, stations, depot and etc. The CBI network is used for connecting the CBI equipments of stations and depot.

The DCS wireless network provides a reliable, continuous and stable bi-directional communication channel for trackside CBI and Onboard CC systems and realizes intermittent-continuous type IATP functions.

3.2.5 MSS subsystem

The IATP, CBI, ATS, DCS, level crossing signaling equipment and power supply equipment have self-diagnosis and monitoring alarm functions. The maintenance support subsystem acquires the alarm information of CBI, ATS, DCS and power supply equipment and realizes remote centralized monitoring and alarms.

3.3 The Axle Counter System

Axle counters are used for track section monitoring and rail vehicle detection purposes as an alternative to track circuits. ACS2000 axle counter is divided into the indoor and outdoor equipment, a wheel sensor is arranged respectively at the starting point and ending point of the track section, and used together with the evaluation board for detecting of information of wheel set of the train. Each wheel sensor includes 2 groups of systems, which are used for distinguishing the driving direction of the train. Each wheel sensor is connected with the evaluation board by four-core signal cable, which supplies the power for the wheel sensor and transfers the data of axle to the evaluation board.

The axle counting board ACB of the axle counting system processes the data of axle of all connected counting probes, and outputs the results of vacancy and occupation of the detected section into the relevant system (e.g. interlocking system) in manner of interface conditions of relay (output of vacant section is DC$\geq$ 21.6V; output of occupied section is DC$\leq$ 2V) [2], [3].

The block diagram of the system composition is shown as follows:

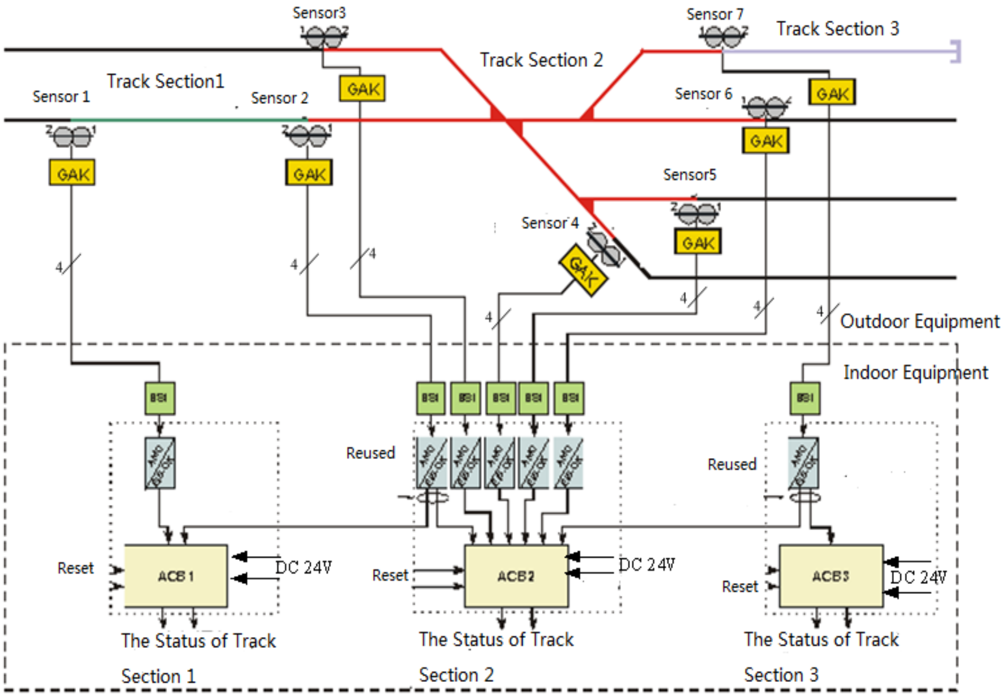


Figure 3.6 Block diagram of Axle Counting System [2], [3].

Outdoor equipments include Wheel sensor RSR180, jig and protecting tube of wheel sensor and cable coupling box of wheel sensor. Indoor components include over-voltage protection board BSI, axle counting floor board ABP, evaluation board IMC, axle counting board ACB and fuse board SIC.

4. RAM ANALYSIS

4.1 Introduction

This research focuses on failure and maintenance of AA-LRT signaling system. Thus, the primary objective is to assess failures from the root cause to the remedial measures and finally evaluate the RAM. In this research study, Failure Mode and Effect Analysis (FMEA) is used to assess failures from the root cause to the remedial measures and finally TBF and TTR data analysis for Best-fit probability distributions to evaluate the RAM.

4.2 Failure Mode and Effect Analysis (FMEA)

Failure mode and effect analysis (FMEA) is a logical process aimed at identifying the potential failure modes of the elements of a system; the respective causes of failures; and the failure effects, initially on that element and then on its particular part of the larger system. A failure effect at a lower level may then be a failure cause for an item in the next higher level, hence the end effect on the system as a whole may be identified [20], [21], [22].

Failure mode is the way in which a failure is observed (which is simply a description of a fault). Failure causes are defects in design, process, quality, or part application, which are the underlying causes of failure or which initiate a process which leads to a failure. A failure mode deals with the present, whereas a failure cause happened in the past and a failure effect deals with the future.

The FMEA identifies the relationship between the element failures and the system failures, malfunctions, operational constraints, and degradation performance, starting with basic element failure characteristics and functional structure of the system.

4.2.1 Why FMEA

FMEA is a deliberate and thoughtful method for focusing on expected quality (i.e. Functions as intended and meets all of the customer’s implicit expectations) that:

- Identifies possible faults (failure modes) in a system (including their causes).
- Evaluates the effects of the fault on the operational status of the system.
- Determines the risk priority of the failure (based on severity, probability of occurrence, and probability of detecting and avoiding the failure.
- Recommends corrective actions for high risk items.
- Implements corrective actions until risk is reduced.

4.2.2 FMEA Procedures

1. Identify Components and Associated Functions

The first step of an FMEA is to identify all of the components to be evaluated. This may include all of the parts that constitute the product (system) and the function(s) of each part within in the product (system).

2. Identify Failure Modes (What could go wrong?)

The failure mode(s) for each part are identified. Failure modes can include but are not limited to complete failures, intermittent failures, partial failures, failures over time, incorrect operation, premature operation, failure to cease and function at allotted time.

3. Identify Effects of the Failure (What would be the consequences of each failure?)

For each failure mode identified, the consequences or effects on product, property and people are listed. These effects are best described as seen through the eyes of the customer.

4. Determine Severity of the Failure (how likely harm will occur?)

The severity or criticality rating indicates how significant of an impact the effect is on the customer. It is used to provide a qualitative indicator of the worst potential effect resulting from the failure mode. Severity can range from insignificant to risk of fatality. Severity is evaluated on a ten-grade scale as shown in Table 4.1. Note that in contrast to the MIL-STD- 1629A FMEA, a higher rating here corresponds to a higher severity (and, consequently, a higher RPN) [20],[21].

5. Identify Cause(s) of the Failure (Why would the failure happen?).

For each mode of failure, causes are identified. These causes can be design deficiencies that result in performance failures, or induce manufacturing errors.

6. Determine Occurrence of Failure (how likely is this failure mode will occur?).

This step involves determining or estimating the probability that a given cause or failure mode will occur. The probability of occurrence can be determined from field data or history of previous products. If this information is not available, a subjective rating is made based on the experience and knowledge of the cross-functional experts. Two of the methods used for rating the probability of occurrence are a numeric ranking and a relative probability of failure. Occurrence is evaluated on a ten-grade scale as shown in Table 4.2 [20].

7. Identify Controls (What controls are currently in place to catch or prevent this failure**)**

Identify the controls that are currently in place that either prevent or detect the cause of the failure mode. Controls that detect the cause allow for corrective action while controls that detect failure allow for interception of the product before it reaches subsequent operations or the customer.

8. Determine Fault Detection (how likely is the failure will be detected?)

Detection is defined as the ability to detect a potential cause/mechanism to system failure. Detection ranking estimates how well the cause or failure mode can be detected and /or prevented (avoided) before it occurs. Detection is evaluated on a ten-grade scale as shown in Table 4.3 [20], [21].

Effect	Rating	Criteria
Hazardous	10	Safety related failure modes causing non-compliance with government regulations without warning
Serious	9	Safety related failure modes causing non-compliance with government regulations with warning
Very high	8	Failure modes resulting in loss of primary system/component Function
High	7	Failure modes resulting in a reduced level of system/component performance and customer dissatisfaction
Moderate	6	Failure modes resulting in a loss of function by comfort/convenience system/component
Low	5	Failure modes resulting in a reduced level of performance of comfort/convenience system/component
Very low	4	Failure modes resulting in a loss of fit and finish, squeak and rattle functions
Minor	3	Failure modes resulting in partial loss of fit and finish, squeak and rattle functions
Very minor	2	Failure modes resulting in minor loss of fit and finish, squeak and rattle functions
None	1	No effect

Table 4.1 Severity Scale of Failure Modes [20], [21].

Likelihood of Failure	Estimated or expected failure frequency	Rating
Very high (failure is almost inevitable)	>1 in 2	10
	1 in 3	9
	1 in 8	8
High (frequently repeated failures)	1 in 20	7
	1 in 80	6
Moderate (occasional failures)	1 in 400	5
	1 in 2000	4
Low (rare failures)	1 in 15,000	3
	1 in 150,000	2
Remote (failures are unlikely)	<1 in 150,000	1

Table 4.2 Occurrence ranging/rating of failure modes [20], [21].

Detection	Rating	Criteria
Uncertain	10	Design control will not and/or cannot detect a potential cause/mechanism and subsequent failure mode.
Very remote	9	Very remote chance the design control will detect a potential cause/mechanism and subsequent failure mode.
Remote .	8	Remote chance the design control will detect a potential cause/mechanism and subsequent failure mode.
Very low	7	Very low chance the design control will detect a potential cause/mechanism and subsequent failure mode.
Low	6	Low chance the design control will detect a potential cause/mechanism and subsequent failure mode.
Moderate	5	Moderate chance the design control will detect a potential cause/mechanism and subsequent failure mode
Moderately High	4	Moderately high chance the design control will detect a potential cause/mechanism and subsequent failure mode.
High	3	High chance the design control will detect a potential cause/mechanism and subsequent failure mode.
Very high	2	Very high chance the design control will detect a potential cause/mechanism and subsequent failure mode.

Almost certain	1	The design control will almost certainly detect a potential cause/mechanism and subsequent failure mode

Table 4.3 Detection rating of failure modes [20], [21].

9. Calculate Risk Priority Number (RPN)

The RPN or a criticality rating may be determined for each failure mode and its resulting effect to help prioritise failure modes for action. The rating is normally based on the probability of the failure occurrence, the severity of the effect, and its detectability.

RPN for the Failure Mode = Severity * Frequency of Occurrence * Detection Ranking.

$$\mathrm{RPN} = \mathrm{S} \times \mathrm{O} \times \mathrm{D} \ldots\ldots\ldots\ldots \quad (13)$$

Its purpose is to assess current risk (and to compare the effects of proposed changes by calculating hypothetical RPNs of different scenarios, to help decide what corrective action to take).

In general, the failure modes that have the greatest RPN receive priority for corrective action. The RPN should not firmly dictate priority as some failure modes may warrant immediate action although their RPN may not rank among the highest.

10. Recommended Actions (Determine actions to reduce risk of failure mode)

Taking action to reduce risk of failure is the most crucial aspect of an FMEA. The FMEA should be reviewed to determine where corrective action should be taken, as well as what action should be taken and when. Some failure modes will be identified for immediate action while others will be scheduled with targeted completion dates.

Conversely, some failure modes may not receive any attention or be scheduled to be re assessed at a later date. Actions to resolve failures may take the form of design improvements, changes in component selection, the inclusion of redundancy in the design, or incorporation design for safety aspects.

4.2.3 FMEA Results

4.2.3.1 FMEA for AA-LRT Signaling Systems

This study tries to get a better categorization of the most critical failure modes in AA-LRT signaling system. The RPN reveals the overall risk of a particular failure mode occurring in a system. Actually, RPN is a threshold value in the evaluation of failure. After ranking the occurrence, severity and detectability the RPN is calculated as RPN = S × O × D. The result is a categorized breakdown of failure modes based on risk.

Table 4.4 shows the potential failure modes, causes and effects of the AA-LRT signaling system with RPN and recommended actions.

Potential Failure Modes	Severity	Potential Failure Effects	Potential Failure causes	Occurrence	Detection	RPN	Recommended Actions
Subsystem and/or Equipment Failures	7	Operator and Customer dissatisfaction Train delay and cancellation	Electrical causes (power failures, short circuits, open circuits…)	5	4	140	Repair or replacement of the failed component Inspection of the system
		Maintenance cost (both personnel and material)	Mechanical causes (wear, fatigue)	5	4	140	Cleaning or removal of obstacles (dust accumulation);
Design related Failures	5	Operational effect	Improper Design and Installation	4	4	80	Adjustment of modules/connections;
		Safety impact	Incorrect operation and maintenance	5	3	75	Scheduled maintenance
Software related Failures	5		Software errors, human errors, viruses	3	4	60	Restart/Reset when the failure is attributed to SW causes

Sensor and communication failures	6		Power supply failures	5	4	120	Check the power supply panel or lines
		Service Availability	Interfacing problem	3	3	54	Check the installation status of sensor and measure the current.
			Cable (Wiring) problem	5	4	120	Measuring line insulation, wire-ground insulation lines and circuit loop resistance
Power supply failures	8		Power board failure	5	2	80	Repair and Replace the board
			Standby power failure	5	3	120	Repair and Replacement of failed part

Table 4.4 FMEA for AA-LRT Signaling System

The failure modes that have the highest RPN should be given the highest priority for preventive maintenance. This means it is not always the failure modes with the highest severity numbers that should be treated first. There could be less severe failures, but which occur more often and are less detectable. From the Table 4.4, Subsystem and equipment failure modes which are caused by electrical and mechanical problems has a high priority to cause risk and should be treated first.

4.2.3.2 RPN of Subsystem and Equipment Failures

RPN calculation of subsystem and equipment failure modes are used to find the most critical subsystem of the current failure of AA-LRT signaling system. Table 4.5, shows the Switch has the highest RPN to cause risk which is the most critical subsystem and should be treated first. When a switch failure happens, its maintenance time should be as much as possible short and more inspection is needed to reduce the risk.

Subsystems failure modes	Severity(S)	Occurrence(O)	Detection (D)	RPN=S*O*D
ATP	7	5	2	70
Axle counter	7	6	2	84
Signaling Filament	5	6	2	60
Switch	9	5	3	135

Table 4.5 RPN of Current Failure Modes of AA-LRT Signaling System

4.2.3.3 Potential Failure Modes of Failed Subsystems

From the current and historical collected failure data, this research find out the potential equipment failures modes of the failed subsystems.

Subsystems	Potential Failure Modes	Current Controls
ATP system	IATP computer failure	Repair and replacement of failed part of ATP.
	DMI failure	
	Beacon failure	
	Odometer failure	
	IATP mode beacon failure	
	LEU failure	
AC system	Software failure	KEY Reset
	Power failures	Check the power supply panel or lines
	Signal source failure(IMC board, BSI Modules, Sensor failure)	Check cable and the sensor splice box.
	Indoor host failure (indoor ACB board failure and other failure)	Replace internet access, replace ACB board, replace ABP board
Switch machine	Turnout failure	Adjust and repair the failed part of the switch.
	Motor failure	
Signaling Filament	Signal filament is broken which is caused by over current	Long term observation and current adjusting, repair and replace.

Table 4.6 Failure Modes for Failed Subsystems and Equipments

4.3 TBF and TTR Data Analysis

For the RAM analysis, TBF and TTR data are collected. The data is quantitative and based on historical raw data collected over a period of 6 months. The data collected is from daily downtime reports and maintenance records, such as work orders created by maintenance personnel. The analysis deals with a repairable system, and the data collected is failure and repair times of the subsystems compiling the entire system.

4.3.1 TBF and TTR

For a repairable system the analysis is concerned with modelling both the time it takes from a performed repair action to the next system failure (life of the system) and the time it takes to restore the system (repair of the system) back to operating state.

The railway operation can be considered to be in one of three possible states depending on whether operation is possible and whether the signalling system is operative:

- ✓ **Operative state:** operation is possible and the signalling 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.
- ✓ **Degraded state:** railway operation is possible in a degraded mode, but the signalling system is not operative due to a failure in one of the signalling subsystems.

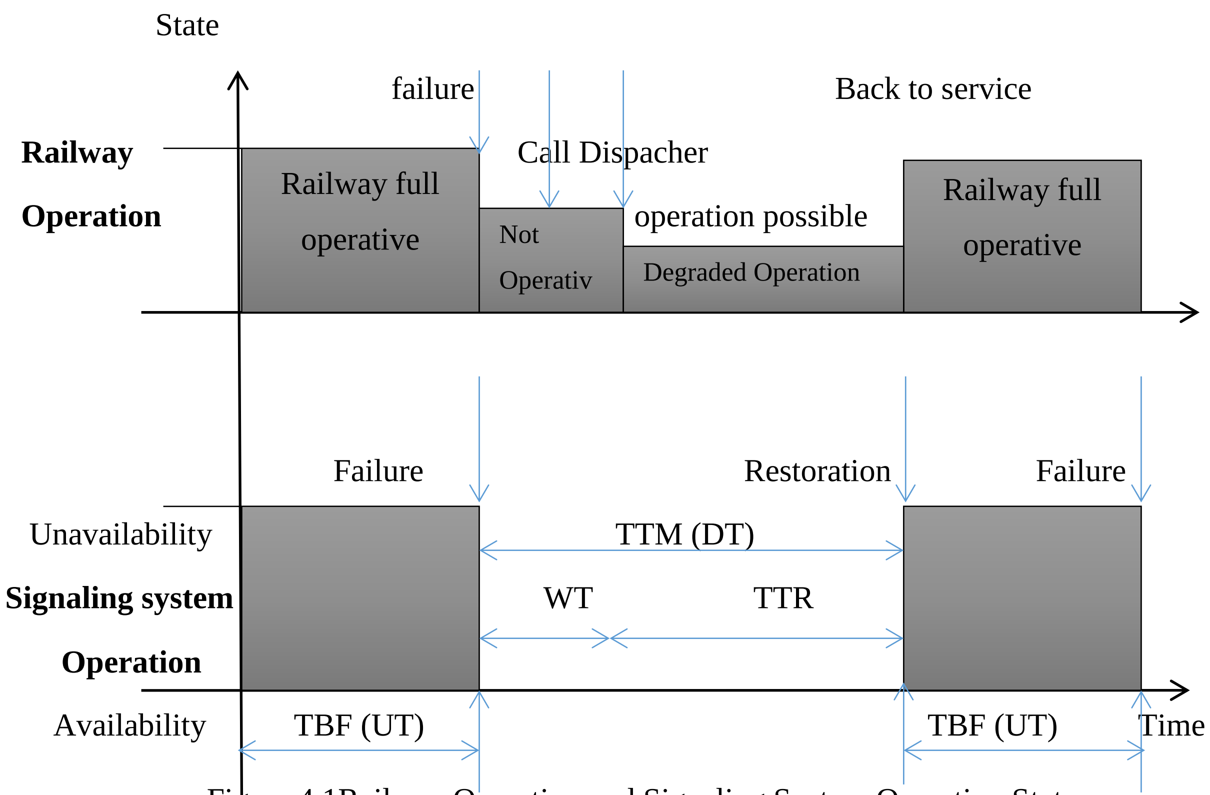


Figure 4.1Railway Operation and Signaling System Operation States

For the signalling system, three possible states can be considered:

- ✓ Up time (UT): the system is fully operative.
- ✓ Waiting time (WT): the time between when a failure occurs until the corrective action is started.
- ✓ Restoration time (RT): corrective actions (repair or replacement) are performed.

