Addis Ababa University
Addis Ababa Institute of Technology
African Railway Center of Excellence

Risk Assessment of the Light Rail Train Braking Systems by Failure Mode, Effects and Criticality Analysis (FMECA): A Case Study of Addis Ababa Light Rail Train

A Thesis Submitted to Addis Ababa Institute of Technology, Addis Ababa University, In Partial Fulfillment for the Degree of Master of Science in Railway Engineering (Rolling Stock)

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Approval

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DECLARATION

I, the signatory, declare that this thesis research is entirely my work, that it has not been presented for a degree at this or any other university, and that all sources of materials utilized in the thesis have been adequately acknowledged.

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Mpiima Isaac
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ABSTRACT

Many light rail train accidents have occurred in recent years despite the development of modern design technology and better safety standards implying there will always be some risk associated with the system. This has been attributed to many reasons, and one of the major contributions is system failures. System failures are normally related to maintenance methods and implementation by an organization. These system failures can prove to be costly and have very high safety-related consequences that may lead to catastrophic events. However these can be eliminated/minimized through selection of effective maintenance practices. Many systems, such as the traction system, the braking system, etc. are utilized in light railway trains, and each system must perform its function effectively and efficiently. This research focused on the braking system due to the identified accumulated minor failures and its crucial role in human mass transportation. The main goal of this thesis research is to identify the most risky components of the light rail braking system using the Failure Mode Effects and Criticality Analysis approach. This approach determines the likelihood of failure, severity, and failure mode detectability and assigns a numerical score to each failure mode to obtain the Risk Priority Number, which is a product of these three ratings. Most Current Failure Mode Effects and Criticality Analysis methods use the risk priority number to evaluate the risk of failure and suggest a maintenance practice. This thesis study makes a significant contribution by proposing a maintenance selection model based on the acquired risk findings and an estimated maintenance repair cost due to component failure utilizing the fuzzy logic mat lab tool. This model aimed to assist in decision-making for maintenance practices of light rail systems. Data was gathered from the Addis Ababa light rail transit using prior failure record analysis, an unstructured interview, and a research questionnaire. 42 failure modes, 22minor events (do not reduce adhesion), 20 major events (reduce brake adhesion) mainly observed on the mechanical components were detected throughout the assessment. The failure assessment revealed that brake pads among other components possess a high risk for the braking system. As obtained by the proposed model, condition-based maintenance and total productive maintenance are suitable for the safety of the light rail braking system.

Keywords: Risk assessment, train braking system, fuzzy logic, maintenance strategy, Failure Mode, Effect and Criticality Analysis (FMECA)

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NOMENCLATURE

AALRT – Addis Ababa Light Rail Trail

BM – Breakdown Maintenance

CBM – Condition-Based Maintenance

CAN – Cable Area Network

CCU – Central Control Unit

DU – Design Upgrade

DDU – Driver Dashboard Unit

ED – Electro-Dynamic

EH – Electro-Hydraulic

EMU – Electric Multiple Units

FMECA – Failure Mode Effects and Criticality Analysis

FTA – Fault Tree Analysis

HCM – Hydraulic Control Module

HU – Hydraulic Unit

HAZOP - Hazard Operability Analysis

I/O – Input/output

MTB – Magnetic Track Brake

PRA – Probabilistic Risk Analysis

PSM – Pump Control Module

RPN – Risk Priority Number

TPM – Total Productive Maintenance

TCU- Traction Control Unit

VCU – Vehicle Control Unit

CHAPTER 1

1.0 Introduction

1.1 Background

As awareness of the need for safety has grown, system safety has evolved into a mature engineering discipline that has been implemented in a variety of industries. Public transportation networks are being consistently indicated as a key player to ensure sustainable, affordable, and high-quality mobility in urban areas these include buses and light rail trains[1]. In the railway industry, safety engineering has been used to safeguard the safety of passengers, rail infrastructure, and the environment. Light railway trains are made up of several systems, each of which must perform its assigned function as successfully and efficiently as feasible. As a result, failure of any of the systems might result in minor or major consequences in terms of safety and repair costs. Many light rail train accidents have occurred in recent years because of system failures, which include the Malaysian Light Rail Transit incident where the event was caused by a malfunction of a door shut confirmation device, according to the Transport Ministry. However, whether the fundamental reason was inadequate maintenance or a failure to follow normal operating procedures when dealing with technological difficulties remains to be determined after further investigation.[2], [3]. Even though new technology and higher safety standards are continuously being implemented, accidents still do occur. There will always be some danger, but it may be decreased by removing the fundamental causes. These factors need an appropriate maintenance strategy to regulate inspection frequency optimization and/or skill and efficiency enhancement.[4].

Various studies on the failure processes of railway infrastructure assets, including tracks, sleepers, bridges, signaling systems, electrical units, brakes, etc[5] are now being conducted by many researchers to improve railway safety. Increasing safety and efficiency of systems can be obtained through the optimization of maintenance tasks, changes in the system design, or the development of new maintenance techniques. However, changes in the system design or development of new maintenance techniques always require additional expenditures implying that the optimal way to prevent is to prevent failures through analyzing the consequences of failures and suggest relevant maintenance tasks[6]. According to Guangzhou Rail Transit's operational failure statistics, the bogies (33.3 percent) and the braking system (16.7 percent) have the greatest failure frequency among the various failures in the vehicle.[7].

Risk assessment is described as analyzing the risks posed by a hazard, taking into consideration the effectiveness of any existing controls, and determining whether the risks are acceptable. Risk management has become increasingly important for railway companies safeguarding their passengers and employees while improving safety and reducing maintenance costs[8]. The risk assessment approaches now in use in the railway are comparably mature tools based on PRA, such as event tree analysis, consequence analysis, fault tree analysis, Monte– Carlo simulation, and comparable fatality analysis. These tool's effectiveness is strongly dependent on the availability and quality of risk data[8]. In this study, the author adopted the use of the failure mode effects and criticality analysis (FMECA) method for risk assessment. Failure Modes, Effects and Criticality Analysis (FMECA) is an assessment method designed for identifying potential failure modes for a product[11], catastrophic, critical and safety-related failure possibilities so they can be eliminated or minimized through design changes[12], operating, inspection, or maintenance strategies to reduce the severity of the effect of specific failure modes[13]. During the design of most engineering systems, a functional FMECA is always used to suggest a maintenance plan to be followed by analyzing the functions of each component, the predicted failure, and life duration. However, after operating any mechanical system for a particular amount of time, the expected failure rate may fluctuate or differ from the manufacturer's anticipation. This calls for an assessment to identify this variation and understand its safety related impact. The FMECA method was selected by the author for risk assessment due to its ability to identify system risky components based on past and projected failures guided by the availability of past system failures, system operators and the systems maintenance team to improve system/component safety. As a result, the application of the FMECA appears to be more appropriate for risk assessment of a system that has been operational for a specified amount of time. Most Current Failure Mode Effects and Criticality Analysis methods use the risk priority number to evaluate the risk of failure and suggest a maintenance practice. This thesis study makes a significant contribution by proposing a maintenance selection model based on the acquired risk findings and an estimated maintenance repair cost due to component failure utilizing the fuzzy logic mat lab tool. This research presents a risk assessment of the light rail braking systems with a case study of Addis Ababa light rail braking system to provide support in maintenance decisions.

1.2 Problem Statement

Many light rail train accidents have occurred in recent years despite the development of modern design technology and better safety standards implying there will always be some risk associated with the system. This has been attributed to many reasons, and one of the major contributions is system failures. System failures are normally related to maintenance methods and implementation by an organization. These system failures can prove to be costly and have very high safety-related consequences that may lead to catastrophic events. Light railway trains are made up of several systems, each of which must perform its assigned function as successfully and efficiently as feasible. As a result, failure of any of the systems might result in minor or major consequences in terms of safety and repair costs. Increasing system safety and efficiency can be accomplished by optimizing maintenance activities or modifying the system design. Changes in system design, on the other hand, always involve extra expenditures, implying that the best approach to prevent system failures is through maintenance activities. The goal of this research is to report on the existing risks related to passenger safety within the light rail train systems through a risk assessment and suggest appropriate maintenance means for the light rail maintenance department to eliminate the root causes of the risks. This thesis study makes a significant contribution by proposing a maintenance selection model based on the acquired risk findings and an estimated maintenance repair cost due to component failure utilizing the fuzzy logic mat lab tool. This model is aimed to assist in maintenance decision-making for light rail train systems. The research was carried out at the Addis Ababa Light Rail Transit and focused on the light rail braking system due to the identified accumulated failures and its crucial role in human mass transportation.

1.3 Research questions

The following research questions were derived from the aforementioned research issue description and drove this study:

1. What are the different types of brake failure and how do they affect the light rail train braking system?
2. What is the root cause of each identified probable failure mode, and how frequently does it occur?
3. How, when, and where can we detect this cause?
4. What is the connection between the risk of component failure and the cost of component maintenance?

1.4 Objectives

1.4.1 General objective

The prime objective of this study is to identify the high-risk situations/components associated with the light rail train braking system and suggest preventive/mitigation means to reduce the risk to an acceptable level through appropriate maintenance practices using a maintenance selection model.

1.4.2 Specific objectives

- To analyses, the past failure records of the Addis Ababa light rail train system and select a system with accumulated failures and safety-related issues concerning passenger transportation.
- Use the FMECA approach to assess the risk associated with the selected system component and to identify the most susceptible components of the system.
- To estimate the current maintenance/repair cost per component.
- To propose a maintenance selection model for the different components utilizing the Mat lab fuzzy logic tool.
- To validate the maintenance selection model.

1.5 Research Methodology

This thesis applies the Failure Mode Effects and Criticality analysis using both expert decision and past failure records of the Addis Ababa light rail train braking system to suggest appropriate maintenance practices for the light rail system (braking system). The initial phase in the paper is to explore the light rail system, analyze the past failure records and identify the system with safety-related issues concerning failure (the braking system was selected). The following stage is to determine the various failure modes of the braking system, as well as their causes and consequences. This was accomplished by studying previous failure records, various research articles, journals, and the expertise of LRT maintenance employees. An expert opinion was gained through an interview and a written questionnaire. The RPN was then calculated to determine the risk priority for each component. After getting the RPN, an estimate of the maintenance /repair cost was performed to assess the cost of maintenance due to component failure. The RPN is then compared to the cost using the suggested fuzzy logic maintenance selection model to determine the most cost-effective maintenance plan. . Finally, a conclusion and recommendation with future work will be given at the end of the paper.

1.6 Scope and Limitation of the study

The study was carried out using failure data and expert opinion; however, automatic diagnostic software might provide better root causes of some failure types for a more accurate study. Furthermore, because the Addis Ababa light rail system is still in its early stages, the author relied on expert opinion rather than available failure facts/failure history.

1.7 Significance of the study

This study will help with maintenance planning/decision making for the light rail trains and ensuring the safety of both passengers and rolling stock equipment since it focuses on identifying the most risk components of the light rail train. This study not only shows maintenance managers how to identify risks using the FMECA technique, but it also demonstrates how to choose an appropriate maintenance practice by formulating a fuzzy maintenance selection model which compares RPN and maintenance costs due to failure (Repair cost). The risk assessment approach will also be utilized to initiate and optimize new or redesigned choices and maintenance procedures, as well as to aid in asset management life cycle cost projections.

1.8 Thesis outline

This thesis comprises five chapters, the first of which discusses the thesis's introduction, including background information, problem formulation, aim, methodology, and the research limitations. The second chapter reviews the literature on FMECA and maintenance practices. The third chapter briefly demonstrates how FMECA does a risk assessment, how RPN is acquired, how the maintenance/repair cost due to failure was estimated, the fuzzy logic maintenance selection model, questioner design, and data collection. The fourth chapter describes the results obtained from the risk assessment and fuzzy logic maintenance selection model. The research is concluded in Chapter 5 with suggested recommendations for further study.

CHAPTER 2

2.0 LITERATURE REVIEW

2.1 Introduction

Risk management is becoming increasingly crucial for railway firms to protect their passengers and staff while enhancing safety and lowering maintenance costs[8]. According to current developments, many researchers are interested in studying and analyzing failure causes for railway infrastructure assets such as rails, sleepers, bridges, signaling systems, electrical units, brakes, etc[5]. Organizations today are under tension to continuously improve their capabilities to create value for their customers and improve the cost-effectiveness of their operations, implying that it is necessary to manage the risks associated with railway systems, understand them, and find ways to avoid/minimize these risks. This can be accomplished by doing a risk assessment on railway systems concerning the operating conditions/environment, such that an effective maintenance plan is chosen to guarantee that low failure rates are reached. Maintenance of high-value locomotives and machinery, formerly regarded as a necessary evil, is now regarded as essential to enhancing operational cost-effectiveness and creating additional value by providing better and more innovative services to customers[9]. The term “risk” refers to the combination of the likelihood of occurrence of harm and the consequences of that harm. This risk must be analyzed to assure the safety of people, systems, and the environment.

An awareness of risk is fundamental to the safe administration of any company, but this is especially true in so-called high-hazard industries such as nuclear energy, petrochemical plants, mining, aircraft, and railways. Strong safety managerial methods, along with solid engineering and skilled personnel, can minimize the likelihood of risks occurring to extremely low levels, assuring extremely good overall safety performance of certain industries, such as road transportation[10]. According to Sekulova et. al[11], hazards to passenger safety may be classified into two types: risks that occur during the transit process and risks that occur at the railway station.

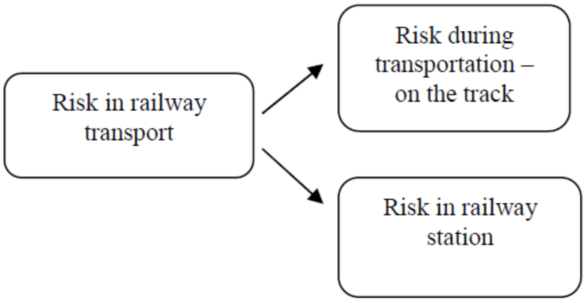


Figure 1: Risk Type Regarding Passenger Safety

Risks during transportation / on the track: These cover all dangers that affect passengers during transportation and may include; Risks caused by the human factor (intentional, unintentional action or negligence, terrorism, vandalism); Risks associated with the nature of railway cars (more specifically, failure of rolling stock systems during operation, the quality of systems utilized, and their availability and reliability); Risks associated with transportation infrastructure (railroad track design features, railway track condition such as wear-related track and corrosion, and economic risk). (These risks occur in such a way as the State interferes in the transport policy of railway undertakings as are: low frequency of train connections, insufficient number of train connections.)