For repairable systems, it is common to assess and analysis the time between failures and to restore. Time between Failure (TBF) is the time it takes from a performed repair action to the next system failure and time To Restore (TTR) is the time it takes to restore the system (repair of the system) back to operating state. To analyse the time data, first calculate Time To Maintain (TTM) which the total downtime (DT) when the system is not available for operation given by Equation (18) and the time to restore (TTR) given by Equation (19).

$$\mathrm{TTM} = \mathrm{DT} = \mathrm{t(finish\ of\ corrective\ action)} - \mathrm{t(failure\ identification)} \ldots. (18)$$

Then, TBF and TTR given by Equation (19) and (20):

$$\mathrm{TBF} = \mathrm{UT} = \mathrm{t\,(operation)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. (19)$$

$$\mathrm{TTR} = \mathrm{t(finish\ of\ corrective\ action)} - \mathrm{t(start\ of\ corrective\ action)} \ldots\ldots. (20)$$

In this research study, Time between failure (TBF) and Time to Repair (TTR) data of signaling subsystems are arranged in chronological order for using statistical analysis to determine the trend of failure. Thus, the collected failure data for AA-LRT signaling system (TBF and TTR data) is given in the APPENDIX II.

In this study, for the evaluation of RAM characteristics of the signaling system of AA-LRT, a database of times of failures and maintenance activities of was prepared over an operation period of 6 months. TBFs and TTRs for all of the failed subsystems were separately calculated. In addition to TBF and TTR data's, the value of Cumulative Number of Failure (CNOF), Cumulative TBF (CTBF) and Cumulative TTR (CTTR) are calculated and presented in APPENDIX II.

4.3.2 Trend and Serial Correlation Test

The trend test is used for investigating the trend of the failure data graphically (as shown in APPENDIX III). Before fitting the data, it is important to check whether the data has a trend, i.e., if the rate of failures for the system/component is increasing, decreasing or constant. The serial correlation tests is used to check the relationship between two variables.

The scatter plots between the two variables (TBF_i and TBF_{i-1}) exhibits the correlation between the two variables (as shown in APPENDIX III).

Thus, from the plot (in APPENDIX III) between the cumulative TBF/ TTR and number of failure for all failed Signaling subsystems (such as ATP, Axle counter, Signaling filament and Switch) shows that the line is linear. This indicates that there is no trend in the data. Similarly, the scatter plot between the two variables (TBFi and TBFi-1, and TTRi and TTRi-1) shows that the data are widely scattered, and thus there is no correlation exists between the data of two consecutive failures. This shows a validating the assumptions of IID of TBF and TTR.

4.3.3 Goodness-of-Fit Test

The goodness-of-fit tests are used to see how well the chosen distribution represent the observed distribution. When choosing a probability distribution its goodness-of-fit should be identified by appropriate test. There exist several goodness-of-fit tests suited for different conditions. Some of the most used are the p-value test, the Chi-squared test, Kolmogorov-Smirnov test and Anderson-Darling test [24]. One goodness-of-fit test often used in RAM analysis is the Kolmogorov-Smirnov (K-S) test where the parameters are calculated based on the data set itself. After fitting distributions to the data sets the parameters of the specific distributions needs to be estimated.

For data analysis and finding the best-fit distributions on available data, Easyfit software was applied. The Kolmogorov- Smirnov (K-S) test was used for the evaluation of goodness-of-fit and selecting the best distributions. The lowest value of K-S test is the best-fitted model.

4.3.3.1 Probability Distributions

TBF and TTR data analysis is used to model the failure and repair processes of the different subsystems. This is done by fitting a probability distribution that best represent the failure data, and fitting a distribution that best represent the repair data, and estimating parameters to fit the distributions to the different data sets.

The most commonly used probability distributions that may be used to model the lifetime of a system and RAM analysis are the following: [see in APPENDIX I]

- ✓ The exponential distribution
- ✓ The gamma distribution
- ✓ The Weibull distribution
- ✓ The normal distribution
- ✓ The lognormal distribution

4.3.3.2 Goodness of Fit for Reliability

The Goodness-of-fit results for determining the best-fit theoretical probability distribution for the time between failures (TBFs) data with common distributions are given in Table 4.7.

Subsystems and Equipments	Goodness of fit (Kolmogorov- Smirnov (K-S) test)						Best fit	Parameters
	Exponential	Lognormal	Lognormal (3P)	Weibull	Weibull (3P)	Gamma		
Switch	0.22042	0.15709	0.10796	0.14579	0.11626	0.13805	Lognormal (3P)	σ=0.05888 μ=3.8896 γ=-43.464
ATP	0.222	0.16612	0.15344	0.14522	0.15965	0.1728	Weibull	α=1.6826 β=17.437
Signaling Filament	0.16754	0.13636	0.08948	0.13059	0.09808	0.12362	Lognormal (3P)	σ=0.06951 μ=4.8703 γ=-114.81
Axle counter	0.15884	0.14471	0.07776	0.1285	0.07879	0.11235	Lognormal (3P)	σ=0.06899 μ=7.0715 γ=-1039.6

Table 4.7 Goodness-of-Fit Results for Determining the Best-Fit PD for TBFs.

The plot of the best-fitted probability density function and the corresponding survival function for the TBF data of signaling subsystems are shown in APPENDIX IV respectively.

4.3.3.3 Goodness of Fit for Maintainability

For maintainability analysis, the results of Goodness-of-fit for selecting the best-fitted repair probability distribution with common distributions are shown in Table 4.8.

Subsystems and Equipments	Goodness of fit (Kolmogorov- Smirnov (K-S) test)						Best fit	Parameters
	Exponential	Lognormal	Lognormal (3P)	Weibull	Weibull (3P)	Gamma		
Switch	0.2204	0.15709	0.10796	0.14579	0.11626	0.13805	Lognormal (3P)	σ=0.05888 μ=3.8896 γ=-43.464
ATP	0.222	0.16612	0.15344	0.14522	0.15965	0.1728	Weibull	α=1.6826 β=17.437
Signaling Filament	0.1675	0.13636	0.08948	0.13059	0.09808	0.12362	Lognormal (3P)	σ=0.06951 μ=4.8703 γ=-114.81
Axle counter	0.1588	0.14471	0.07776	0.1285	0.07879	0.11235	Lognormal (3P)	σ=0.06899 μ=7.0715 γ=-1039.6

Table 4.8 Goodness-of-Fit Results for Determining the Best-Fit PD for TTRs.

The plot of the best-fitted probability density function and the corresponding survival function for the TTR data of signaling subsystems are shown in APPENDIX V respectively.

5. RESULT AND DISCUSSION

5.1 Failure Analysis Results

The study considers the whole system (East-West line and North-South line) of AA-LRT, having a total length of approximately 34 kilometres. The failure data of the components of signalling systems were collected from a period of six months (i.e. from November 2016 to April 2017). In this chapter, the most relevant results obtained are summarised.

The data analysis shows that 40% the failure frequencies of the failure and maintenance records are related to signalling systems (as shown Figure 5.1). For the failure effects of AA-LRT, such as; train delays and cancellation, travel time variation, number of passengers-per trip-costs (passenger flow rate) and safety of transportation system, signaling system failure has great contribution.

This results show that signalling systems play an important role in corrective maintenance, and improving their maintenance would bring about a general improvement in maintenance.

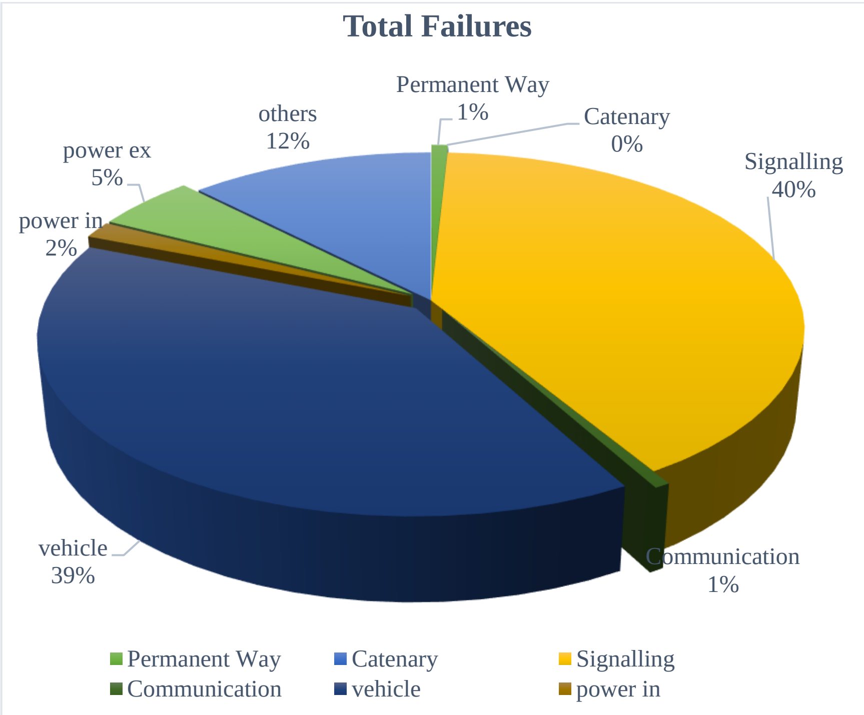


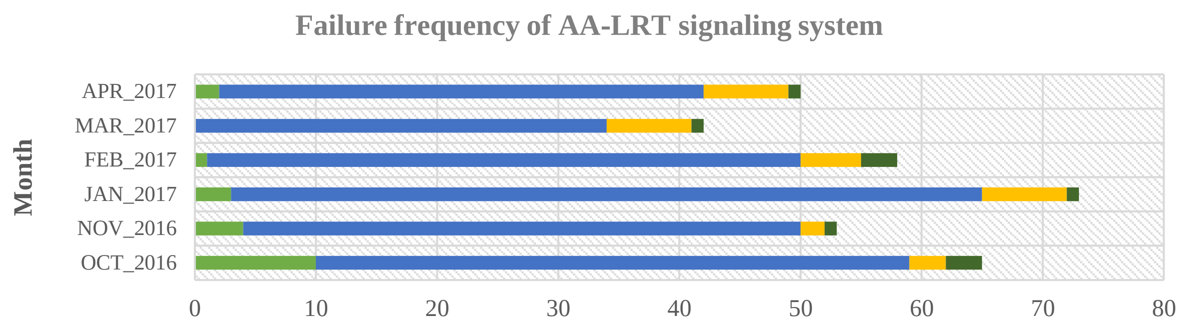
Figure 5.1 Percentage Failure of AA-LRT

The aim of this analysis is to find out the most critical components of signalling systems, which are to be controlled to minimise the number of failures per month. This study also necessitates pointing out corrective and preventive measures to reduce the failure effects of the signalling systems.

5.1.1 Failure Frequency

From the failure data and maintenance reports, the frequency of the failure with Monthly failures are shown in the Figure 5.2. To get a clearer view of the frequency of failures of the subsystems and components, a bar chart with table is produced.

Figure 5.2 clearly illustrates that the Axle counter is the most frequent failure component and the switch (point machine) has the lowest frequency of failure. But it doesn’t mean that the switch is not critical failure; i.e. the failure of a switch is one of the most critical subsystem which has effect on safety, train delay and cancelation rate.



	OCT_2016	NOV_2016	JAN_2017	FEB_2017	MAR_2017	APR_2017
ATP	10	4	3	1	0	2
Axle Counter	49	46	62	49	34	40
Signaling Filament	3	2	7	5	7	7
Switch	3	1	1	3	1	1

Number of failures

ATP Axle Counter Signaling Filament Switch

Figure 5.2 Monthly Number of Failure Data with Bar Chart

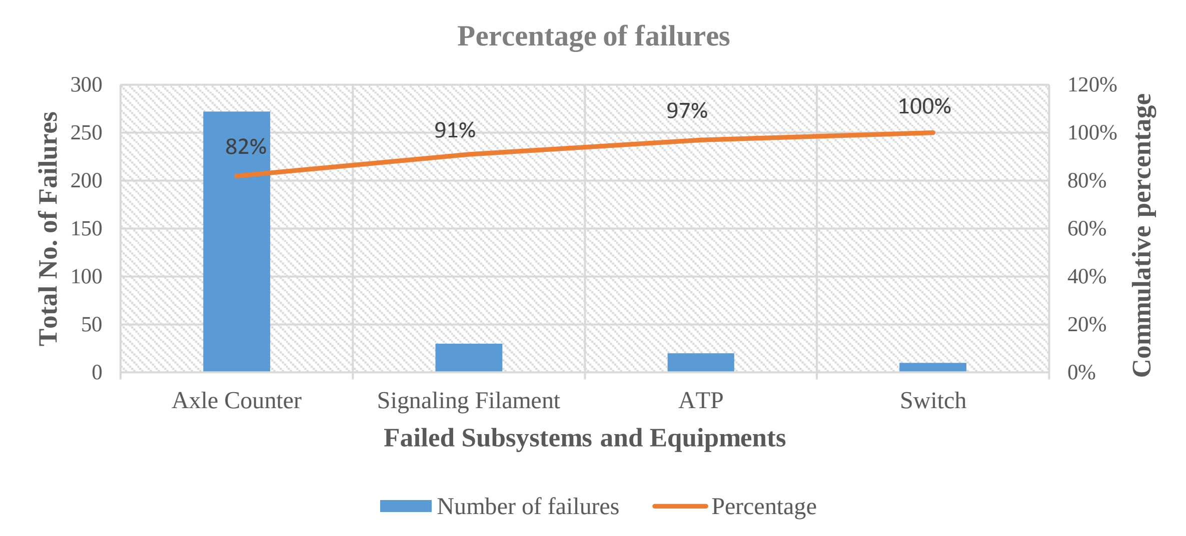


Figure 5.3 Pareto Chart for Failure Frequency of AA-LRT Signaling System

From Figure 5.2 and Figure 5.3, Since the date of October 1, 2016 to November 30, 2016 and January 1, 2017 to the date of April 30, 2017, the main faults of the signaling system shows: axle counter fault (82% of total faults), signaling filament (9% of total faults), ATP (6% of total faults) and switch faults (3% of total faults).

The Pareto analysis showed in the figure 5.3 that the Axle counter system has more frequency of failure and repair as compared to the other subsystems and Equipments. The reason why axle counter faults happen so frequent is mainly because there is no trail run and empty running is adopted during commissioning, whereas the train body weight increases sharply after operation, which caused the change of physical distance between axle counter and train body. Since axle counter needs high accuracy, so that it should be steady and the fault times should have been reduced sharply by cooperating with supplier to adjust and test for the whole line axle counters again and again.

5.1.2 Downtime Frequency

Another way of illustrating the effect of the failures is by using a bar chart of the downtime frequency of the subsystems. In Figure 5.6 the downtime frequency is reported, showing that the Axle counter subsystem is the subsystem causing the most downtime on the AA-LRT signaling system. The failure frequency and the downtime frequency can be combined in order to investigate the average downtime per failure for each subsystem.

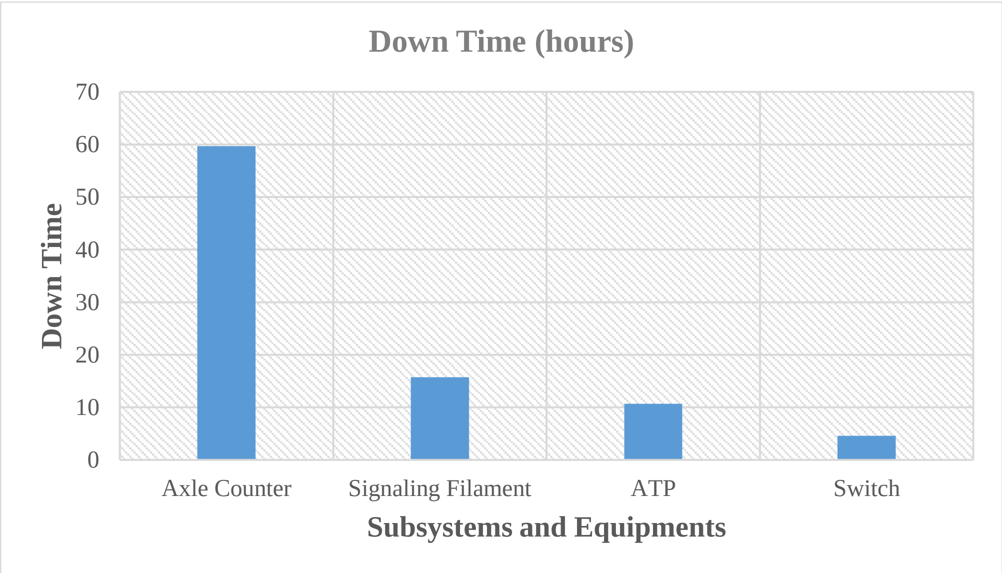


Figure 5.4: Downtime Frequency of the Subsystems

By combining the two graphs (Figure 5.3 and 5.4) it can be found that Axle counter subsystem has the highest number of failures of all subsystems. From that observation, it is evident that the reliability performance of this subsystem should be improved, rather than its maintainability performance.

5.2 RAM Analysis Results

Availability of each subsystem were determined from Equation 11.

$$A = \frac{MTBF}{MTBF + MTTR}$$

Where the values of MTBF and MTTR are determined by the following formulas:

$$MTBF = \frac{CTBF}{CNOF}\text{; and } MTTR = \frac{CTTR}{CNOF}\text{;} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 21$$

Where, CTBF: cumulative time between failures

CTTR: cumulative time to repair

CNOF: total number (frequency) of failure

The CTBF and CTTR are calculated from 6 month operation assuming that signaling system operates 24 hours per day. The respective values of MTBF and MTTR for each subsystem and Equipments along with the frequency of failure are produced in Table 5.1. It is clear from the results that all the subsystems are available for more than 96 % of the time.

Subsystems and Equipments	Failure Frequency (CNOF)	CTBF	CTTR	MTBF	MTTR	Availability (A)
ATP	28	4329.02	14.98	154.61	0.535	0.996
Axle Counter (AC)	280	4200.05	143.950	15.0002	0.514	0.967
Signaling Filament	31	4328.05	15.95	139.615	0.515	0.996
Switch	10	4333.35	10.650	433.335	1.065	0.997

Table 5.1 Availability Analysis of Signaling Systems

Failure frequency results indicated that the Axle counter subsystem needs more inspection for maintenance than the other subsystems of AA-LRT since it is the most frequently failed subsystem. Similarly, from availability results of the failed signaling subsystems, the Axle counter subsystem has less MTBF and availability but the Switch has high MTBF and availability with a relatively high MTTR than other subsystems. Since the switch machine is most critical subsystem so as to ensure safe operation of transportation system, it needs more repair and its repair time should be short.