Risks at the railway station: This would include the dangers encountered by travelers in railway stations, such as those induced by human causes (internal employees and external human factors such as crime, vandalism, inadaptable citizens, or terrorism.); Risk deriving from the quality and equipment of railway stations (station design and layout, availability of platforms, passageways, and so on); and Risk of an economic character. (Include human factor or technical equipment of railway stations and others.)

The risk management procedure is done to detect events or possible events, that may influence the achievement of the organization's goals and to maintain the risk at a low/acceptable level. Each organization/industry is vulnerable to certain risks which might seriously disrupt its functioning. Railway transportation is particularly important in this regard as it is a component of the nation's key infrastructure[12]. Risk management as shown in fig.2 has various benefits, including cheaper maintenance costs owing to increased knowledge of failure occurrences, readiness for crisis scenarios, and the selection of security measures suitable to mitigate or eliminate possible losses.

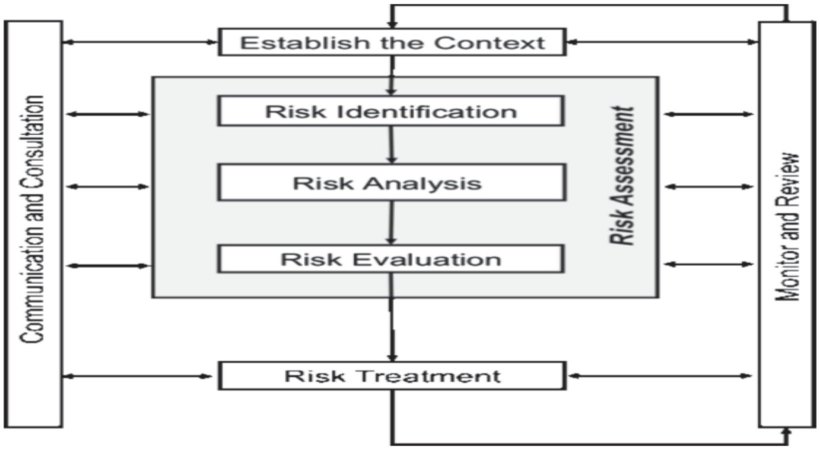


Figure 2: Risk Management Process[13]

The core spine of the risk management process is focused on risk assessment, which leads to risk evaluation and risk treatment. The process starts by defining what the organization wants to achieve during its operations and the internal and external factors that may influence the achievement of those objectives.

2.2 Risk assessment

This is a systematic process that usually involves evaluating the potential risks in a projected activity. ISO 31000[13] defines risk assessment as three steps: risk identification, risk analysis, and risk evaluation. Risk identification refers to the use of a step-by-step approach to understanding what might happen, how, when, and why it may happen. Risk analysis is gaining knowledge of each identified risk related to the project, its repercussions, and the possibility of those outcomes occurring. Risk assessment entails measuring the risk, assessing if it is acceptable, and making a decision. Risk assessment helps to identify risks that offer possibilities as well as risks that represent possible hazards. A risk assessment's principal aspects include ensuring that risk management is consistent and supports the achievement of organizational strategic objectives, providing a high-quality service to customers, initiating actions to prevent or reduce the adverse effects of risk, enabling informed decision-making, minimizing human safety risks, and minimizing all other adverse implications with shortfalls and claims

2.2.1 Risk assessment methods

Risk assessment methodologies might vary depending on the industry, whether it is for general financial choices or for environmental, ecological, or public health risk assessment. There are several methods of risk assessment being used in the railway industry, which can help identify risk, assess the risk appropriately, and help in risk management. Some of these most used methods for risk assessment include:

1. **Failure Modes, Effects, and Criticality Analysis (FMECA)**

Failure Modes, Effects, and Criticality Analysis (FMECA) is a methodology that assists to identify potential failure modes for product[14], catastrophic, critical, and safety-related failure possibilities so they can be removed or minimized via maintenance or design modification[15]. FMECA provides a variety of conceivable failure modes in the system, their causes, local and ultimate consequences that indicate the impact of each recognized failure on the overall system/component operation, and alternative proposed remedial measures to reduce or eliminate each discovered failure[16]. The United States Military created FMECA in the late 1940s as part of a shift from "find failure and fix it" to "anticipate failure and avoid it." On November 9, 1949, "Procedures for performing a failure mode, effects, and criticality analysis" were established[17]. FMECA is defined by Ying Chen et al. as a reliability analysis approach that investigates the probable failure modes inside a system and is often used to improve the dependability of a product/system[18]. The methodology may also be applied throughout the design, production, and process of equipment to examine every failure mode, cause, and effect (find possible weak links and propose improvement methods and design plans) to increase the product's dependability. The FMECA is used to identify failure modes that provide an unwanted and unacceptable risk, to remove or decrease them as soon as feasible by a well-designed rectification maintenance action[19]. Failure mode can be explained as to how an item/component fails to execute its required function. Component failure can happen in many different ways and its failure modes describe all the possible states of component failure. Failure modes might have a considerable or negligible influence on the component's performance/operation. The FMECA determines the likelihood of failure, severity and failure mode detectability and assigns a numerical score to each failure mode to obtain the Risk Priority Number (RPN). The RPN is calculated as the product of these three rankings and shows which component deserves greater attention. The findings of the assessment always represent the system's most risky components, which require more attention.

Many authors have used the FMECA approach for risk assessment in railway systems which include; Kim et. al[20] applied FMECA and concluded that the optimal way to prevent/avoid failures while increasing safety and efficiency is to analyze and evaluate the repercussions of failures to measure the appropriateness of relevant maintenance tasks, giving this method credit and effectiveness for safety analysis. Lu et al.[21] used FMECA to make a Study for the Door System in a High-Speed Train and identified four critical components (driving device, platform compensator, door control unit, and locking mechanism) impacting the high-speed train's door system safety. Liu et al.[22] Conducted a Reliability Test on Metro Door System, which was based on FMECA, using the approach to assess four components with a high failure rate. Twelve failure types were determined to have a crucial influence on the metro door system, and the results were compatible with the experience of field engineers, proving the method's usefulness. Vernez and Vuille[23] proposed a functional failure mode, effects, and criticality analysis (FMECA) technique for optimizing the dependability of large and complex systems (Applied to the railway signaling system). Its application on a commercialized software package also enabled active connectivity across the system's functional levels, facilitating data processing and retrieval and actively contributing to system improvement. Li P et al.[24] Performed an FMECA-based Bogie Failure Mode Analysis on Railway Freight Cars. As the review related to FMECA demonstrates; the various writers employed FMECA methodologies as a risk assessment tool and proposed maintenance practices to mitigate the risk based only on the probability risk analysis. However, in this study, the probability risk analysis was combined with the component failure maintenance/repair cost to suggest a maintenance practice to minimize the risks and this was using fuzzy logic.

FMECA Analysis Procedure

(1) ***System understanding:*** this is the first and most crucial part of the risk assessment process. The system (braking system) to be assessed has several components that must be clearly understood by the analyst. This involves the functional purpose of each component and its attribute to the system as a whole. Some of the questions to enhance the researchers understanding of the system include;

- What is the purpose of the component on the system?

- Is this component a key component of the system?
- Can the system work without this component?
- How does this component contribute to other component’s performance?

(2) ***Specifying possibilities*****:** This stage focuses on determining potential failure modes in the light rail braking system based on the primary data and secondary data. Different components have different failure modes, which can be mechanical or electrical. The primary data plays a significant role in the identification of these potential failures concerning the system under assessment since it reflects the real-life failures of the system under the defined operating conditions. In this research, the failure modes were divided into two i.e.;

- Minor events/fault messages; represent events that do not reduce the brake force substantially and normally show for only maintenance and diagnosis. These events are defined as operational failures and can be cleared by the operator since they have no safety issues at the instant
- Major events; represent events that lead to a loss of friction brake force (serious fault). These call for an immediate response from the train operator, as they cannot be ignored. These events may call for the activation of security/ emergency braking.

(3) ***Specifying root causes:*** the root cause is the spark-off factor for the potential failure of the component. This is normally identified by carrying out interviews with experienced personnel concerning maintenance, design, and operations and the interview questions include;

- What caused the failure of the component/system?
- Was it possible to identify the fundamental cause?

(4) ***Quantifying the risk:***

This stage involves ranking/quantifying the severity of effect, the occurrence of failure, detection (effectiveness of controls to prevent cause), and determining the risk priority number. Severity (S); the effect of the failure can have high/low consequences on the passengers, rolling stock, and the environment thus in this study, the severity effect is ranked on a scale of 1-10 as shown below[25];

Table 1: Criteria for Ranking Severity

Criteria for ranking severity	**effect**	**rank**
Failure occurs without warning	Deadly	10
Failures occur with a warning	Hazardous	9
System inoperable, with loss of function	Very serious	8
System operable but with loss of performance	Serious	7
System operable but with loss of performance	Moderate	6
System operable but with low effect on performance	Low	5
Noticeable effect on the operation	Very low	4
Discernible impact on the operation.	Minor	3
No influence on the operation.	Very minor	2
No effect on the operation	none	1

Detection (D) is the ability of the action or process of identifying the presence of something concealed. It will involve monitoring the nature/performance of a component during operation. It may involve the use of sensors for visual monitoring by personnel. In this research, we shall scale from 1-10 the level of detectability ie the ability to detect a propagating event leading to failure as shown below.

Table 2: Detection Ranking

Chances of detection of failure mode	**Rank**
No known controls are available	10
Very remote detection chances	9
Remote chances of detection	8
Very low detection chances	7
Low chances of detection	6
Moderate chances of detection	5
Moderately high detection chances	4
High detection chances	3
Very high detection chances	2

Almost certain to detect	1

Rate of Occurrence of failure (O); this is based on how often the failure of a given component occurs per year as shown below;

Table 3: Occurrence Ranking

Occurrence	**Failure rate**	**Criteria**	**Rank**
Very high	>1 in 2	Failure is nearly unavoidable.	10
	1 in 3		9
High	1 in 8	Repeated failures	8
	1 in 20		7
Moderate	1 in 80	Occasional failures	6
	1 in 400		5
	1 in 2000		4
Low	1in 15000	few failures	3
	1 in 150,000		2
remote	<1 in 1,500,000	Failure is unlikely	1

(5) ***Correcting the high-risk causes***

In this stage, the failure modes according to the level of their criticality are categorized in order of risk priority number. **RPN** is the product of the ranks of severity, occurrence, and failure detection chances. For each component of the system, the RPN is calculated and the components that will possess a high RPN are declared more critical and requires more attention in terms of monitoring and maintenance. Carrying out FMECA requires the analyst to understand that RPN ratings are relative to a given analysis and never to relate the RPN to another analysis as it’s always different due to the variation in working conditions and environment[4].

$$\boldsymbol{RPN = S \times O \times D}$$

2. Fault tree analysis (FTA)

This is a top-down method of failure analysis that begins with a probable unwanted occurrence/accident known as a TOP event and then determines all of the possible outcomes. The analysis proceeds by determining how the TOP event can be caused by individual or combined lower-level failures or events. The causes of the TOP event are "connected" through logic gates. The starting point of an FTA is often an existing FMECA and a system block diagram [26]. FTA is reliable when analyzing new system designs for which no historical data exists. Wolfe et. al[27] states that this method has a limitation that the fault tree for complex systems is hard to construct and the correlations between basic events (e.g. failure of components belonging to the same batch) are difficult to model and exact solutions to correlated events do not exist. Authors have used this method to analyze risks in railway systems eg; Ming et. al[28] used the fault tree analysis to analyze derailments in urban transit trains.

3. Hazard operability analysis (HAZOP)

Hazard and Operability Analysis (HAZOP) is a structured and systematic technique for system examination and risk management for identifying potential hazards in a system and operability problems likely to lead to nonconforming systems. It is based on a theory that assumes risk events are caused by deviations from design or operating intentions[29]. The HAZOP is made up of a team of specialists with various experiences and skills who are brought together during HAZOP meetings to conduct a complete evaluation of the process under consideration through a collaborative brainstorming effort that promotes creativity and new ideas[30]. Jong et. al[31] carried out a hazard Identification of the railway signaling system using the HAZOP Method

Many other techniques and concepts for risk assessment have already been suggested as the awareness of safety in railway transportation have grown, including safety checklists, safety analysis, and evaluation methods, human inferential statistics, and classification scheme utilized on UK rail safety, six-stage safety, risk index evaluation methods, and artificial neural networks[5]. On analysis of the risk assessment methods, none of the assessment methods incorporates the component failure cost, which is crucial to the system during maintenance decisions. In this research, the FMECA was selected for the risk assessment as it provides the analyst with the opportunity to assess the past failures and the projected future failures with the actual real-life events/failures of a system operated under a given environment and after a given period. Additionally, other risk assessment tools rely on the FMECA data analysis.

2.3 System Failure Analysis

Systems failure analysis is a study into the possible reasons and circumstances for nonconformance towards system performance criteria, or the system failure to attain its design criteria. Systems failure analysis is carried out to identify the causes of this nonconformance to propose relevant preventive/corrective actions. Analyzing a failure can be related to rewinding a movie, looking for the reasons for what happened after the story. However, in reality, analysis, there is no record of all the events at his or her disposal. Although the investigation can bring to light most of the history, quite often some parts of it remain unknown[32]. As shown in Fig. 4, system analysis has three levels of structure: subsystem, component, and system. Similarly, the system's functional structure is divided into three levels: component function, system function and. subsystem function. The components are the beginning point/foundation of the actual system structure. The performance of any system function is based on the capability of each component to perform its respective functions as per the design. Component faults often arise during the system operational stage and can lead to operational breakdowns at the component level of the system's functional structure. These functional failures penetrate a system, subsystem, and management barrier, ultimately leading to an accident or incident. Barriers may be regarded as physical systems, subsystems, and human actions based on specified procedures or administrative controls and are intended to prevent/minimize/limit the frequency of events[33]. The functional failures upgrade from component to subsystem level and then to the system level. As functional failures upgrade/increase, system safety decreases.