5.3 Suggestions for RAM Improvement

RAM improvement of AA-LRT signaling system can be achieved by means of the use of both qualitative and quantitative methods.

The possible causes that may lead to signaling system unreliability and railway system unavailability that has been gathered from the unstructured interviews, literature studies and from the railway station depot visits are mainly:

- ✓ Manufacturing defects and internal defects,
- ✓ Design defects (Poor design of components and systems),
- ✓ Operating conditions and maintenance,
- ✓ Environment factors and others.

This study recommends two concepts for the improvement of the RAM of AA-LRT signaling system through design modification and maintenance management optimisation.

5.3.1 Design Modification

The reliability, maintainability and availability of AA-LRT signaling system can be improved by means of design, such as the following:

- ✓ The designing of signaling system with high reliability characteristics, involving the choosing of components with good RAMS features, as well as a high MTBF, and a low MTTR.
- ✓ Improved designs for signaling system components, such as wayside and onboard equipments, switch machine and turnouts.
- ✓ The incorporation of online and smart failure detection systems
- ✓ Design that accommodates (includes) future expansion and loading.

In doing so, AA-LRT signaling system should contribute to ensure the safety and quality of the transportation system with high availability.

5.3.2 Maintenance Improvement

RAM improvement of AA-LRT signaling system can also be improved by following certain maintenance strategies that are aimed at increasing signaling subsystems and components service life and at failure prevention. The improvement of signaling system reliability by means of the implementation of improved maintenance policies could be achieved by way of selecting the appropriate maintenance strategy that is based on the consequence and risk of failure.

For AA-LRT signaling system to have acceptable set target RAM, a maintenance strategy must be in place to achieve the following:

- ✓ Improved system reliability and maintainability
- ✓ Decreased system downtime and increased uptime
- ✓ Improved spares inventory management
- ✓ Decreased cost of replacing signaling system components

Maintenance management activities that can be used to improve RAM, include the following:

- ✓ Improved structuring and organisation of the operation and maintenance service
- ✓ Standardisation of operation and maintenance activities
- ✓ Performance measurement and cost-benefit analysis of maintenance management
- ✓ Introducing measures of redundancy in critical subsystems and applications.

The bulk of maintenance is done for correcting in the unscheduled and unplanned way which may cost high related to the high frequency of failure. Maintenance costs may be lowered by increasing the preventive work for the signaling subsystems and components.

The AA-LRT signaling system can also be improved with the scheduled maintenance of the subsystems and components at an appropriate time, when there is either relatively little, or no traffic.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Reliability, availability and maintainability analyses should always be an integral part of AA-LRT signaling system for the effective and quality of transportation service in Addis Ababa, Ethiopia. The primary objective of the present study is to analyze reliability, availability and maintainability of the signaling system in the AA-LRT. The study was conducted with the failure and repair data of signaling system. The research study illustrates how the reliability and maintainability of the Signaling system affect the overall quality of transportation service.

The AA-LRT signaling system has five subsystems such as IATP subsystem, CBI subsystem, ATS subsystem, DCS subsystem and MSS subsystem. The failed subsystems and equipments that analysed in this research are ATP, Axle Counter, Signaling Filament and Switch.

Failure and down frequency results indicated that the Axle counter subsystem needs more inspection for maintenance than the other subsystems of AA-LRT since it is the most frequently failed subsystem. FMEA results shows the Switch has the highest RPN to cause risk which is the most critical subsystem and its maintenance time should be as much as possible short and more inspection is needed to reduce the risk.

Reliability and Maintainability of signaling subsystems was determined from the corresponding best-fit probability distribution functions. The respective best-fit probability density functions for signaling subsystems (such as Switch, ATP, Signaling filament and Axle Counter) were observed as Lognormal 3-Parameter, Weibull 2-Parameter, Lognormal 3-Parameter, and Lognormal 3-Parameter (Table 4.7 and Table 4.8). The results revealed that the Axle counter has the lowest level of reliability (i.e. low MTBF) and the switch has highest level of reliability (i.e. high MTBF). Whenever failure occurs in the switch, it takes much time to restore (i.e. has high MTTR) than other subsystems. The availability results indicated that all the subsystems and equipments are available for more than 96% of the time (Table 5.1).

To improve the RAM of the AA-LRT signaling system preventive and scheduled maintenance is needed for each subsystem.

6.2 Recommendations

RAM analysis should be a continual process for AA-LRT to keep and improve the availability and quality transportation system. Thus, this research recommends AA-LRT should investigate and research new technologies with regards to subsystems that needs more inspection and repair.

6.2.1 Collection of Data

The lack of proper data can lead to incorrect failure identification, which, in turn, means more time spent on corrective maintenance and lower system availability. The data collection and reporting procedures employed for analysis and improvement must be reproducible, dependable, and accurate.

This thesis recommends a better way for both manual and computer based field failure recording. Thus, a failure data and maintenance report form must collect adequate information about:

- ✓ The causes, modes and effects of failures.
- ✓ Time related data's such as Operating time, waiting time and repair time.
- ✓ Fault location – exact position and detail of component.
- ✓ Environmental and operating conditions.
- ✓ Action taken – exact nature of replacement or repair.
- ✓ Personnel involved, and Equipment and Spares used.
- ✓ Costs of failure, etc.

It can be concluded that increased visibility of the information and reduced time to gather the required data needed for maintenance activities will improve the efficiency of corrective maintenance of AA-LRT signalling systems.

6.3 Future Work

Based on the results of this thesis, further research can consider the following areas:

- ✓ Evaluate RAMS for each signalling subsystems and components during the operation and maintenance.
- ✓ Develop models for RAM improvement based on Design and Maintenance.
- ✓ Develop a Life Cycle Cost model for cost effective maintenance policies.

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APPENDICES

APPENDIX I: Probability Density Function Formulas

Probability Distributions (Continuous)	Two Parameters	Three Parameters
Exponential distribution	$f(x) = \lambda e^{-\lambda(x-\gamma)}$	$f(x) = \lambda e^{-\lambda x}$ (one parameter only)
Gamma distribution	$f(x) = \frac{x^{\alpha-1}}{\beta^{\alpha}\,\Gamma(\alpha)}\; e^{-x/\beta}$	$f(x) = \frac{(x-\gamma)^{\alpha-1}}{\beta^{\alpha}\,\Gamma(\alpha)}\; e^{(-(x-\gamma)/\beta}$
Weibull distribution	$f(x) = \frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1}\; e^{(-\frac{x}{\beta})^{\alpha}}$	$f(x) = \frac{\alpha}{\beta}\left(\frac{x-\gamma}{\beta}\right)^{\alpha-1}\; e^{(-(\frac{x-\gamma}{\beta}))^{\alpha}}$
Normal distribution	$f(x) = \frac{e^{(-\frac{1}{2}(\frac{x-\mu}{\sigma})^2)}}{\sigma\sqrt{2\pi}}$	
Lognormal distribution	$f(x) = \frac{e^{(-\frac{1}{2}(\frac{lnx-\mu}{\sigma})^2)}}{x\sigma\sqrt{2\pi}}$	$f(x) = \frac{e^{(-\frac{1}{2}(\frac{\ln(x-\gamma)-\mu}{\sigma})^2)}}{(x-\gamma)\sigma\sqrt{2\pi}}$
Survival (Reliability) Functions	$S(x) = P(X > x) = 1 - F(x)$	

APPENDIX II: TBF and TTR Data

(A) TBF and TTR Data for ATP

ATP								
DATE	**NOF**	**CNOF**	**TBF (Min)**	**CTBF (Min)**	**CTBF (Hr)**	**TTR (Min)**	**CTTR (Min)**	**CTTR (Hr)**
2016.10.1	3	3	1119	1119	18.65	321	321	5.35
2016.10.2	2	5	1338	2457	40.95	102	423	7.05
2016.10.6	1	6	5752	8209	136.82	8	431	7.18
2016.10.13	1	7	10067	18276	304.60	13	444	7.40
2016.10.21	1	8	11500	29776	496.27	20	464	7.73
2016.10.24	1	9	4300	34076	567.93	20	484	8.07
2016.10.25	1	10	1379	35455	590.92	61	545	9.08
2016.10.26	1	11	1420	36875	614.58	20	565	9.42
2016.10.27	1	12	1391	38266	637.77	49	614	10.23
2016.10.28	2	14	1340	39606	660.10	100	714	11.90
2016.10.29	1	15	1400	41006	683.43	40	754	12.57
2016.11.23	4	19	34520	75526	1258.77	40	794	13.23
2016.11.25	2	21	2874	78400	1306.67	6	800	13.33
2016.11.28	1	22	4311	82711	1378.52	9	809	13.48
2017.01.6	1	23	15796	98507	1641.78	44	853	14.22
2017.01.9	1	24	4316	102823	1713.72	4	857	14.28
2017.01.16	1	25	10064	112887	1881.45	16	873	14.55
2017.02.08	1	26	33100	145987	2433.12	20	893	14.88
2017.04.27	1	27	112317	258304	4305.07	3	896	14.93
2017.04.30	1	28	4317	262621	4377.02	3	899	14.98

(B) TBF and TTR Data for Axle Counter

Axle Counter								
DATE	NOF	CNOF	TBF (Min)	CTBF (Min)	CTBF (Hr)	TTR (Min)	CTTR (Min)	CTTR (Hr)
2016.10.3	2	2	4189	4189	69.82	131	131	2.18
2016.10.4	4	6	1243	5432	90.53	197	328	5.47
2016.10.6	2	8	2794	8226	137.10	86	414	6.90
2016.10.7	2	10	1418	9644	160.73	22	436	7.27
2016.10.8	1	11	1417	11061	184.35	23	459	7.65
2016.10.9	3	14	1426	12487	208.12	14	473	7.88
2016.10.10	2	16	1344	13831	230.52	96	569	9.48
2016.10.14	1	17	5742	19573	326.22	18	587	9.78
2016.10.15	1	18	1390	20963	349.38	50	637	10.62
2016.10.16	2	20	1338	22301	371.68	102	739	12.32
2016.10.17	1	21	995	23296	388.27	445	1184	19.73
2016.10.18	2	23	1402	24698	411.63	38	1222	20.37
2016.10.19	3	26	1335	26033	433.88	105	1327	22.12
2016.10.20	1	27	1400	27433	457.22	40	1367	22.78
2016.10.21	5	32	1279	28712	478.53	161	1528	25.47
2016.10.22	2	34	1377	30089	501.48	63	1591	26.52
2016.10.23	2	36	1398	31487	524.78	42	1633	27.22
2016.10.24	3	39	1379	32866	547.77	61	1694	28.23
2016.10.25	1	40	1363	34229	570.48	77	1771	29.52
2016.10.26	3	43	1391	35620	593.67	49	1820	30.33
2016.10.27	1	44	1407	37027	617.12	33	1853	30.88
2016.10.28	1	45	1430	38457	640.95	10	1863	31.05
2016.10.29	1	46	1421	39878	664.63	19	1882	31.37
2016.10.30	2	48	1414	41292	688.20	26	1908	31.80
2016.10.31	1	49	1436	42728	712.13	4	1912	31.87
2016.11.01	4	53	1389	44117	735.28	51	1963	32.72
2016.11.02	2	55	1370	45487	758.12	70	2033	33.88
2016.11.03	1	56	1433	46920	782.00	7	2040	34.00
2016.11.04	5	61	1379	48299	804.98	61	2101	35.02
2016.11.06	1	62	2874	51173	852.88	6	2107	35.12
2016.11.08	1	63	2859	54032	900.53	21	2128	35.47
2016.11.09	1	64	1418	55450	924.17	22	2150	35.83
2016.11.10	1	65	1429	56879	947.98	11	2161	36.02
2016.11.11	4	69	1321	58200	970.00	119	2280	38.00
2016.11.12	1	70	1426	59626	993.77	14	2294	38.23
2016.11.13	1	71	1434	61060	1017.67	6	2300	38.33

2016.11.14	2	73	1393	62453	1040.88	47	2347	39.12
2016.11.16	3	76	2812	65265	1087.75	68	2415	40.25
2016.11.17	4	80	1356	66621	1110.35	84	2499	41.65
2016.11.18	1	81	1407	68028	1133.80	33	2532	42.20
2016.11.19	2	83	1409	69437	1157.28	31	2563	42.72
2016.11.21	1	84	2872	72309	1205.15	8	2571	42.85
2016.11.22	1	85	1428	73737	1228.95	12	2583	43.05
2016.11.23	3	88	1355	75092	1251.53	85	2668	44.47
2016.11.26	1	89	4283	79375	1322.92	37	2705	45.08
2016.11.27	1	90	1434	80809	1346.82	6	2711	45.18
2016.11.29	3	93	2782	83591	1393.18	98	2809	46.82
2016.11.30	2	95	1333	84924	1415.40	107	2916	48.60
2017.01.1	1	96	1435	86359	1439.32	5	2921	48.68
2017.01.2	3	99	1417	87776	1462.93	23	2944	49.07
2017.01.3	2	101	1424	89200	1486.67	16	2960	49.33
2017.01.4	2	103	1432	90632	1510.53	8	2968	49.47
2017.01.5	4	107	1267	91899	1531.65	173	3141	52.35
2017.01.6	5	112	1342	93241	1554.02	98	3239	53.98
2017.01.7	3	115	1353	94594	1576.57	87	3326	55.43
2017.01.8	1	116	1434	96028	1600.47	6	3332	55.53
2017.01.9	1	117	1437	97465	1624.42	3	3335	55.58
2017.01.11	3	120	2786	100251	1670.85	94	3429	57.15
2017.01.12	2	122	1377	101628	1693.80	63	3492	58.20
2017.01.14	3	125	2800	104428	1740.47	80	3572	59.53
2017.01.16	2	127	2880	107308	1788.47	0	3572	59.53
2017.01.18	1	128	2831	110139	1835.65	49	3621	60.35
2017.01.19	3	131	1387	111526	1858.77	53	3674	61.23
2017.01.20	2	133	1380	112906	1881.77	60	3734	62.23
2017.01.21	1	134	1380	114286	1904.77	60	3794	63.23
2017.01.22	2	136	1361	115647	1927.45	79	3873	64.55
2017.01.23	1	137	1386	117033	1950.55	54	3927	65.45
2017.01.24	2	139	1365	118398	1973.30	75	4002	66.70
2017.01.25	3	142	1283	119681	1994.68	157	4159	69.32
2017.01.26	3	145	1173	120854	2014.23	267	4426	73.77
2017.01.27	1	146	1421	122275	2037.92	19	4445	74.08
2017.01.28	1	147	1418	123693	2061.55	22	4467	74.45
2017.01.29	1	148	1434	125127	2085.45	6	4473	74.55
2017.01.30	4	152	1278	126405	2106.75	162	4635	77.25
2017.01.31	4	156	1292	127697	2128.28	148	4783	79.72
2017.02.1	3	159	1299	128996	2149.93	141	4924	82.07
2017.02.2	4	163	1310	130306	2171.77	130	5054	84.23

2017.02.3	1	164	1418	131724	2195.40	22	5076	84.60
2017.02.5	2	166	2794	134518	2241.97	86	5162	86.03
2017.02.6	1	167	1350	135868	2264.47	90	5252	87.53
2017.02.7	1	168	1390	137258	2287.63	50	5302	88.37
2017.02.9	4	172	2786	140044	2334.07	94	5396	89.93
2017.02.10	2	174	1290	141334	2355.57	150	5546	92.43
2017.02.11	2	176	1409	142743	2379.05	31	5577	92.95
2017.02.13	3	179	2804	145547	2425.78	76	5653	94.22
2017.02.14	1	180	1426	146973	2449.55	14	5667	94.45
2017.02.15	1	181	1416	148389	2473.15	24	5691	94.85
2017.02.16	1	182	1428	149817	2496.95	12	5703	95.05
2017.02.17	1	183	1425	151242	2520.70	15	5718	95.30
2017.02.18	2	185	1363	152605	2543.42	77	5795	96.58
2017.02.19	3	188	1320	153925	2565.42	120	5915	98.58
2017.02.20	5	193	1271	155196	2586.60	169	6084	101.40
2017.02.21	2	195	1385	156581	2609.68	55	6139	102.32
2017.02.22	1	196	1435	158016	2633.60	5	6144	102.40
2017.02.23	3	199	1367	159383	2656.38	73	6217	103.62
2017.02.24	3	202	1350	160733	2678.88	90	6307	105.12
2017.02.25	2	204	1358	162091	2701.52	82	6389	106.48
2017.02.27	1	205	2866	164957	2749.28	14	6403	106.72
2017.03.1	4	209	2658	167615	2793.58	222	6625	110.42
2017.03.2	1	210	1426	169041	2817.35	14	6639	110.65
2017.03.3	3	213	1341	170382	2839.70	99	6738	112.30
2017.03.4	4	217	1347	171729	2862.15	93	6831	113.85
2017.03.5	1	218	1382	173111	2885.18	58	6889	114.82
2017.03.6	4	222	1307	174418	2906.97	133	7022	117.03
2017.03.7	1	223	1397	175815	2930.25	43	7065	117.75
2017.03.8	1	224	1414	177229	2953.82	26	7091	118.18
2017.03.10	1	225	2846	180075	3001.25	34	7125	118.75
2017.03.12	1	226	2840	182915	3048.58	40	7165	119.42
2017.03.14	1	227	2861	185776	3096.27	19	7184	119.73
2017.03.16	2	229	2847	188623	3143.72	33	7217	120.28
2017.03.18	2	231	2818	191441	3190.68	62	7279	121.32
2017.03.19	2	233	1367	192808	3213.47	73	7352	122.53
2017.03.20	2	235	1421	194229	3237.15	19	7371	122.85
2017.03.21	1	236	1417	195646	3260.77	23	7394	123.23
2017.03.25	1	237	5755	201401	3356.68	5	7399	123.32
2017.03.31	2	239	8598	209999	3499.98	42	7441	124.02
2017.04.2	1	240	2870	212869	3547.82	10	7451	124.18
2017.04.3	3	243	1335	214204	3570.07	105	7556	125.93

2017.04.4	3	246	1380	215584	3593.07	60	7616	126.93
2017.04.5	2	248	1382	216966	3616.10	58	7674	127.90
2017.04.6	1	249	1390	218356	3639.27	50	7724	128.73
2017.04.7	2	251	1421	219777	3662.95	19	7743	129.05
2017.04.9	2	253	2842	222619	3710.32	38	7781	129.68
2017.04.10	2	255	1407	224026	3733.77	33	7814	130.23
2017.04.15	1	256	7192	231218	3853.63	8	7822	130.37
2017.04.17	4	260	2797	234015	3900.25	83	7905	131.75
2017.04.19	1	261	2822	236837	3947.28	58	7963	132.72
2017.04.20	2	263	1386	238223	3970.38	54	8017	133.62
2017.04.23	1	264	4301	242524	4042.07	19	8036	133.93
2017.04.24	1	265	1349	243873	4064.55	91	8127	135.45
2017.04.25	2	267	1406	245279	4087.98	34	8161	136.02
2017.04.26	3	270	1392	246671	4111.18	48	8209	136.82
2017.04.27	4	274	1402	248073	4134.55	38	8247	137.45
2017.04.28	2	276	1393	249466	4157.77	47	8294	138.23
2017.04.29	4	280	1097	250563	4176.05	343	8637	143.95