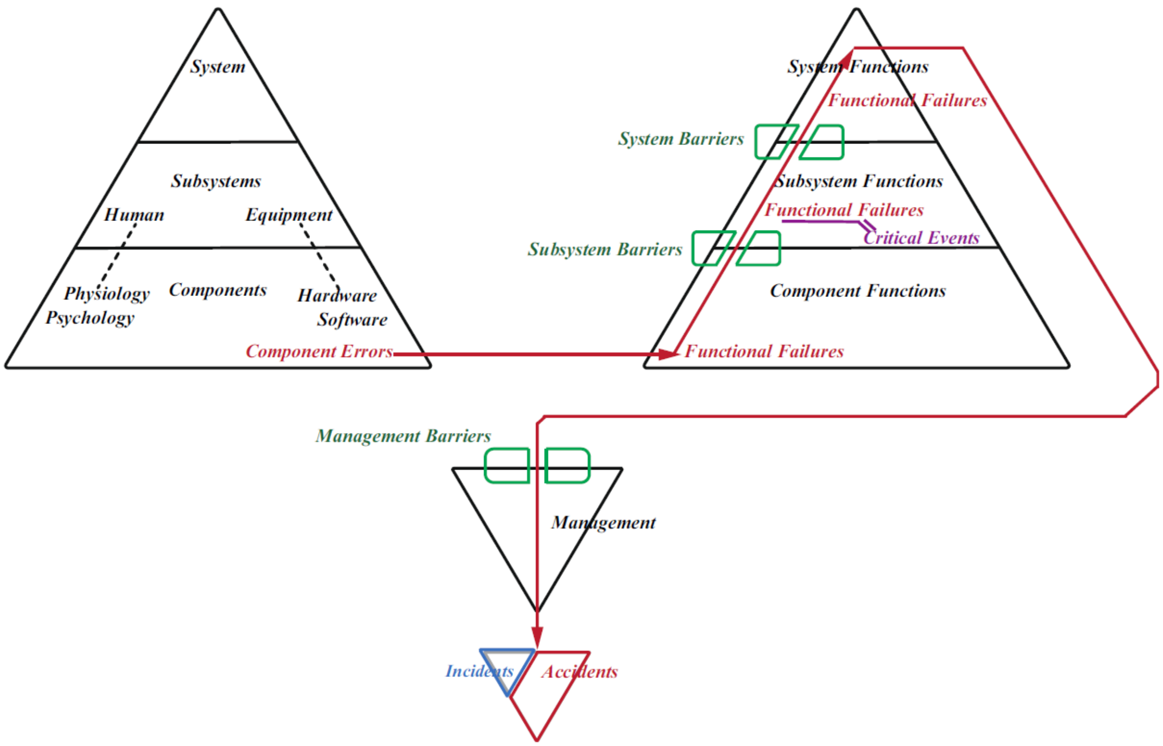


Figure 3: Systems Analysis

2.4 Train Braking System

The train braking system is an essential mechanism in train control that is used to slow or stop the train in the shortest amount of time and distance feasible. The train brakes are used on coaches/trains to enable deceleration, controlling acceleration usually along downhill, or to keep them standing while parked[34]. Noor et. al[1] indicate that controlling the train speed is a significant factor to railway safety ie rolling stock or traction fault/failure may lead to train speed violation resulting in railway accidents through various ways such as overshooting during stops, skidding, collision, and overturning of trains. There have been a few attempts to define and develop the elements and critical sections of the train's braking system, thus we must pay more systematic and active attention to this braking mechanism, which plays a critical role in human mass transit safety[35].

2.4.1 Ababa Light Rail Train Braking System analysis

The AALRT braking system design is for a maximum speed of 70 km/h. The vehicle is equipped with 2 motor bogies and 1 trailer bogie each fitted with different brake systems:

- Electro dynamic (**ED**) brake system in a motor bogie, controlled by TCU
- Passive step-less electro-hydraulic (**EH**) friction brake system in trailer bogie, controlled by BCU
- Passive 3-step EH friction brake system in a motor bogie, controlled by VCU via HCM
- Magnetic track brake(**MTB**) units in each bogie, controlled by wiring and VCU

However, regarding the electrohydraulic brake system, for the motor car, a brake disc is installed on the axle whereas, for the trailer car, each wheel is given a separate brake caliper. The braking system components were categorized in terms of classes for the sub-components as shown in fig.4 ie

- Class 1; braking systems
- Class 2; Class 1 components
- Class 3: class 2 sub-components

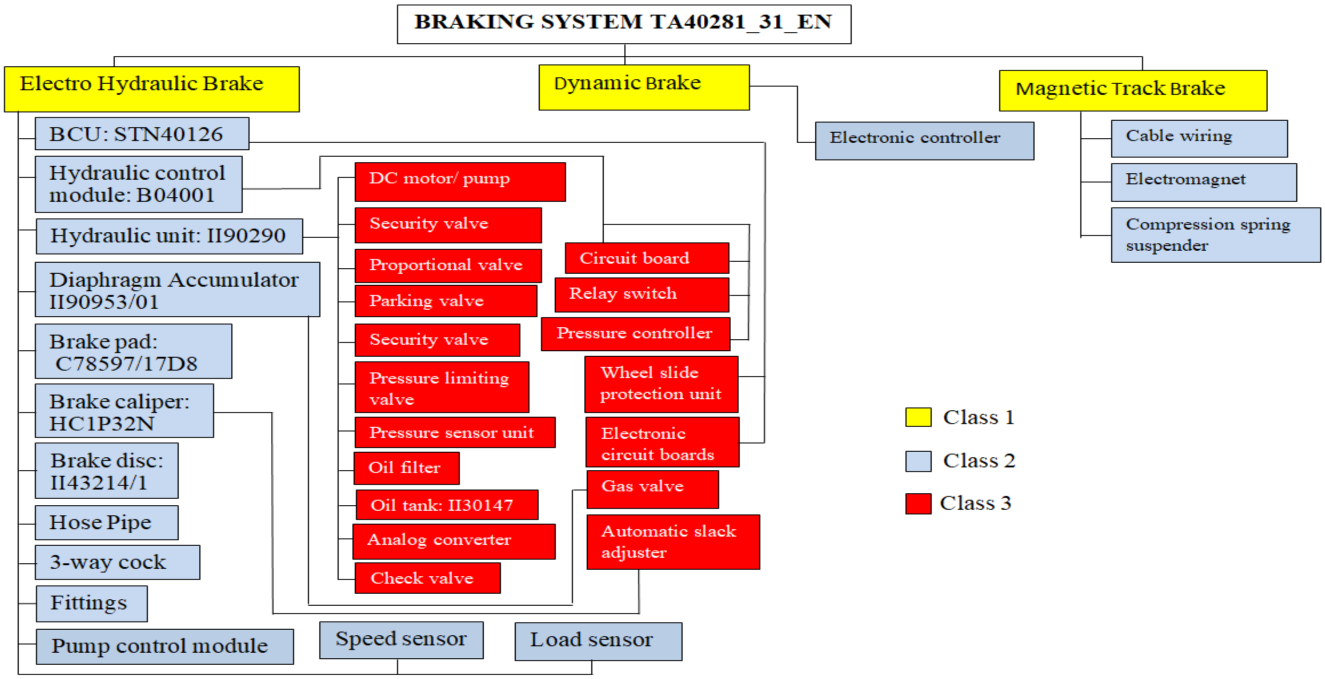


Figure 4: AALRT Braking System Components

a) **ED brake system**

The electro dynamic brake (ED brake) is wear-free thus preferred to be used in the brake system on the vehicle. ED braking is not enough to stop the rolling stock, as its braking effect diminishes so rapidly hence it is always used in conjunction with another braking system i.e. EH and MTB in this case. This combined system is controlled by TCU and participates in the Service brake mode and emergency brake mode. The ED is also referred to as regenerative braking normally used where the load on the motor has very high inertia (e.g. in EMU).