(C) TBF and TTR Data for Signaling Filament

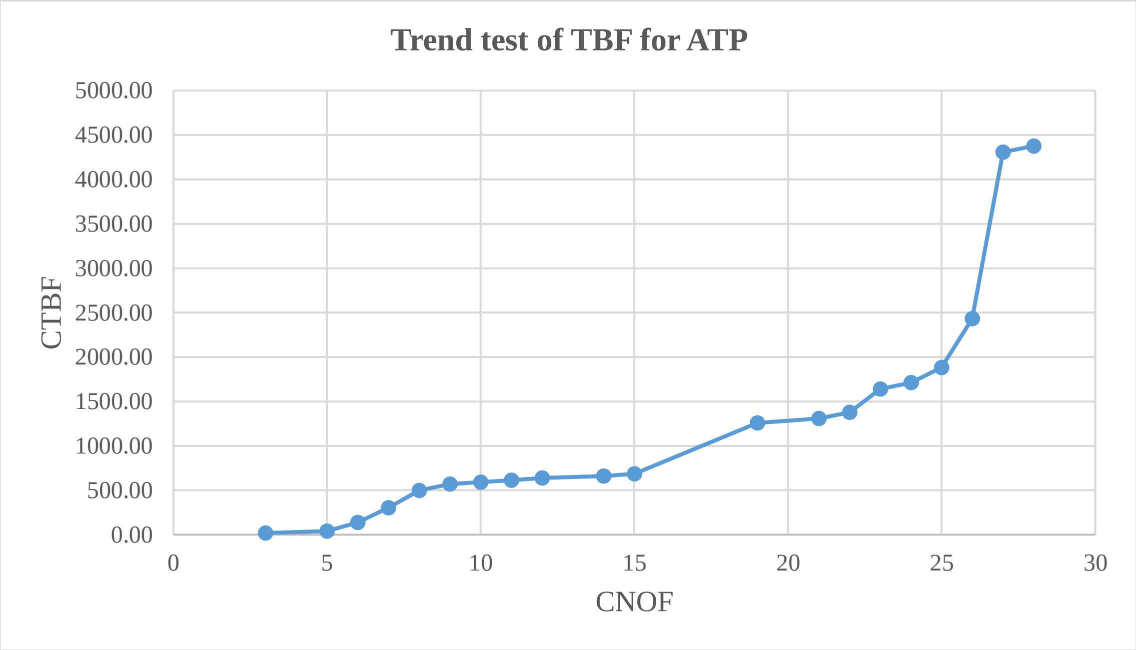
Signaling Filament								
DATE	NOF	CNOF	TBF (Min)	CTBF (Min)	CTBF (Hr)	TTR (Min)	CTTR (Min)	CTTR (Hr)
2016.10.1	1	1	1430	1430	23.83	10	10	0.17
2016.10.20	1	2	27352	28782	479.70	8	18	0.30
2016.10.26	1	3	8633	37415	623.58	7	25	0.42
2016.11.8	1	4	18686	56101	935.02	34	59	0.98
2016.11.12	1	5	5757	61858	1030.97	3	62	1.03
2017.01.7	1	6	35951	97809	1630.15	49	111	1.85
2017.01.10	1	7	4277	102086	1701.43	43	154	2.57
2017.01.11	1	8	1407	103493	1724.88	33	187	3.12
2017.01.15	1	9	5755	109248	1820.80	5	192	3.20
2017.01.16	1	10	1393	110641	1844.02	47	239	3.98
2017.01.27	1	11	15800	126441	2107.35	40	279	4.65
2017.02.5	1	12	12926	139367	2322.78	34	313	5.22
2017.02.7	1	13	2874	142241	2370.68	6	319	5.32
2017.02.9	1	14	2817	145058	2417.63	63	382	6.37
2017.02.21	1	15	17228	162286	2704.77	52	434	7.23
2017.02.26	1	16	7141	169427	2823.78	59	493	8.22
2017.03.1	1	17	4315	173742	2895.70	5	498	8.30
2017.03.4	1	18	4281	178023	2967.05	39	537	8.95
2017.03.13	1	19	12951	190974	3182.90	9	546	9.10
2017.03.17	2	21	5652	196626	3277.10	108	654	10.90
2017.03.21	1	22	5706	202332	3372.20	54	708	11.80
2017.03.25	1	23	5720	208052	3467.53	40	748	12.47
2017.03.30	1	24	7161	215213	3586.88	39	787	13.12
2017.04.3	1	25	5748	220961	3682.68	12	799	13.32
2017.04.4	1	26	1435	222396	3706.60	5	804	13.40
2017.04.5	1	27	1422	223818	3730.30	18	822	13.70
2017.04.6	1	28	1373	225191	3753.18	67	889	14.82
2017.04.7	1	29	1408	226599	3776.65	32	921	15.35
2017.04.11	1	30	5750	232349	3872.48	10	931	15.52
2017.04.13	1	31	2854	235203	3920.05	26	957	15.95

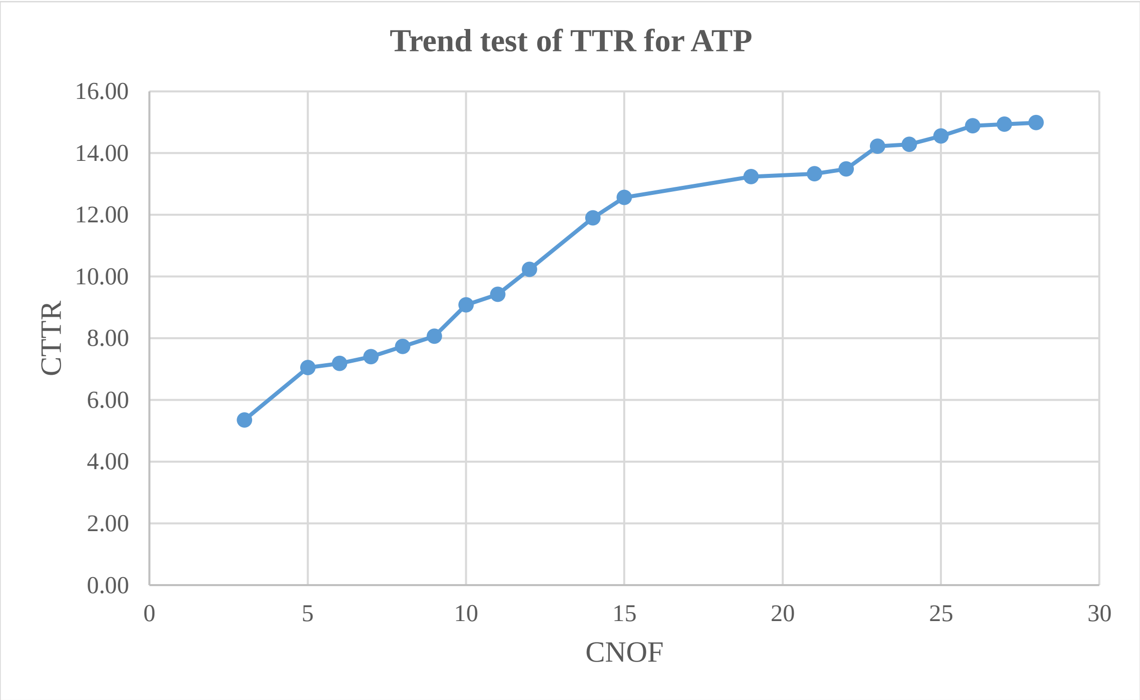
(D) TBF and TTR Data for Switch

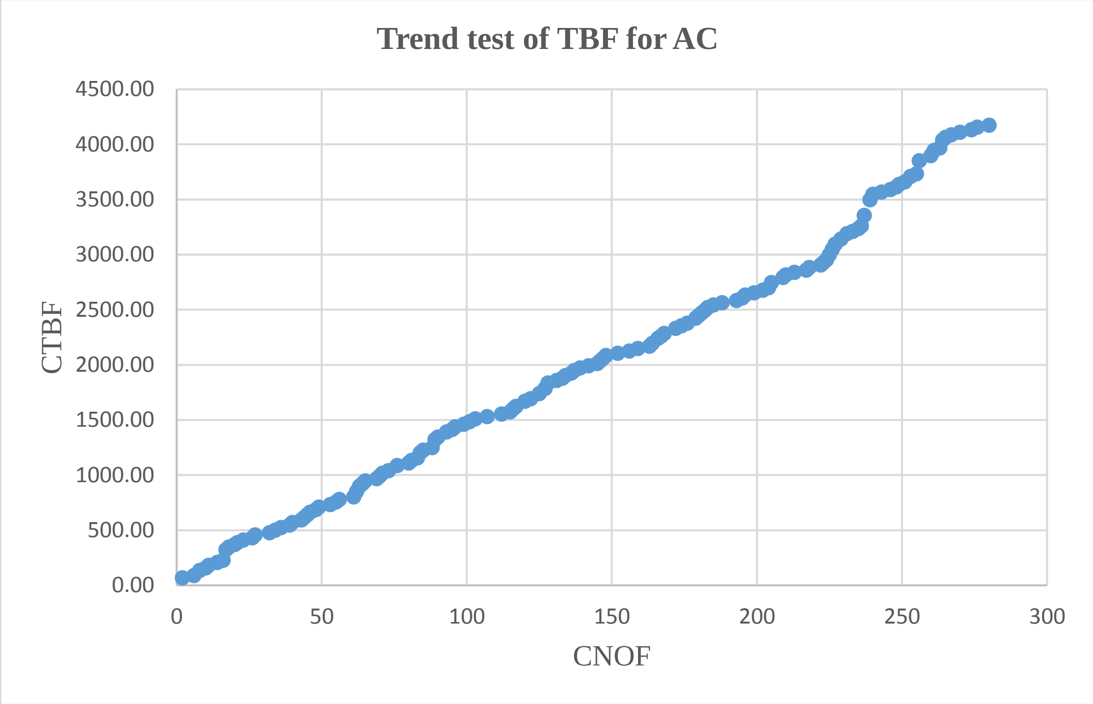
Switch								
DATE	NOF	CNOF	TBF (Min)	CTBF (Min)	CTBF (Hr)	TTR (Min)	CTTR (Min)	CTTR (Hr)
2016.10.8	1	1	11514	11514	191.90	6	6	0.10
2016.10.9	1	2	1438	12952	215.87	2	8	0.13
2016.10.22	1	3	18711	31663	527.72	9	17	0.28
2016.11.7	1	4	23003	54666	911.10	37	54	0.90
2017.1.8	1	5	44624	99290	1654.83	16	70	1.17
2017.2.13	1	6	51692	150982	2516.37	148	218	3.63
2017.2.19	1	7	8518	159500	2658.33	122	340	5.67
2017.2.21	1	8	2791	162291	2704.85	89	429	7.15
2017.3.12	1	9	27290	189581	3159.68	70	499	8.32
2017.4.13	1	10	45940	235521	3925.35	140	639	10.65

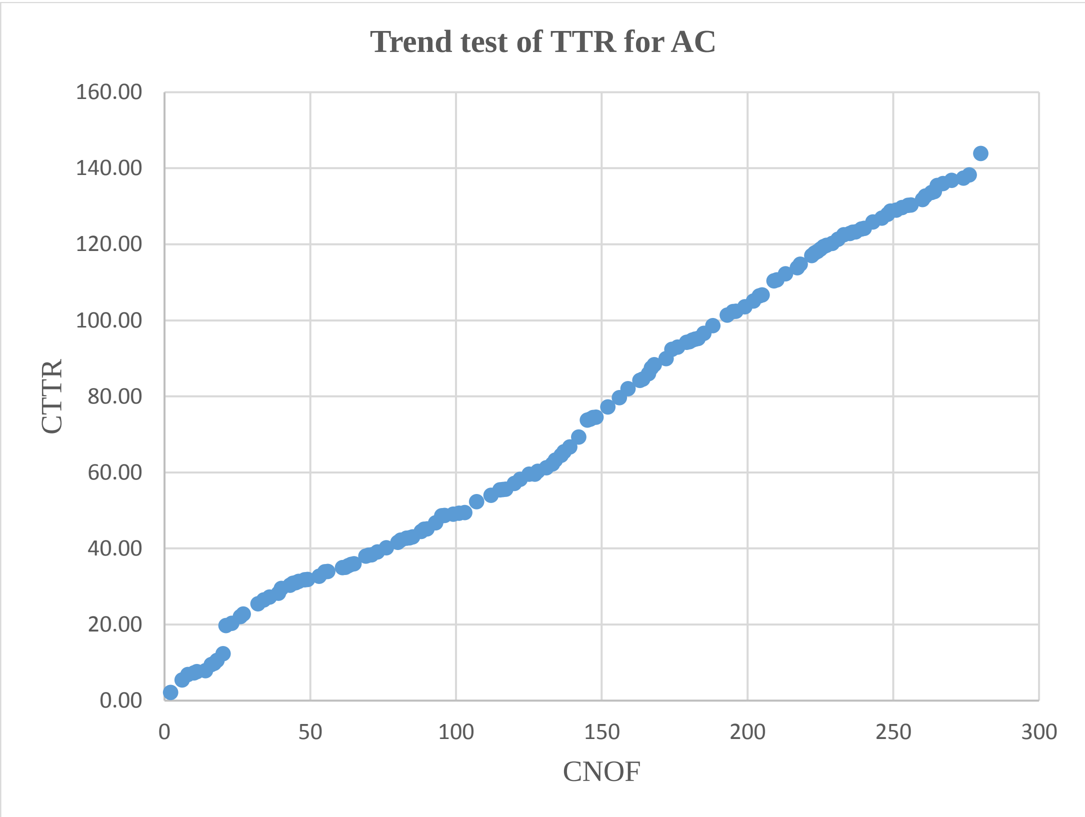
APPENDIX III: Trend and Serial Correlation Test Results

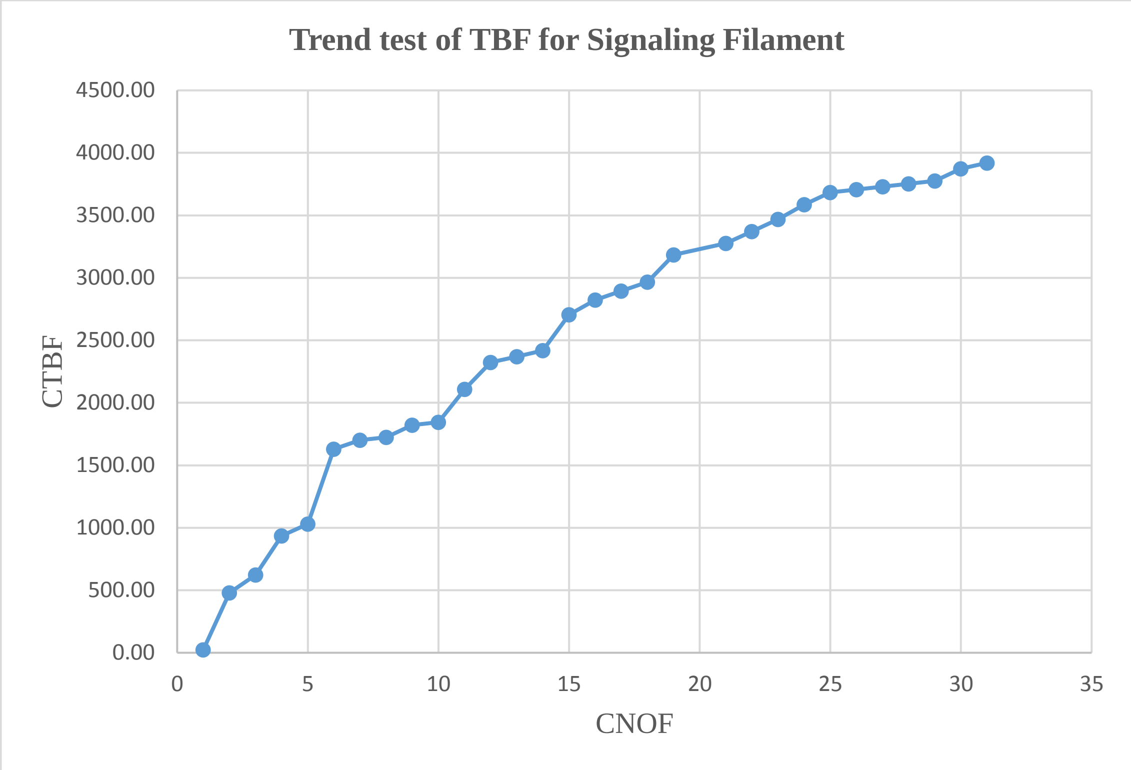
A. Trend Tests Results

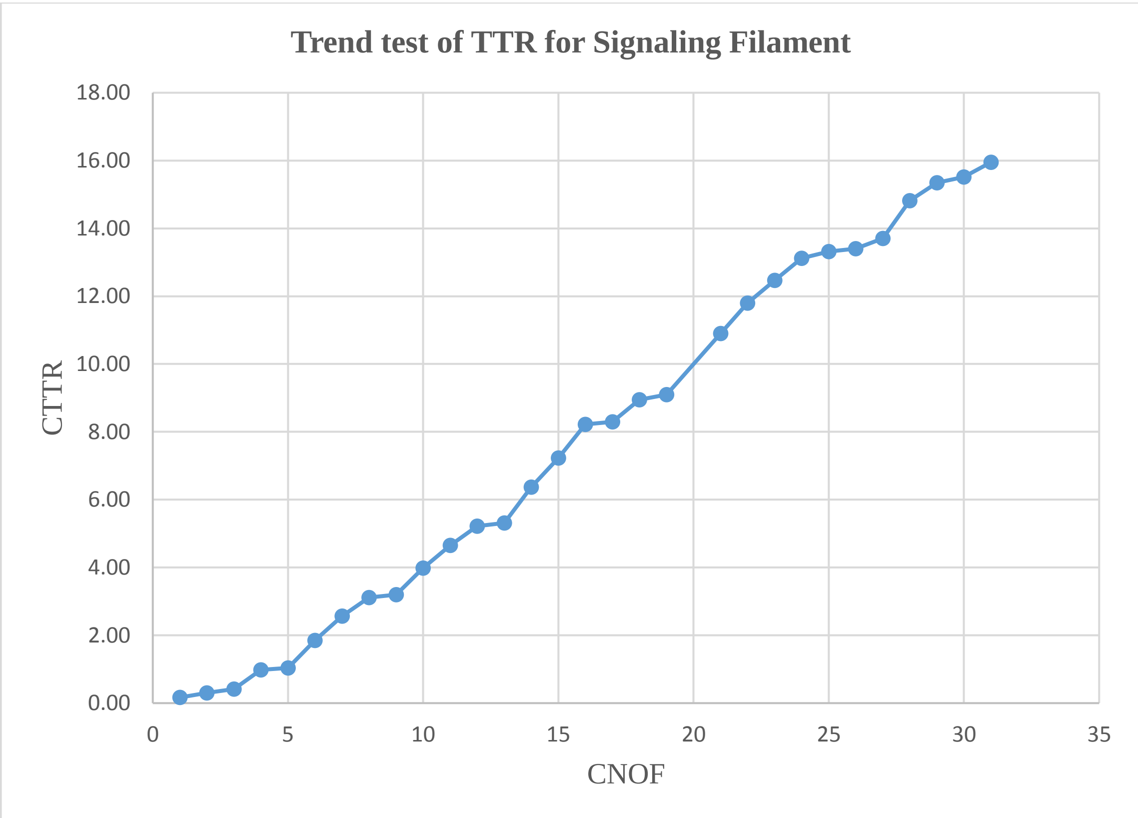


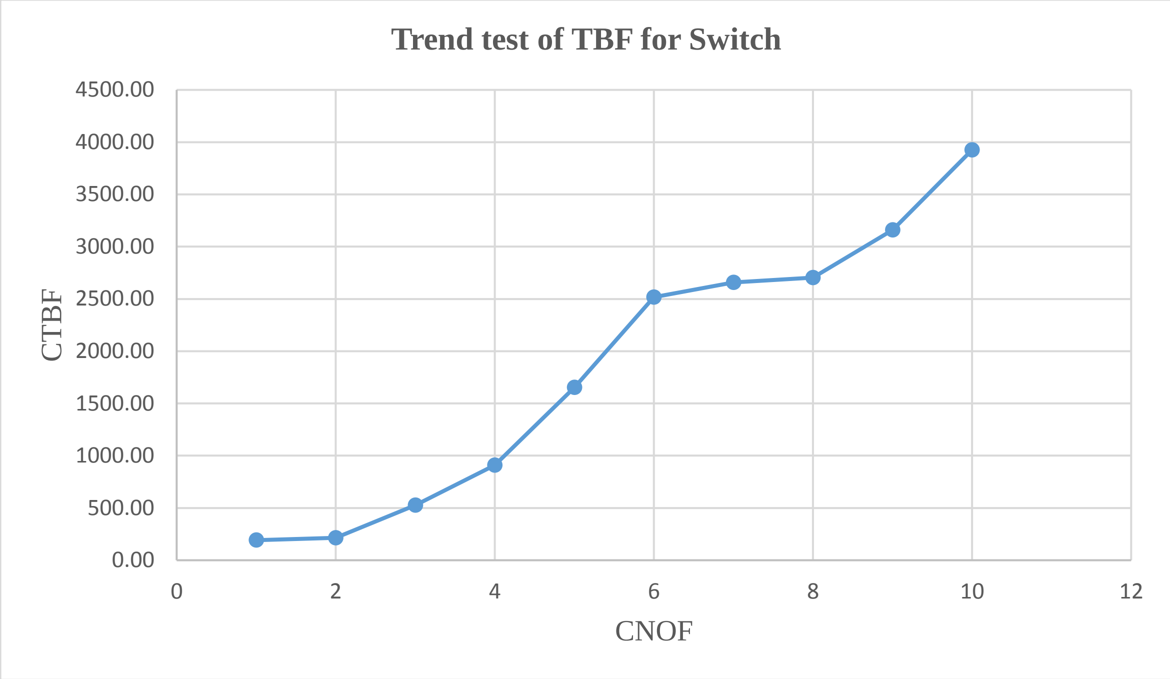


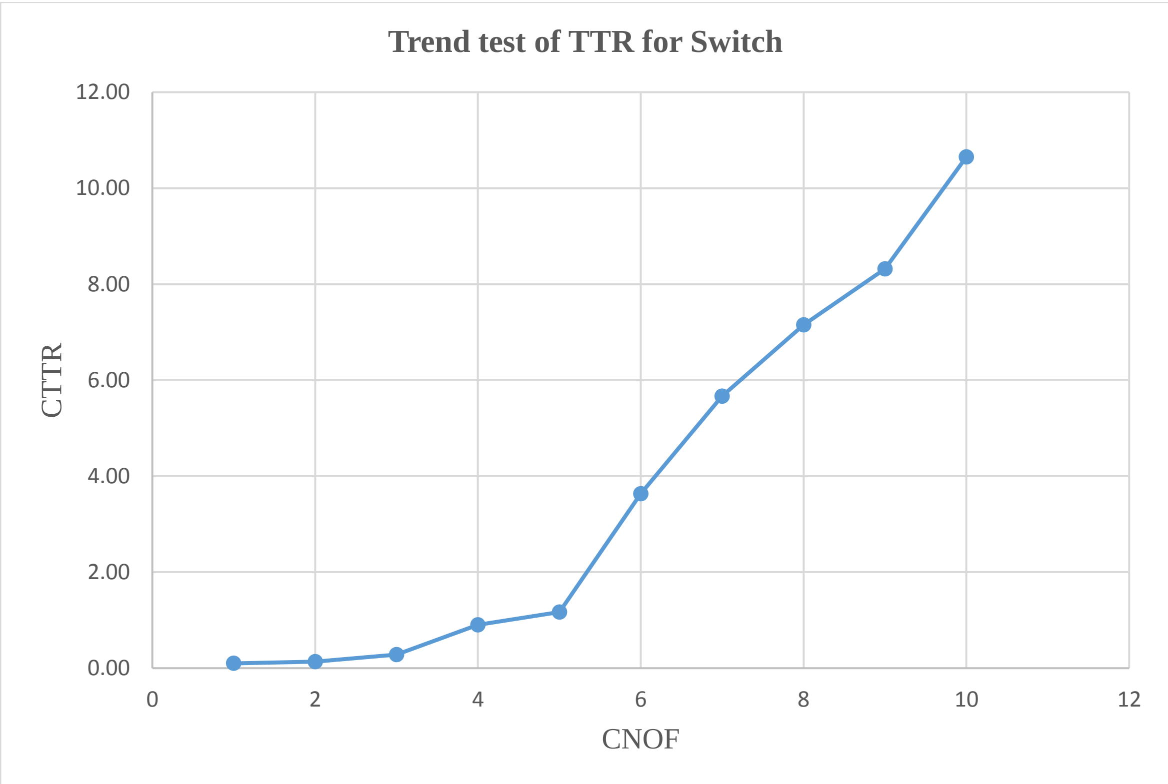

Trend test of TBF for AC
CTBF
4500.00
4000.00
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
0
50
100
150
200
250
300
CNOF


Trend test of TTR for AC
CTTR
160.00
140.00
120.00
100.00
80.00
60.00
40.00
20.00
0.00
0
50
100
150
200
250
300
CNOF

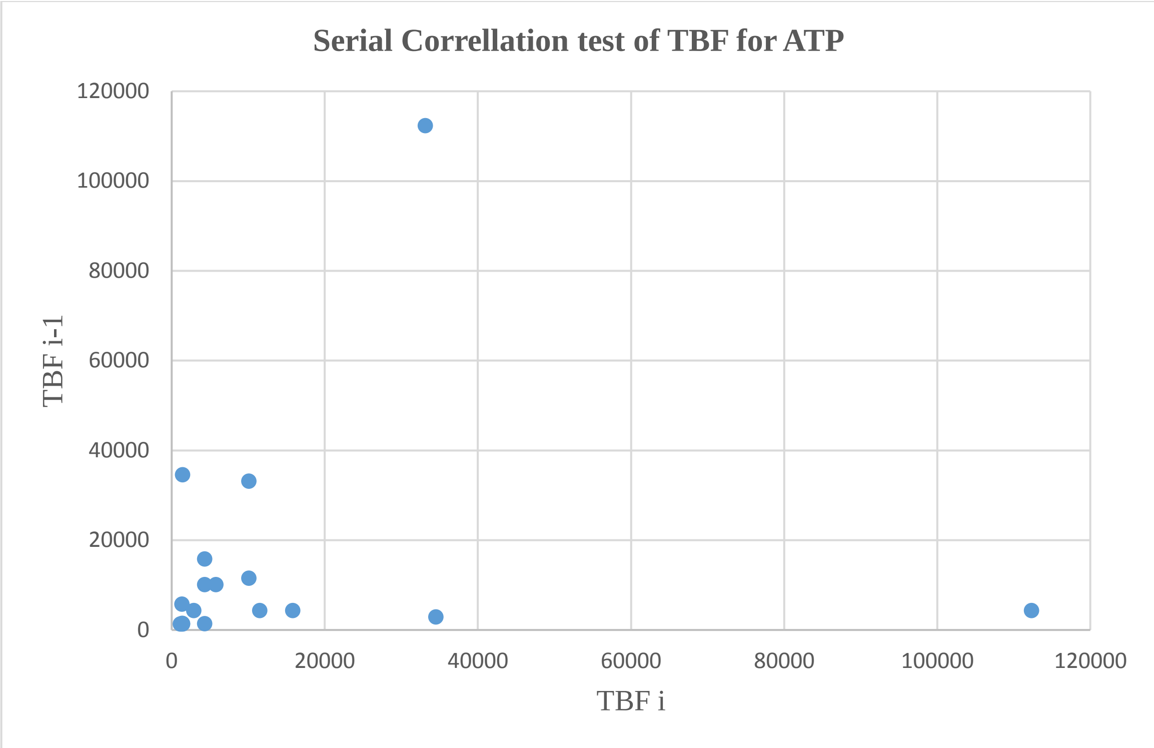

Trend test of TBF for Signaling Filament
4500.00
4000.00
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
CTBF
0
5
10
15
20
25
30
35
CNOF

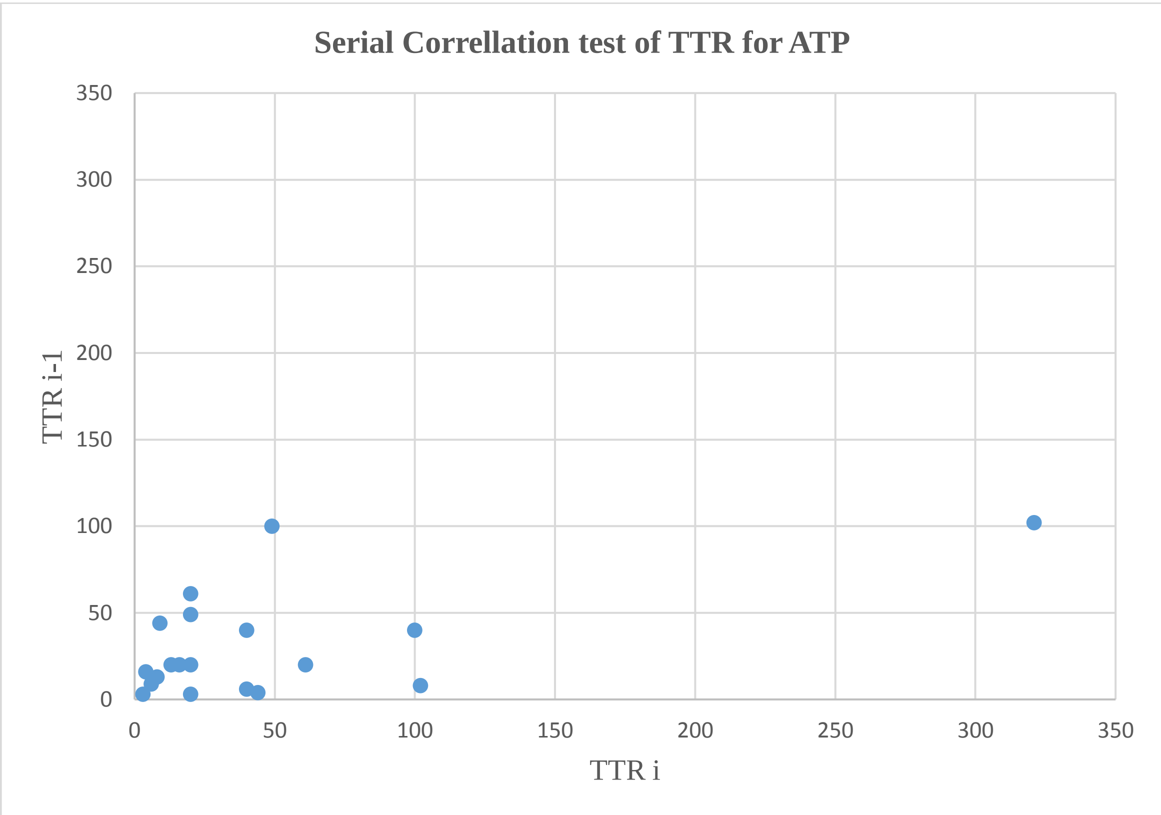

Trend test of TTR for Signaling Filament
18.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
CTTR
0
5
10
15
20
25
30
35
CNOF

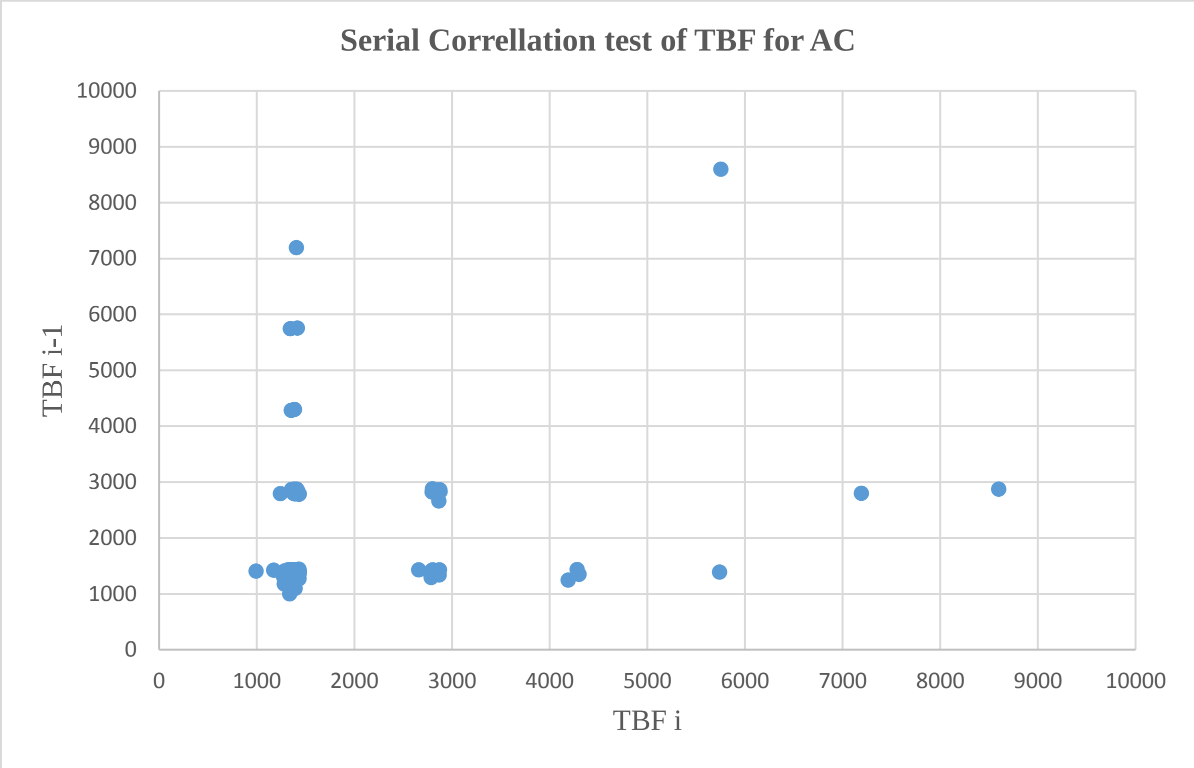

Trend test of TBF for Switch
CTBF
4500.00
4000.00
3500.00
3000.00
2500.00
2000.00
1500.00
1000.00
500.00
0.00
0
2
4
6
8
10
12
CNOF

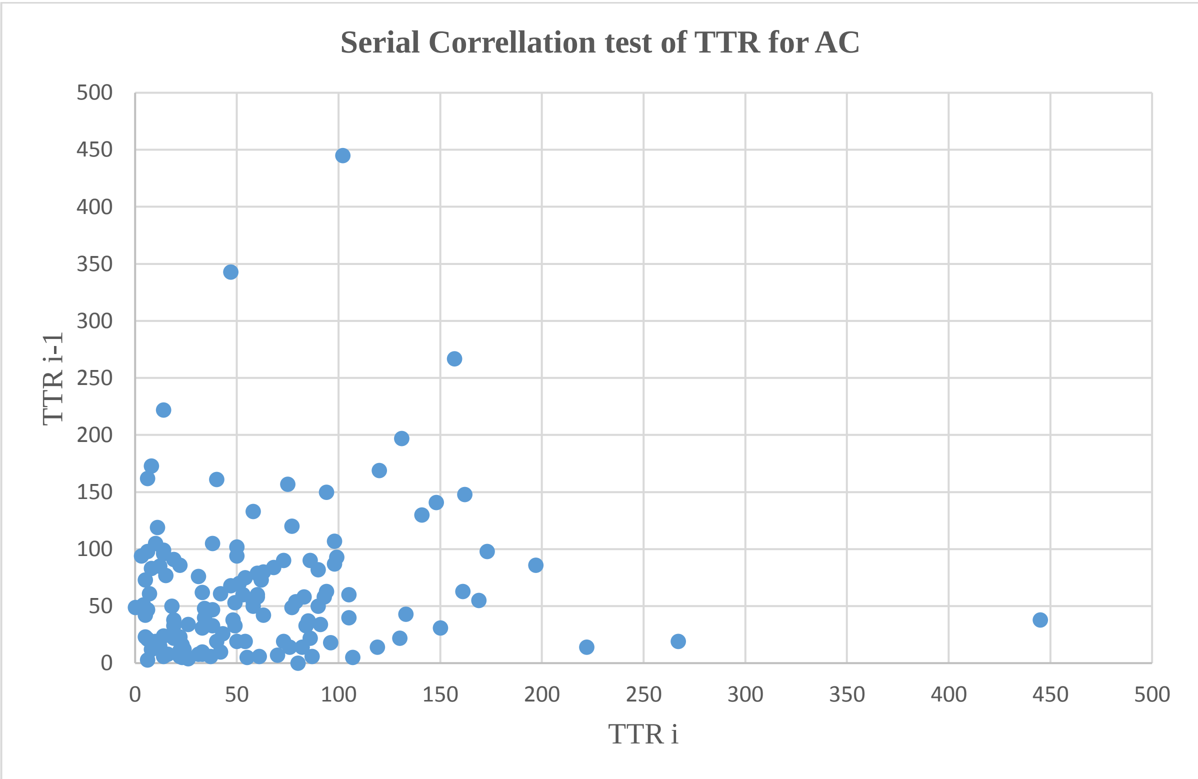

Trend test of TTR for Switch
CTTR
12.00
10.00
8.00
6.00
4.00
2.00
0.00
0
2
4
6
8
10
12
CNOF