b) EH brake system in motor bogie

EH brake in motor bogie is controlled by the vehicle control unit (**VCU**) via I/Os and will be used if the ED brake of the specific bogie fails. It will also be used during the stopping brake phase, holding brake phase, and parking brake. Brake pressure can be adjusted in 3 steps ie Step 1 for degraded modes (ED-brake failure), Step 2 for stopping brake application at speeds lower than 5 km/h, and step 3 is the maximum braking pressure for holding brake application (equivalent to parking brake force). In the case of a safety brake, an independent safety brake valve in the hydro unit will open and adjust a specific brake cylinder pressure. Parking brake will be activated by an open parking brake valve, together with the safety brake valve; therefore 0 bar brake pressure will be reached. The passive EH brake system in the motor bogie consists of the following main parts:

- HCM: Electronic module for controlling pressure and pump without wheel slide protection. Interface to the vehicle via I/O.
- PSM/ Pump control module: Electronic switch for pump activation and limiting of inrush current
- HGE-28PN: Electro-Hydraulic unit with analog converter, pressure reservoir, safety brake valve, and parking brake valve.
- Mechanical parts (e.g. brake caliper)

c) EH brake system in trailer bogie

EH brake in trailer bogie is controlled by BCU. Brake pressure can be adjusted continuously. In the case of a safety brake, an independent safety brake valve in the hydro unit will open and adjust a specific brake cylinder pressure. Parking brake will be activated by an open parking brake valve, together with the safety brake valve; therefore 0bar brake pressure will be reached. Interface to VCU is done via Controller Area Networks connection and hardwired lines. The passive EH brake system in the trailer bogie consists of the following main parts:

- BCU: Electronic module for controlling pressure and pump. Interface to the vehicle via CAN and I/O, with the function of wheel slide protection (based on bogie level), load correction, jerk limitation.
- PSM: Electronic switch for pump activation and limiting of inrush current
- HGE-28PNL: Electro-Hydraulic unit with analog converter, pressure reservoir, safety brake valve, parking brake valve, and release function.
- Each wheel is equipped with a dual-channel speed sensor.
- Mechanical parts (e.g. brake caliper)

d) Magnetic track brake (MTB)

The MTB is used as an emergency brake that is not dependent on wheel-rail adhesion. The retarding effect of adhesive brakes eg hydraulic friction brakes is significantly impacted by the adhesion between wheel-rail. When a magnetic field is generated, the magnetic rods are magnetically attracted to the rails, and contact friction between the magnetic rod and track rail creates a braking force. They are commonly used during automatic braking and emergency braking. The MTB activates automatically in the case of an emergency brake application and is activated by a push-button on the driver's dashboard. A track brake magnet is an electromagnet or solenoid. It consists of a coil that is wound on an iron core generating a magnetic field when direct current is applied. Soft-iron parts attached to the magnet rule how the induced magnetic lines of force close about the rail head. The MTB brake system consists of an electromagnet and a spring suspension

Brake Mode

I. Service brake

By Electric-Dynamic (ED) brake alone in the motor bogies. This is normally used to decelerate the train during operation and it is not to stop the train but to reduce speed. The train service brake is used by the driver to decelerate the vehicle. The brake demand for service brake comes from the master controller. The train service brake is load corrected, jerk limited, and wheel slide protected. It's normally done by the ED brakes, however, when some ED fail, EH brake will be employed on motor or trailer bogies depending on the different failure cases. The service brake has the lowest priority.

II. Service braking upon 50% failure of ED brake force

- Speed restriction – approx. 45 km/h.
- The remaining ED brake is in the second motor bogie.
- Passive EH brake with load correction and wheel slide protection control in the trailer bogie.
- Passive EH brake with brake force step one, to take over some of the missing ED brakes in the defective motor bogie (without wheel slide control).

III. Emergency braking

The emergency brake is used by the driver in hazardous situations. The emergency brake should decelerate the train as high as possible. Therefore the emergency braking is without jerk limitation but with load correction and wheel slide protection

- ED brake in the motor bogies.
- Passive EH brake with load correction and wheel slide control in the trailer bogie.
- Electro-magnetic track brake in all bogies.
- The emergency brake has a high priority

IV. Emergency braking upon 50% failure of ED brake force

- The remaining ED brake is in the second motor bogie.
- Passive EH brake with load correction and wheel slide protection control in the trailer bogie.
- Passive EH brake with brake force step one, to take over some of the missing ED brakes in the defective motor bogie (without wheel slide control).
- Electro-magnetic track brake in all bogies.

V. Parking brake application

The train parking brake is used to avoid a disarmed train from rolling. The parking brake is activated by the parking brake valves in the EHU of the motor and trailer cars. It is only used at the standstill. There is no separate trigger button for the parking brake, so parking brake will be activated when the vehicle power supply is completely switched off. Spring-actuated EH brake with maximum brake force in all bogies.

VI. Stopping brake application

Stopping brake function assumed in the lower speed range by the friction brake (EH-brake) in the motor bogies with additional braking force by EH-Brake in the trailer bogie according to the vehicle load. Holding brake function assumed at standstill with maximum spring-actuated brake force in all bogies

VII. Security/ safety brake

Engaged driver's push-button or safety loop. The safety brake should decelerate the train until standstill in error cases but not in hazard situations. The safety brake is activated by the safety loop without using the brake control units HCM and BCU. The safety brake is without load correction, wheel slide protection, and jerk limitation. The safety brake has the highest priority. If the safety loop is opened, the security brake valves in the EHU's will be de-energized thus producing a fixed pre-set pressure value in all calipers. This will allow the train to stop without additional ED brakes and electronic control. In case of a malfunction in the safety brake circuit, the same pressure will be set by the analog converters as redundancy. The Electro-magnetic track brake is also active in all bogies