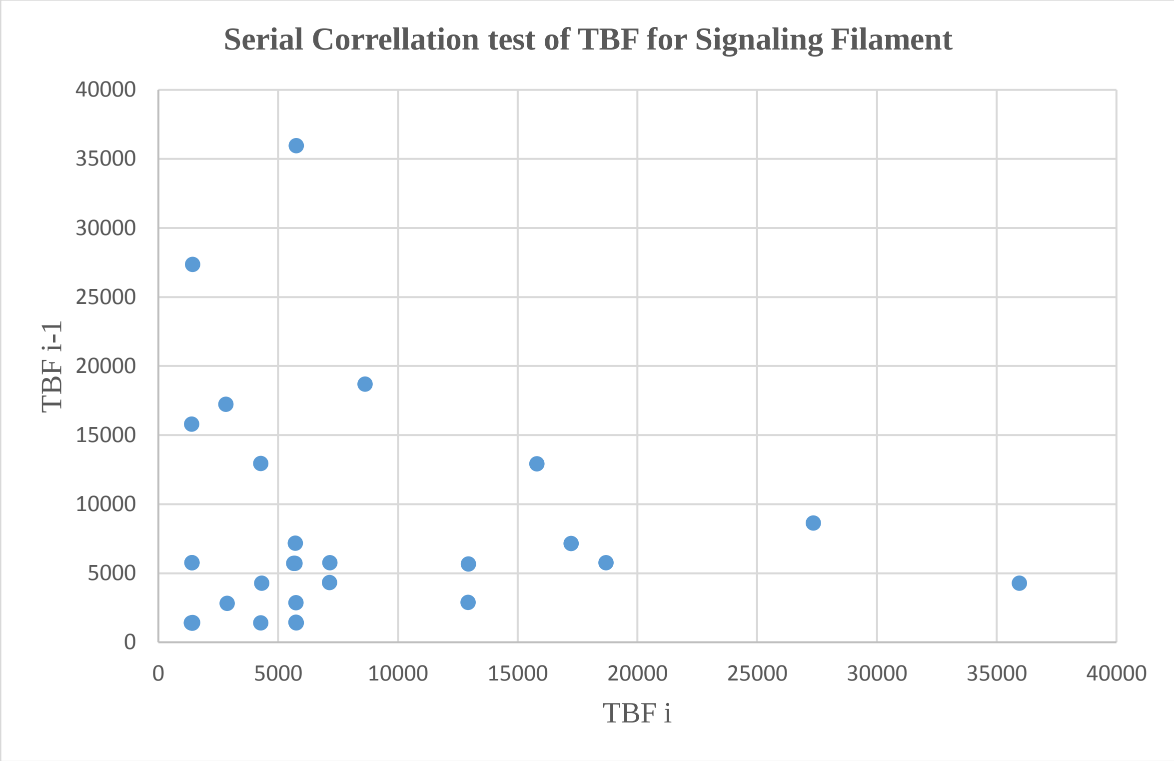
B. Serial Correlation Test Results

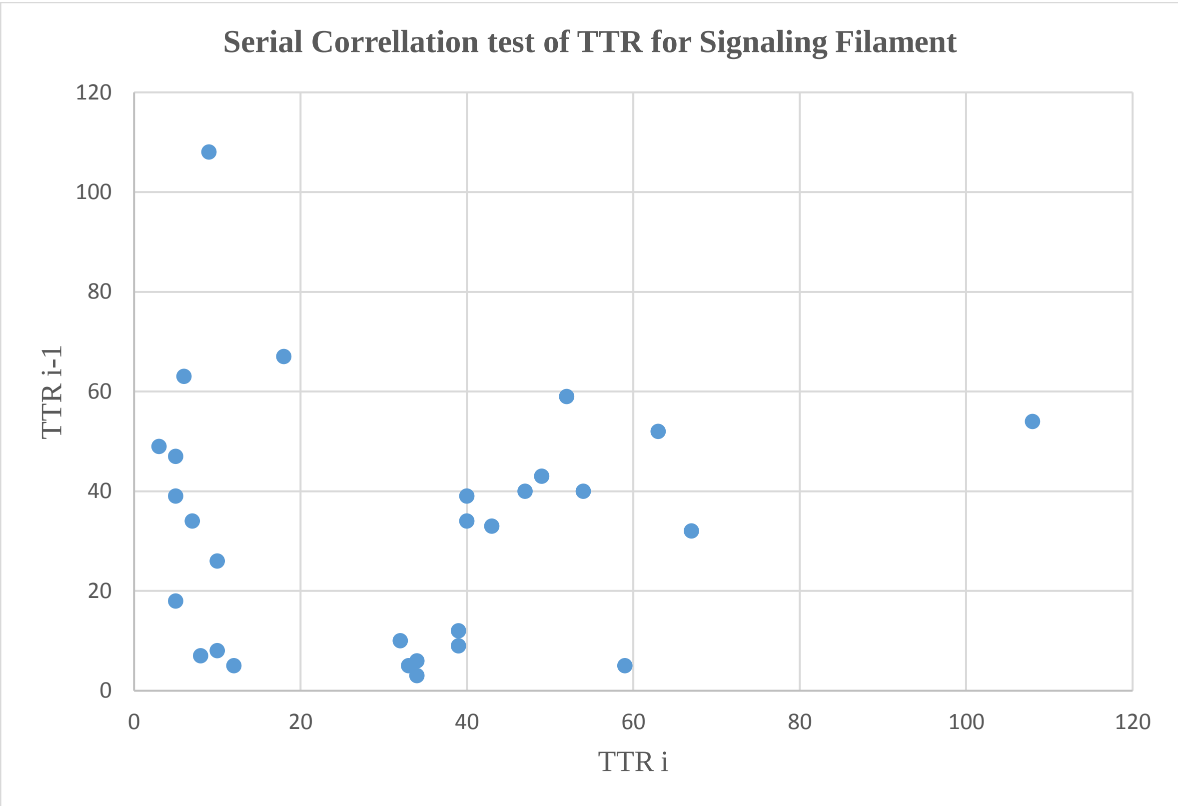


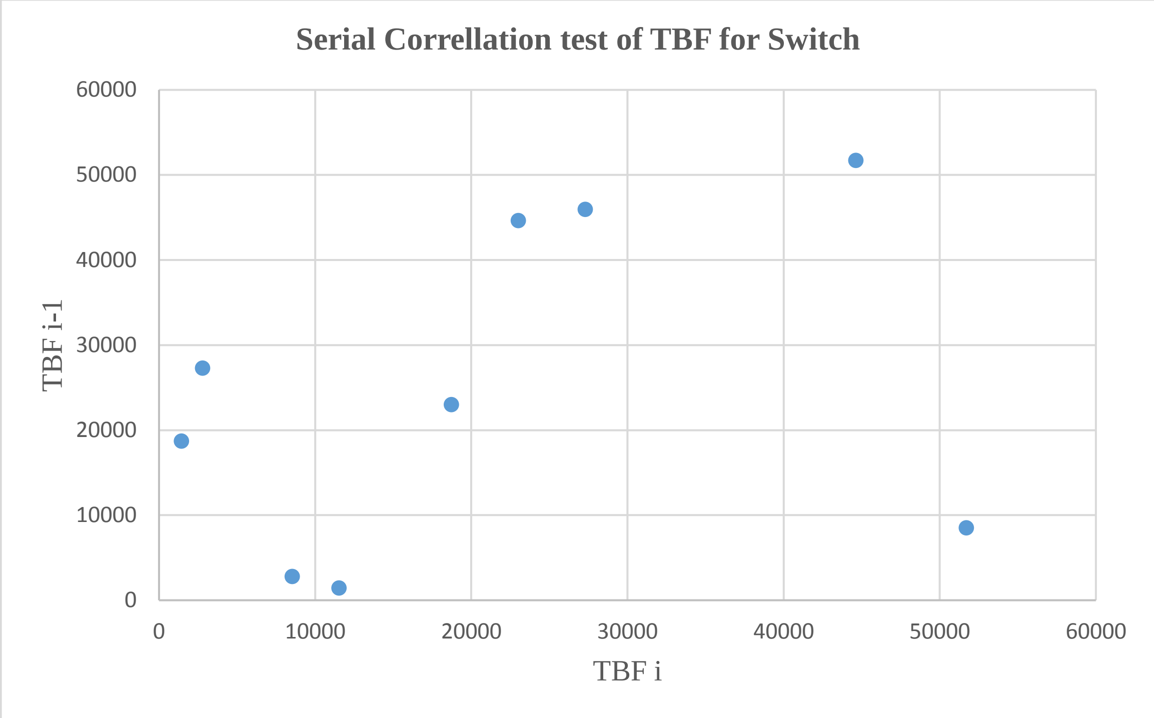


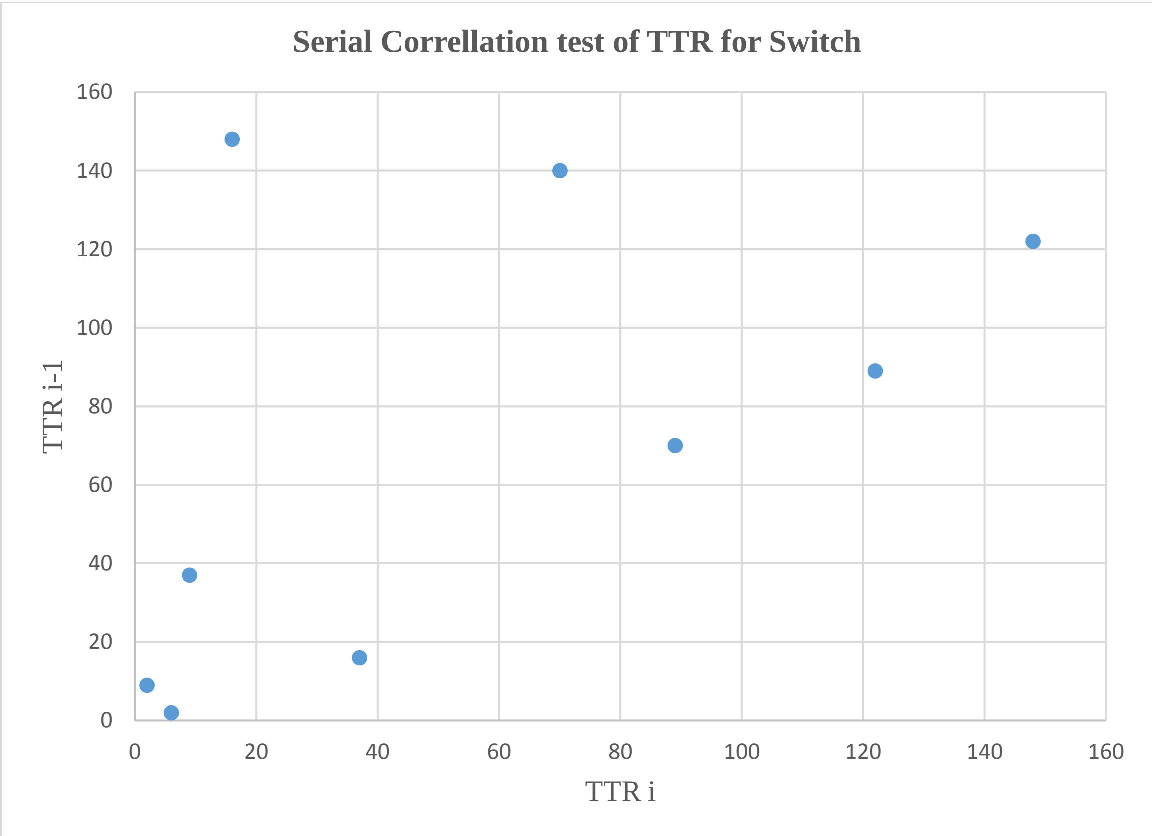

Serial Correllation test of TBF for AC
TBF i-1
TBF i
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000


Serial Correllation test of TTR for AC
TTR i-1
TTR i
0
50
100
150
200
250
300
350
400
450
500

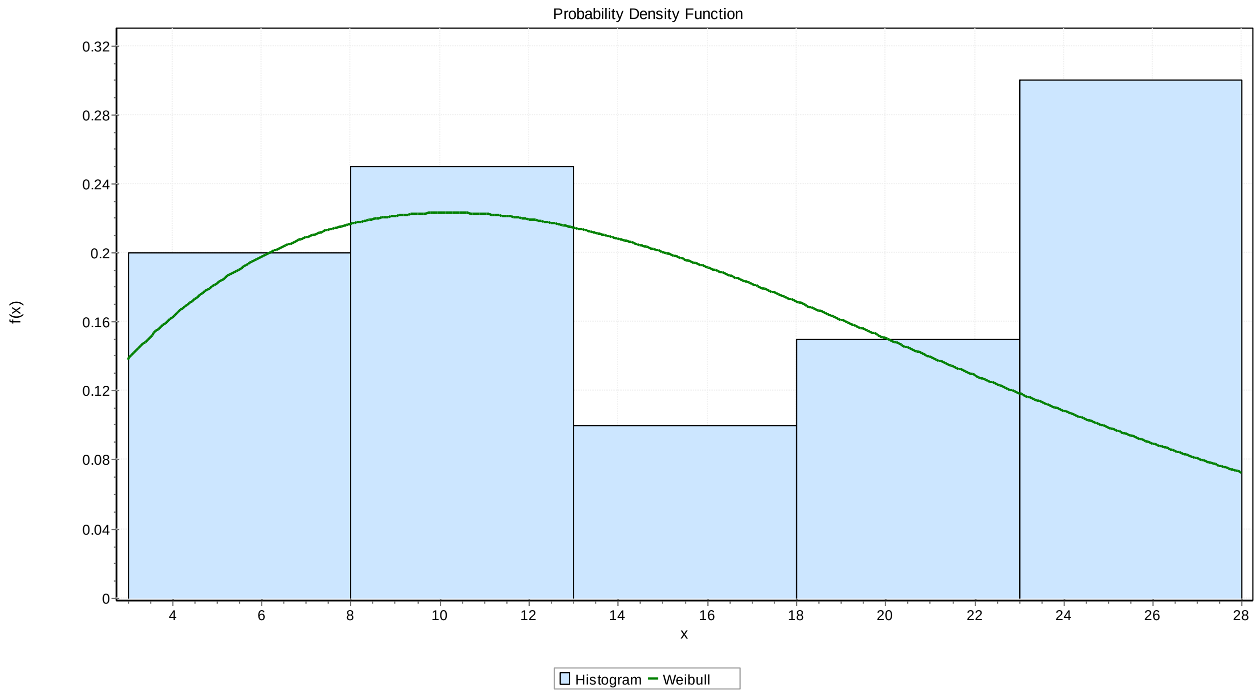

Serial Correllation test of TBF for Signaling Filament
TBF i-1
TBF i
0
5000
10000
15000
20000
25000
30000
35000
40000


Serial Correllation test of TTR for Signaling Filament
TTR i-1
TTR i
0
20
40
60
80
100
120

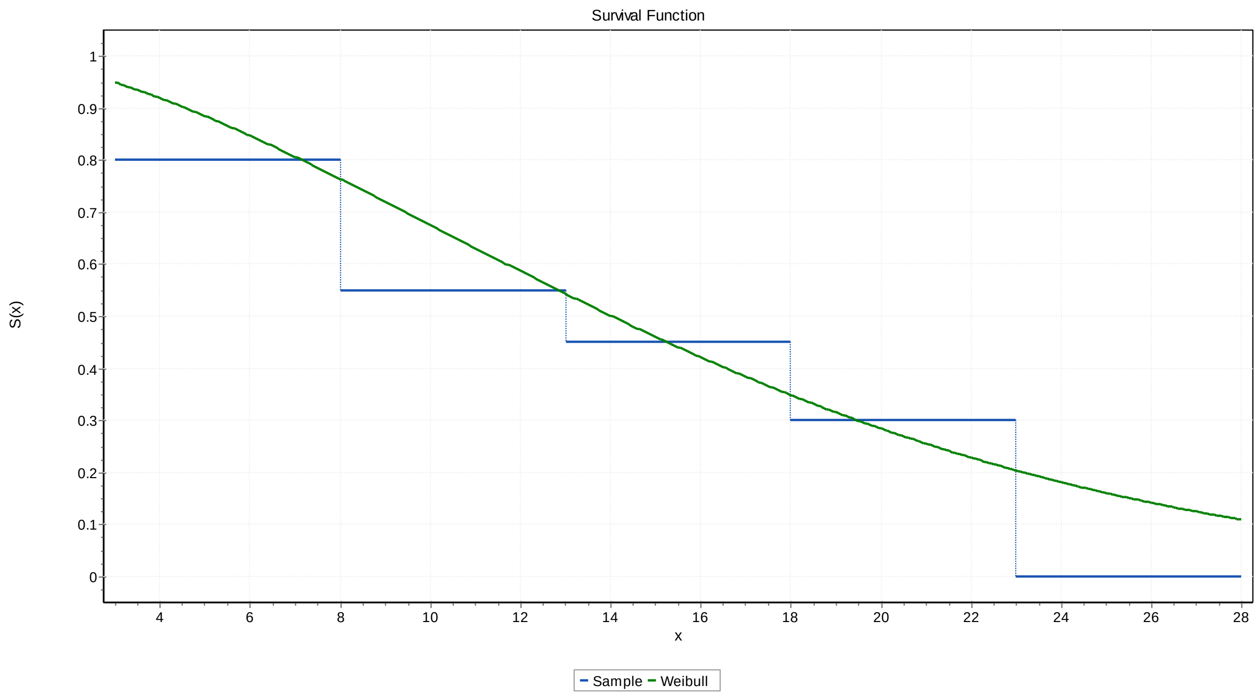

Serial Correllation test of TBF for Switch
TBF i-1
TBF i
0
10000
20000
30000
40000
50000
60000


Serial Correllation test of TTR for Switch
TTR i-1
TTR i
0
20
40
60
80
100
120
140
160

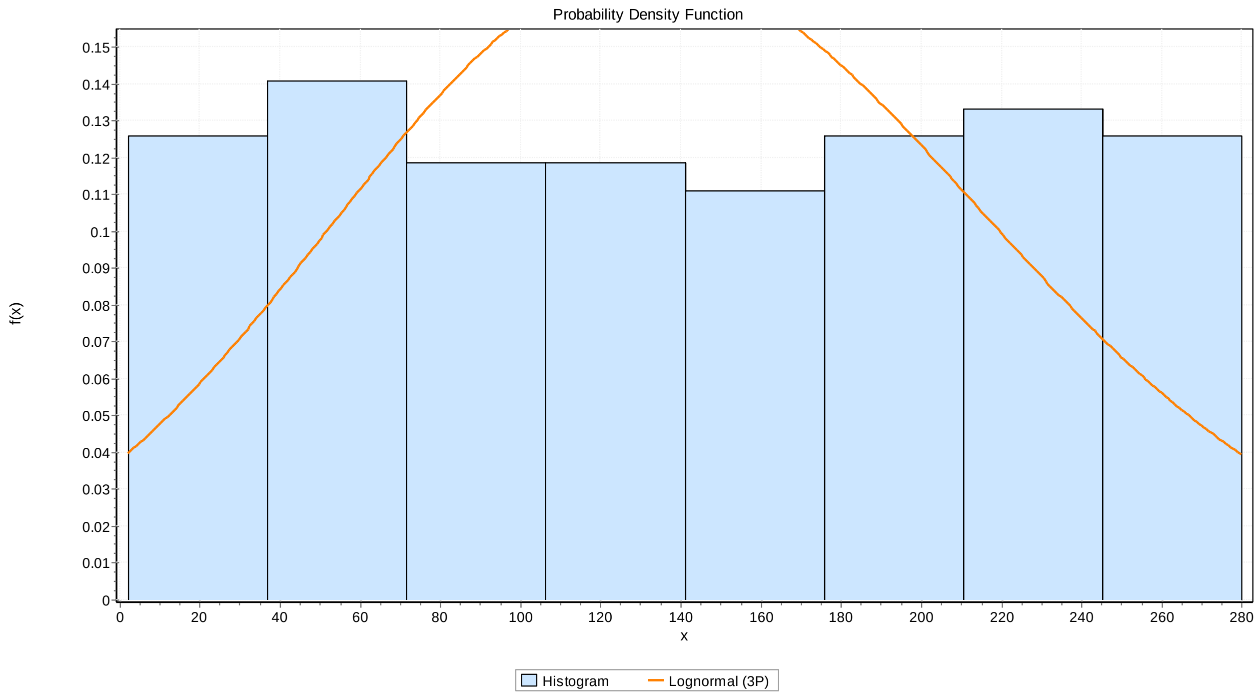
APPENDIX IV: Best Fit PDF and Survival Function for TBF



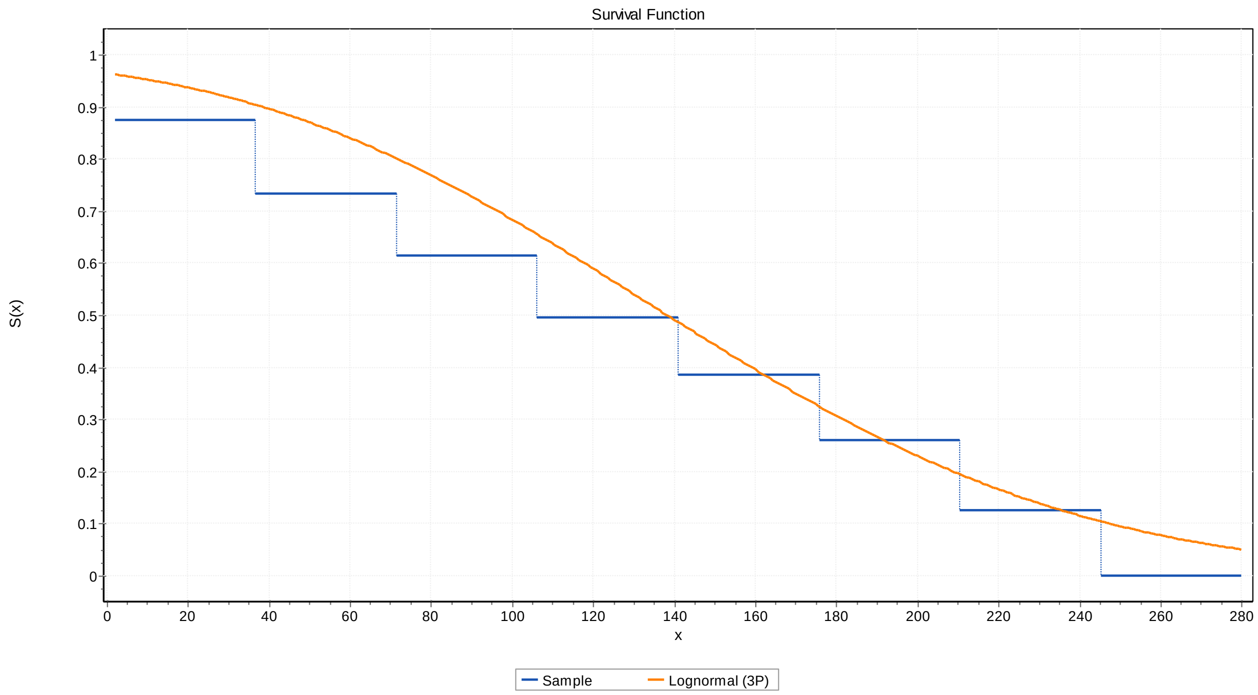
(a) Probability Density Function for TBF of ATP



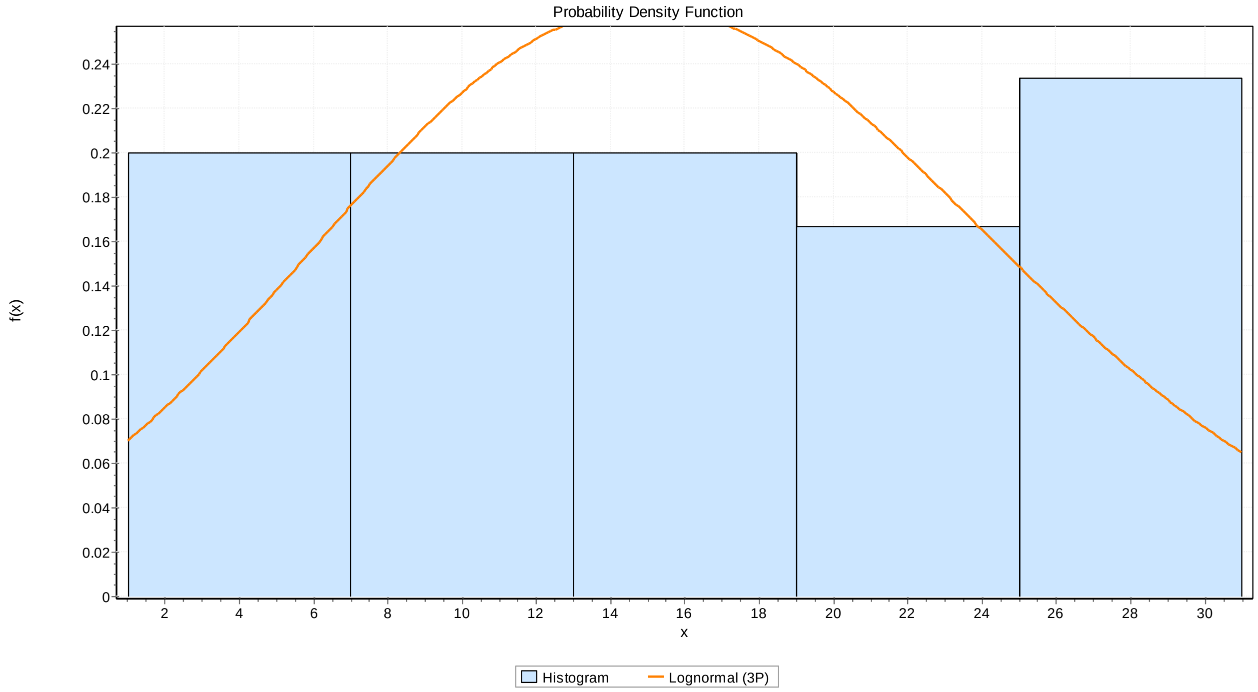
(b) Survival Function for TBF of ATP



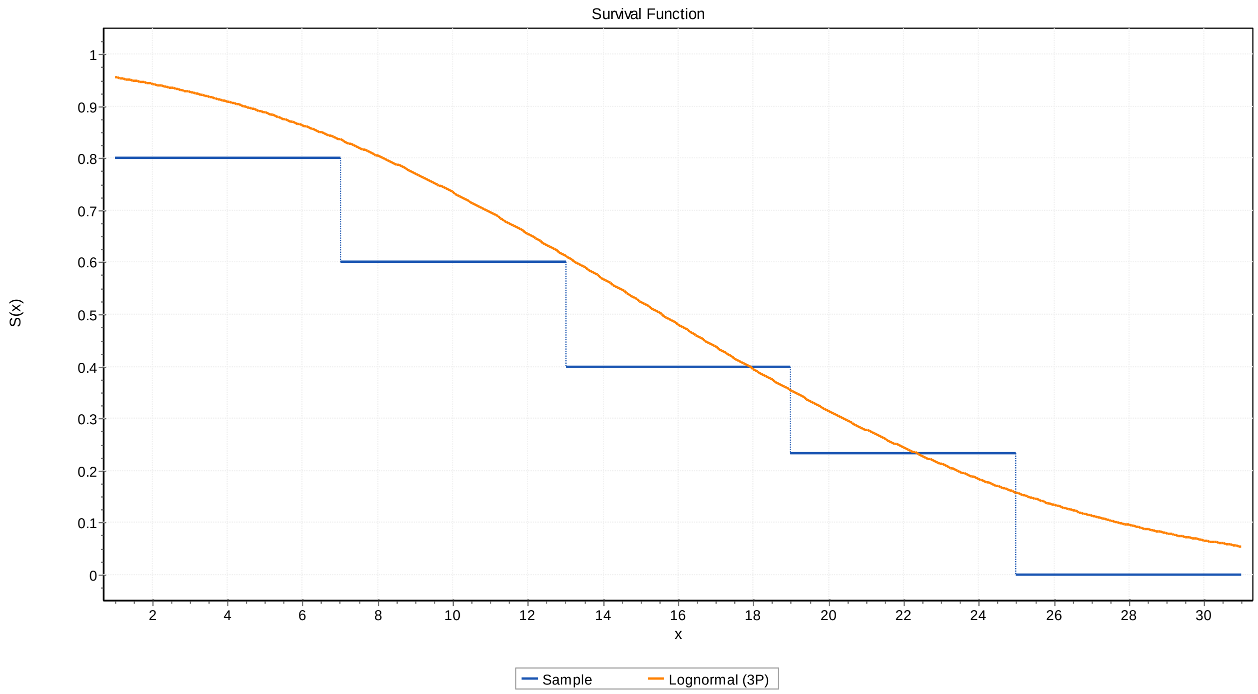
(a) Probability Density Function for TBF of Axle Counter



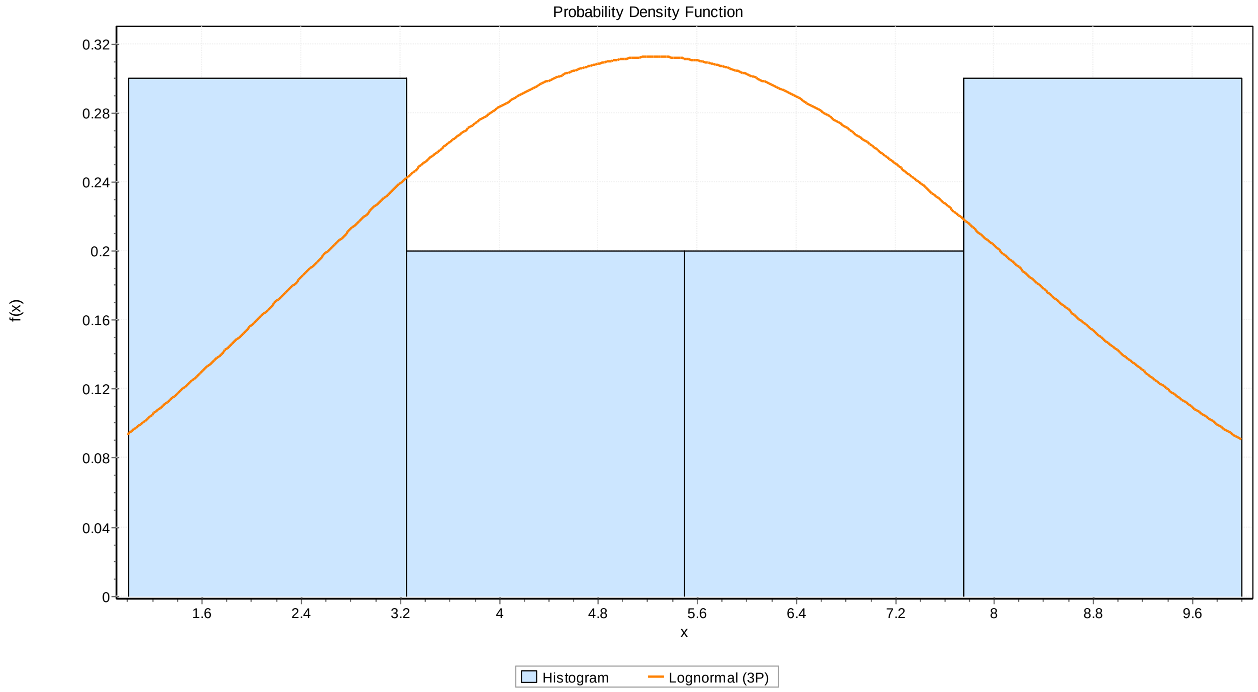
(b) Survival Function for TBF of Axle Counter



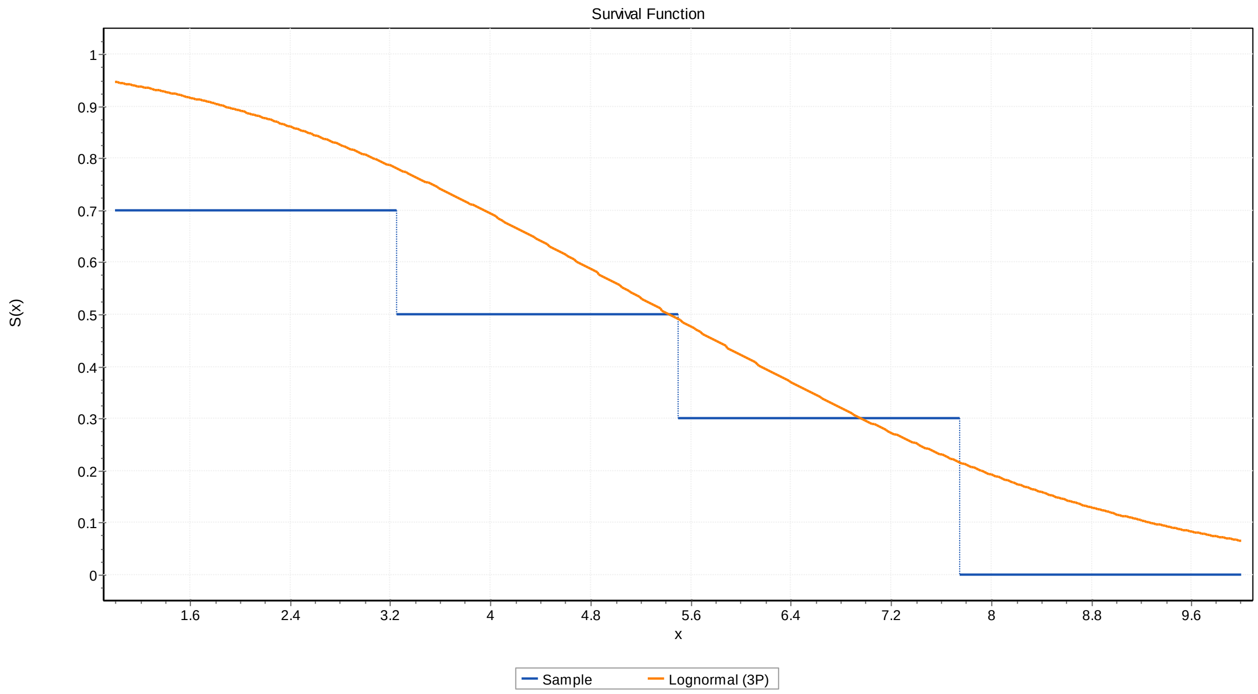
(a) Probability Density Function for TBF of Signaling Filament