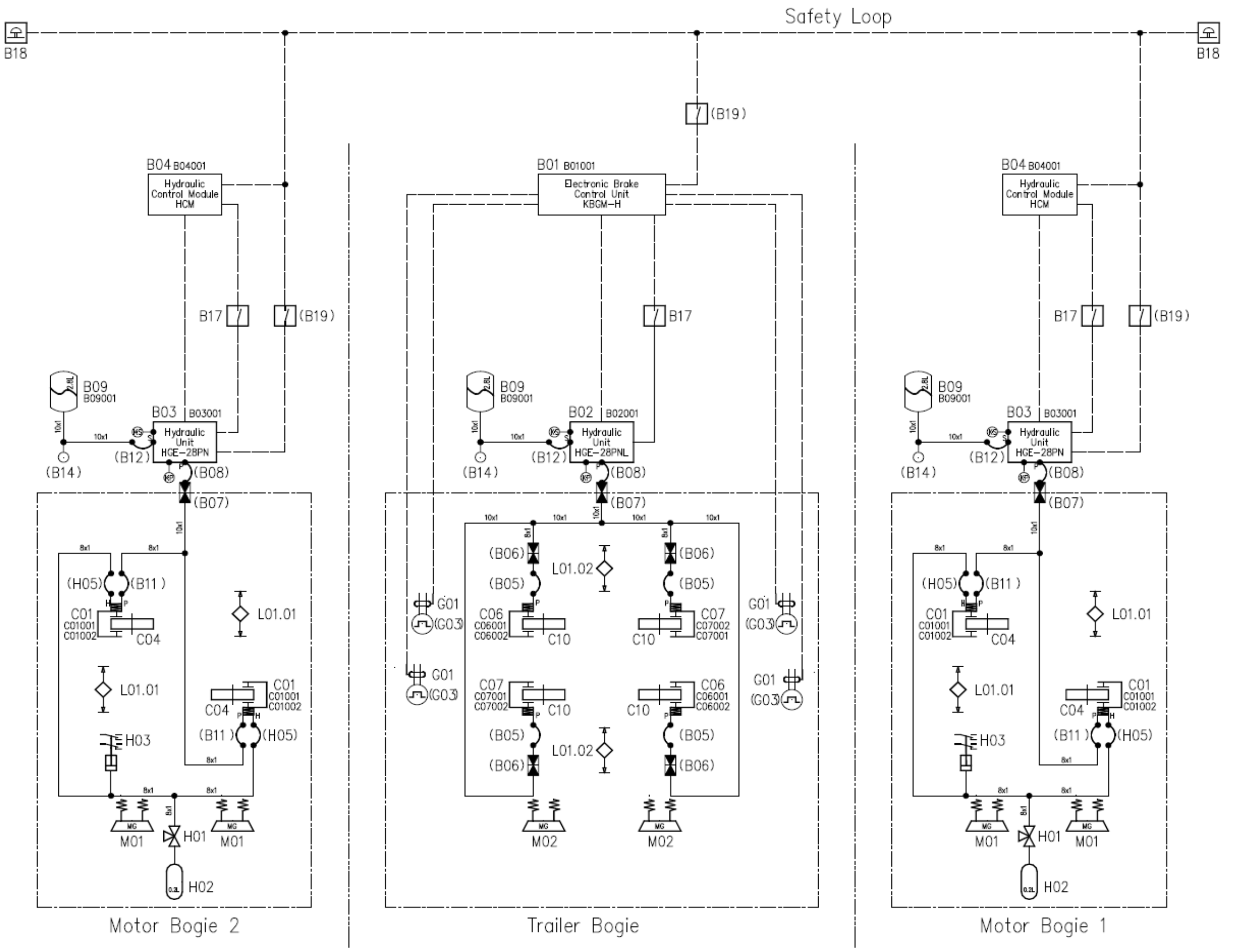


Figure 5: Piping Schematic of Electro-Hydraulic System

B01 -Electronic control unit BCU

B02 -Trailer hydraulic pressure unit

B03 -Motor hydraulic pressure unit

B04 -Electronic control unit HCM

B09 -Energy accumulator composition

B17 -Pump control module

C01 -Motor brake caliper clamp

C01.001 C01.002 -Mc Car Brake pads

C04 -Motor brake disc

M02 -Trailer magnetic track

H02 -Oil tin

H03 -Pressure Switch

L01.1 L01.2 -Loading sensor

H01 -3_3 way cocks

G01- Speed sensor

C10 -Trailer brake disc

C06 C07 -Trailer brake caliper clamp

M01 -Motor magnetic track

In the occurrence of a failure system, both the HCM (motor car) and BCU (trailer car) send a signal through the VCU to the DDU that is observed by the train operator as a fault message/event. The BCU and HCM show any event as a 4-character alphanumeric code on the man-machine interface. Current events and past events are displayed together with status information on the service terminal.

Brake equipment functionality

a) HCM (B04)

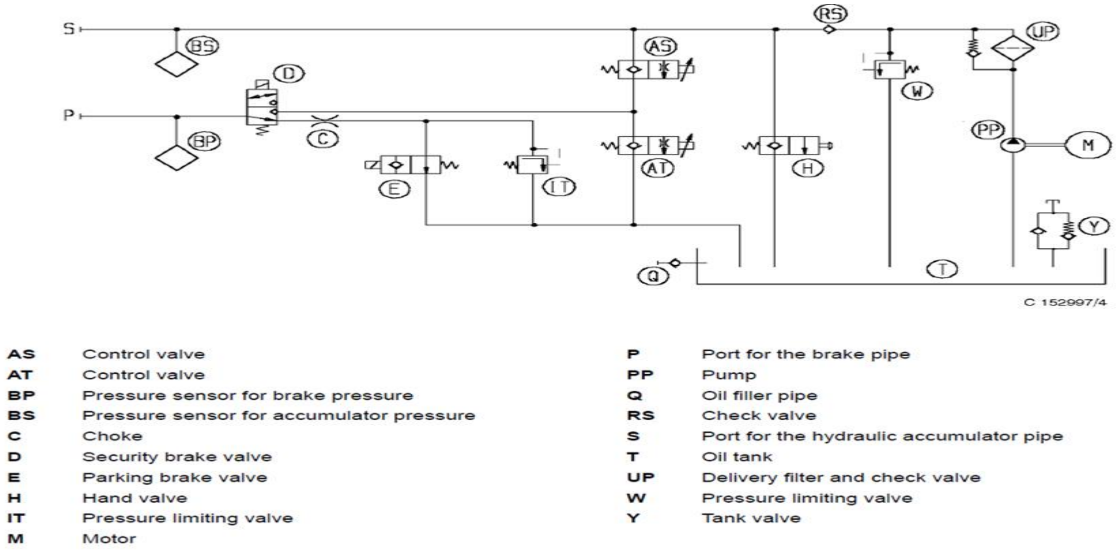
The hydraulic control module (HCM) is an all-purpose control unit for use between CCU and the hydraulic unit in a rail vehicle's brake system. The HCM processes the brake signal from the CCU, as well as the signals output by the pressure sensors in the hydraulic brake system. These latter signals are converted into proportionate control signals to drive the valves and pump motor of the hydraulic unit The HCM board transforms the brake force demand signals from the VCU into proportionate brake steps. The signals provided for the respective braking steps are converted via the HCM (B04) to a signal adapted for the EHU (B03). It drives the pump motor of the hydraulic unit both on to obtain the required pressure and off for cooling. The hydraulic pressure is inputted and regulated by pressure transducers. The HCM has no wheel slide protection functionality. The pump motor control of the HCM ensures that there is always enough pressure in the hydraulic system and checks the system for leakage. Step 1 for degraded modes (ED-brake failure), Step 2 for stopping brake application at speeds lower than 5 km/h, and step 3 is the maximum braking pressure for holding brake application (equivalent to parking brake force). The board assumes its failsafe state during unacceptable operating conditions (watchdog not being triggered, under voltages, etc.) and during reset. The power outputs are then disabled and the voltage to the power outputs is cut off.