(b) Survival Function for TBF of Signaling Filament

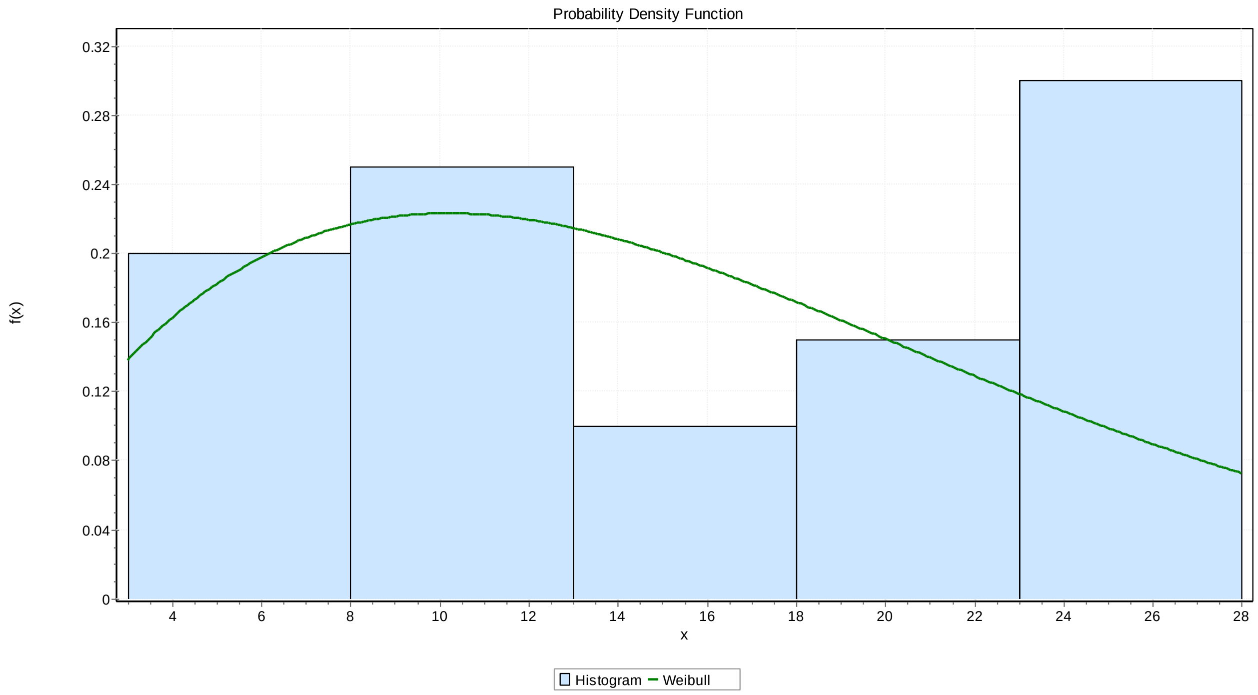


(a) Probability Density Function for TBF of Switch

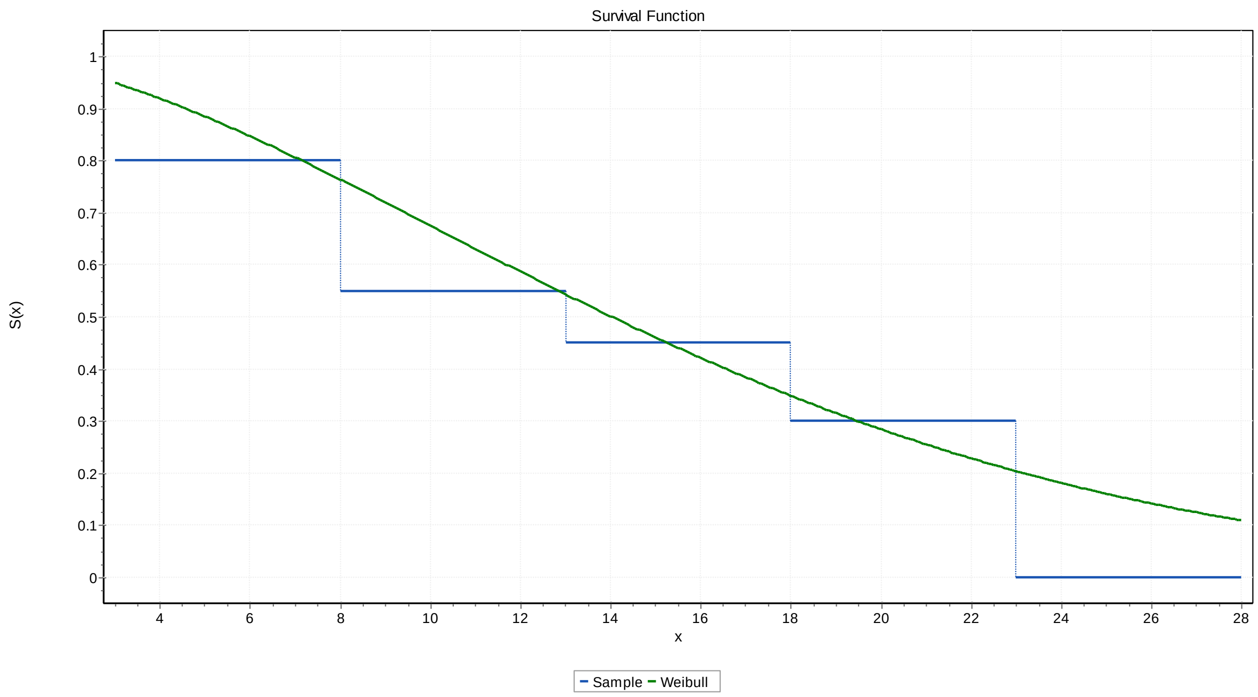


(b) Survival Function for TBF of Switch

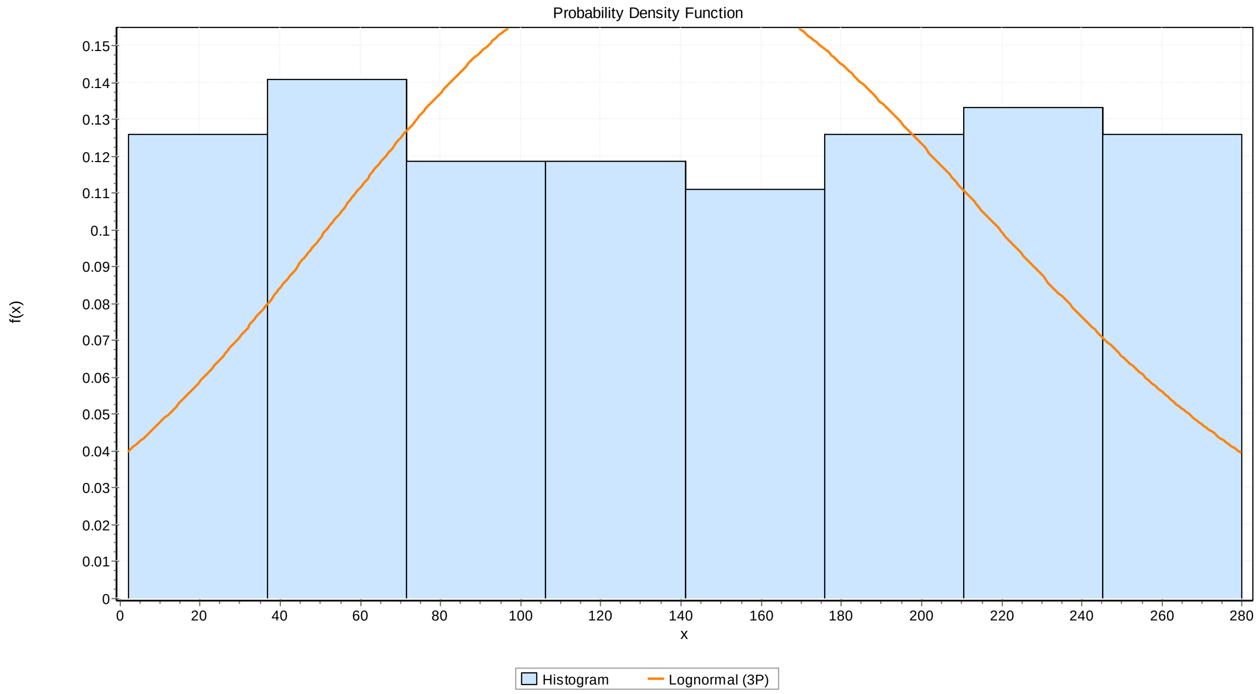
APPENDIX V: Best Fit PDF and Survival Function for TTR



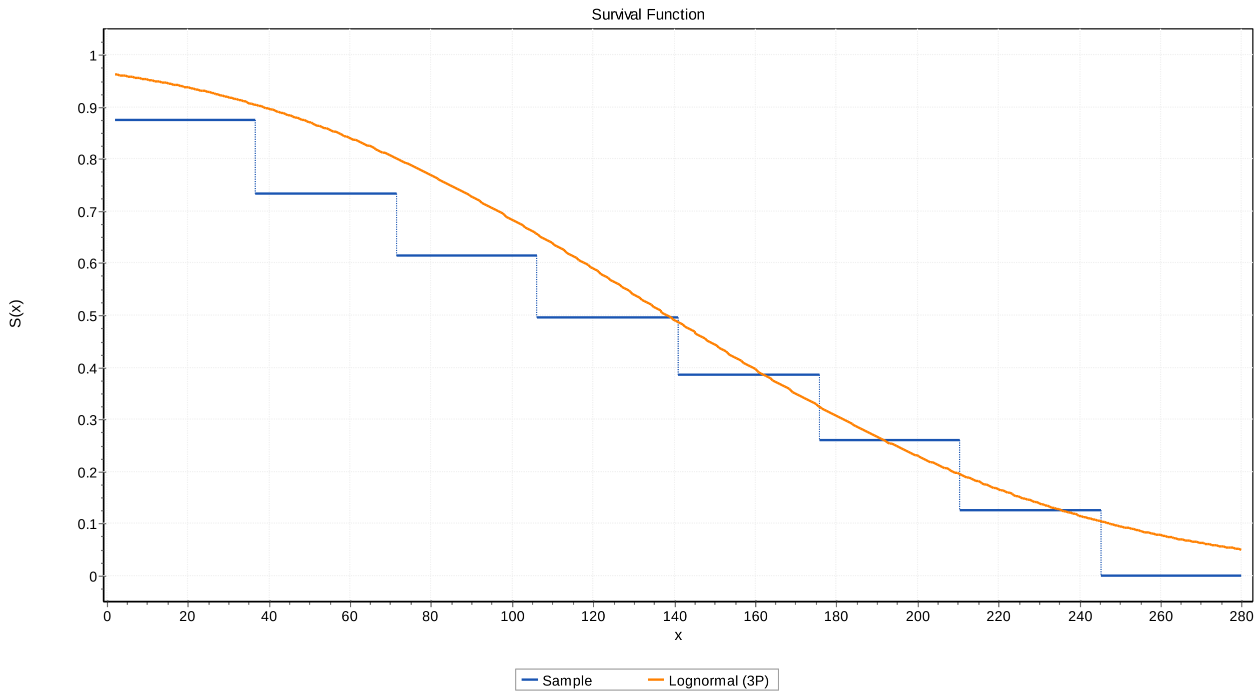
(a) Probability Density Function for TTR for ATP



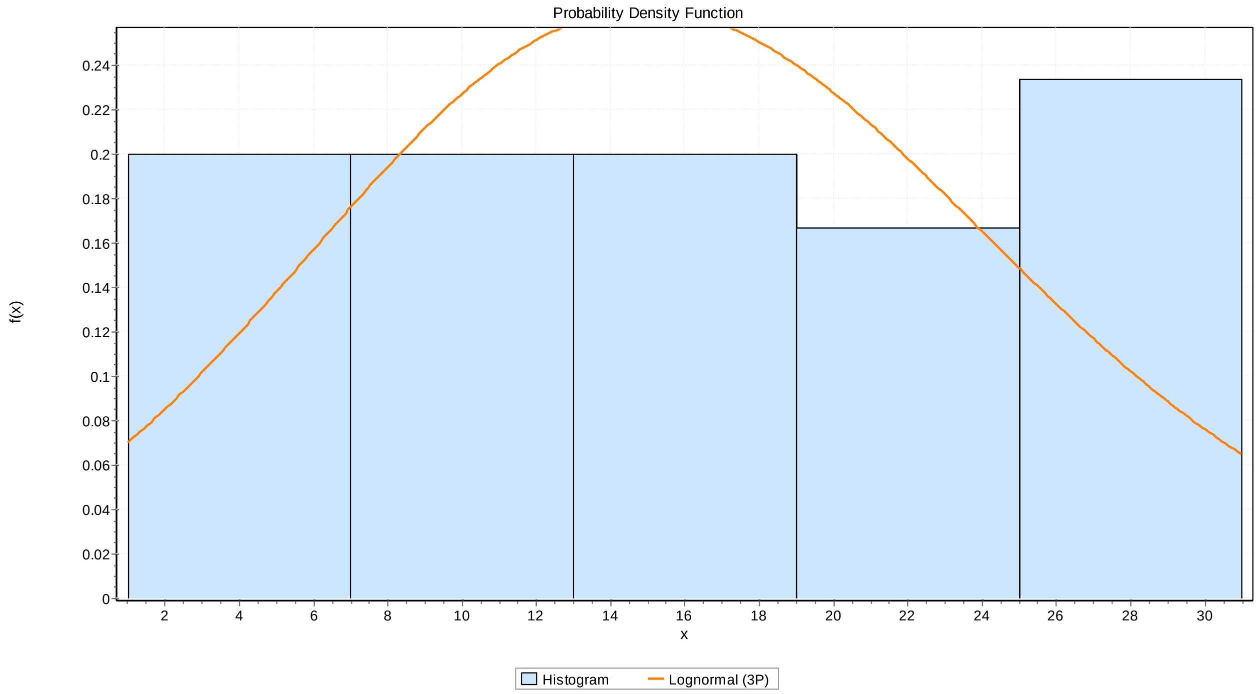
(b) Survival Function for TTR for ATP



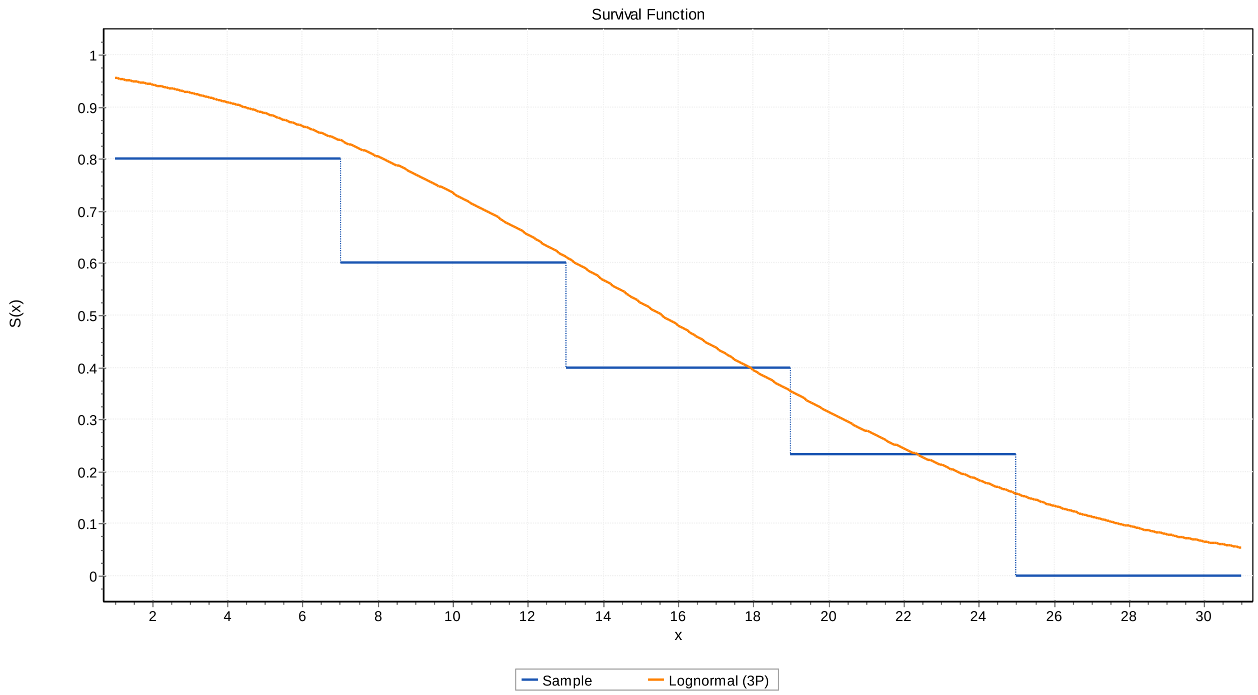
(a) Probability Distribution Function for TTR for Axle Counter



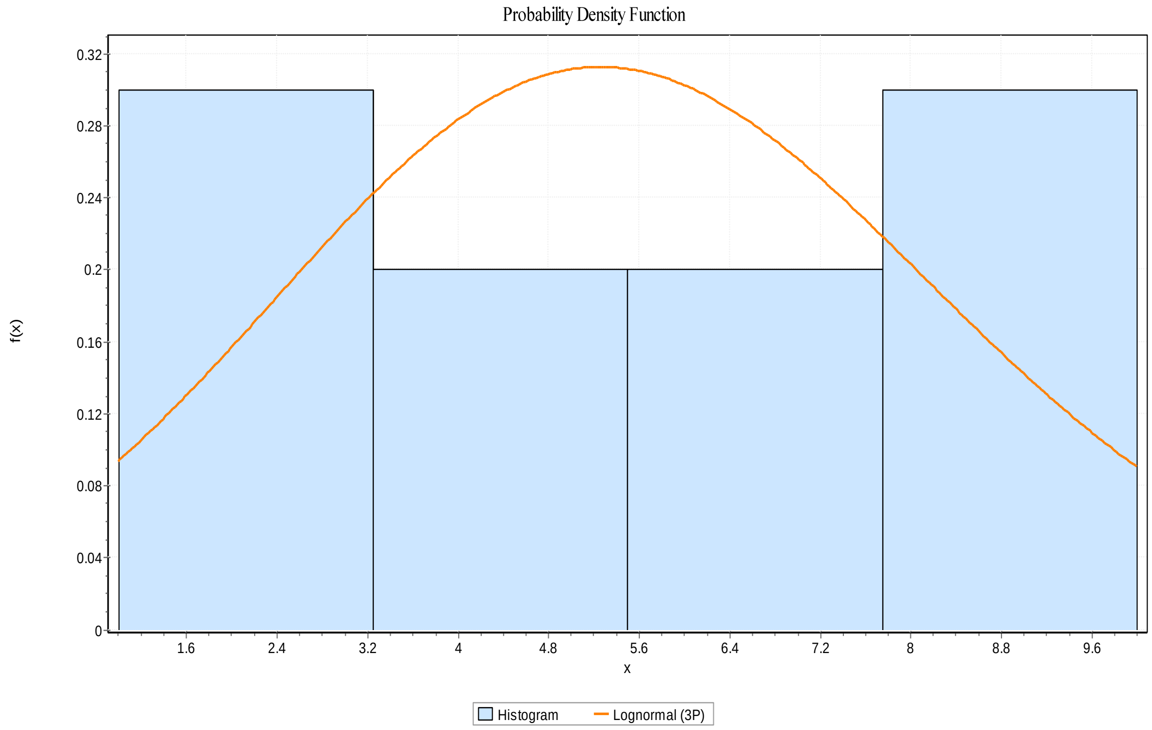
(b) Survival Function for TTR for Axle Counter



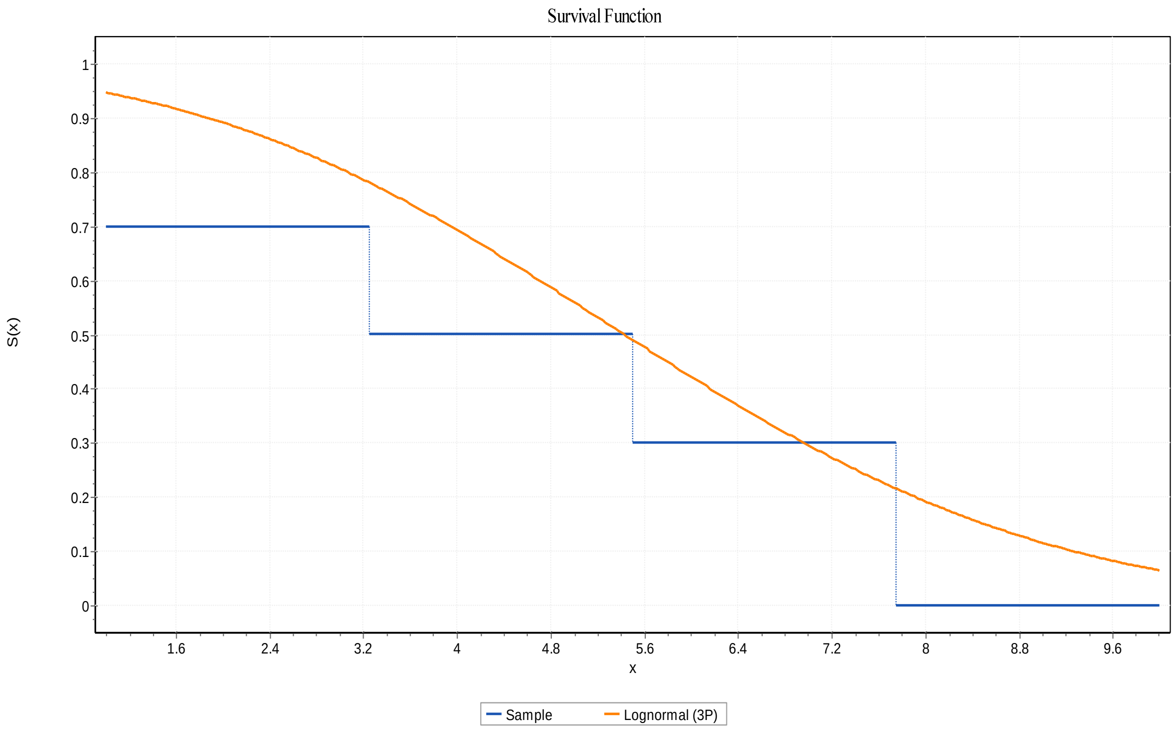
(a) Probability Density Function for TTR for Signaling Filament



(b) Survival Function for TTR for Signaling Filament



(a) Probability Density Function for TTR for Switch



(b) Survival Function for TTR for switch