b) Electronic brake unit (B01)

The BCU is a fully functional brake control unit. It is used to control the hydraulic unit in the trailer car. The BCU controls the brake pressure of the hydraulic unit (**B02)**. The microprocessor-controlled unit contains the electronic components for brake control and wheel slide protection control. The electronic component processes a vast set of diverse signals to produce a brake set-point, which is translated into pressure by the control unit's related analog converter (B02). It additionally assumes the task of providing jerk limitation, stopping brake application, and load correction. It is integrated with a wheel slide protection controller which uses the brake pressure to adjust the brake force to inadequate wheel-to-rail adhesion, accomplishing short stopping distances by optimally utilizing wheel-to-rail slip in the trailer truck. It suppresses wheel lock and eliminates the risk of wheel flats in this way.

c) Hydraulic Unit (B02&B03)

Hydraulic units **B02&B03** generate and regulate the pressure for operating passive brake actuators. The only difference between **B02&B03** is that HU (B02) has the hydraulic auxiliary release function. Throughout brake application, the hydraulic brake pressure is constantly adjusted to the electric brake demand signal sent to the hydraulic unit from the brake control unit. When the hydraulic unit is powered down or the pipe pressure is unloaded, the brake actuator goes active at the maximum brake force. The brakes are fully released when the hydraulic pressure in the brake pipes reaches or exceeds the brake actuator's specific release pressure.



AS	Control valve	P	Port for the brake pipe
AT	Control valve	PP	Pump
BP	Pressure sensor for brake pressure	Q	Oil filler pipe
BS	Pressure sensor for accumulator pressure	RS	Check valve
C	Choke	S	Port for the hydraulic accumulator pipe
D	Security brake valve	T	Oil tank
E	Parking brake valve	UP	Delivery filter and check valve
H	Hand valve	W	Pressure limiting valve
IT	Pressure limiting valve	Y	Tank valve
M	Motor		

Figure 6: Hydraulic Unit

d) Diaphragm accumulators

Diaphragm accumulators are used in electro-hydraulic brake systems to store energy, helping to reduce the required pump capacity in intermittent mode, and as energy reservoirs in the event of a pump failure. The diaphragm accumulator is a pressure vessel that is subdivided into two chambers by an elastic diaphragm. One chamber holds nitrogen at a gas charging pressure unique to the relevant hydraulic system, while the other is linked to the hydraulic system and contains hydraulic fluid. When hydraulic fluid is injected under pressure into the diaphragm accumulator, the elastic diaphragm deforms and expands the hydraulic fluid chamber. The volume of the nitrogen chamber is decreased accordingly; the nitrogen is compressed still further. The nitrogen expands correspondingly when hydraulic fluid is withdrawn. The volume of the hydraulic fluid chamber is reduced, yielding certain pressure in the hydraulic system according to the amount withdrawn. The pump only has to be restarted when the pressure has reached a lower threshold set by the system.

e) wheel slide protection equipment

The passive, continuously variable (analog) EH brake in the trailer bogie incorporates wheel slide protection control. There are four double-channel speed sensors (G01) and rotating gears [G03] for recording the wheel speeds. The signals generated by them, are transmitted to BCU and are used for brake and wheel slide control. The wheel slide protection control logic integrated with the BCU unit activates the analog converters inside the EHU, operating the brakes in their optimum slip range. This arrangement ensures optimum wheel slide control at wheels that have a strong tendency to lock.

f) C01 Car Brake caliper (motor car)

The brake caliper converts the pressure in the hydraulic piping of a hydraulic brake into brake force on rail vehicles. The brake caliper acts as a passive spring actuator, i.e. the brake force is generated as spring force in the brake actuator. This spring force is counteracted by the hydraulic pressure delivered by the hydraulic unit to the brake caliper. The brake force is metered according to the magnitude of the pressure. If the pressure is 0 bars, the brake caliper will brake by the maximum force; the brake caliper is entirely released when the force due to the hydraulic pressure within the brake actuator exceeds the spring force. The hydraulic brake caliper comprises the actual brake caliper, the caliper bracket by which the caliper is bolted to the vehicle, U-shaped spring plugs, brake caliper yoke into which a hydraulically powered brake force actuator, a lever which transmits the force to one brake pad, Pins pressed into the caliper bracket for adjustment and lock the unit positively to the vehicle for good power transmission. The caliper bracket has two bolts onto which the brake caliper floats. Because the brake caliper floats on the bolts, the brake caliper yoke presses the second brake pad onto the brake disc. The brake actuator is distinguished by automatic slack adjustment, hydraulic auxiliary release gear, and mechanical emergency release gear.

g) C01.001 C01.002 Car Brake pads

The hydraulic brake pad is a solid component of the braking unit that dissipates kinetic energy by rubbing against the friction surface. It generates the braking power and fits in the brake pad holder of a brake caliper. A brake caliper holds two identical or two mirror-imaged brake pads with one brake pad at either side of the brake disc.

h) G01 Speed Sensor

The speed sensor is a device designed to sense the speed of a ferromagnetic gear wheel (pole wheel) without actual contact. It is used preferably in conjunction with the microprocessor-based wheel slide controller for recording the axle speed. The unit scans the teeth and gaps around a rotating, ferromagnetic gear wheel of a given geometry. Changing magnetic flux changes the resistance in the magneto resistor. The magnetic field changes are converted into electric signals by the sensing device. The succeeding amplifier stage generates powerful output signals from this input. The axle speed is then ascertained from the number of pulses per unit time.

i) H01 3_3 way cocks

3/3-way cocks of this type are used to activate and deactivate the auxiliary release pipe in hydraulic brake systems. The 3/3-way cock is designed for use in the auxiliary release circuit of hydraulic brake systems. Depending on how the train brake system is configured and on which working position is selected, the cock serves to build up, hold or discharge pressure in the auxiliary release pipe.

j) H02 Oil tank

The oil reservoir is a transparent plastic container that is closed by a cover having an integrated seal and breather hole for balancing the tank pressure. The oil reservoir is permanently joined to the connecting pipe via its outlet by the hydraulic pipe attached to the hose union. The fluid can therefore accumulate in, or run out of, the tank as required. It serves to take up fluid from the brake actuator's inactive auxiliary release pipe and thereby prevents pressure from rising undesirably, e.g. as a result of temperature fluctuations.

k) L01.001 L01.002 LEVEL SENSOR

The unit works based on a synchro. When the orientation of the monitored vehicle component changes concerning the unit's mounting point, the change is transmitted to the unit's shaft via the actuator and the unit's lever and translated into a rotary motion. This rotary motion causes the unit to regulate its electric output signal accordingly.

l) M01 Magnetic track brake/MTB

A track brake magnet is an electromagnet or solenoid. It consists of a coil that is wound on an iron core generating a magnetic field when direct current is applied. Soft-iron parts attached to the magnet rule how the induced magnetic lines of force close about the railhead. Once activated, the MTB is pressed onto the rails by its magnetic pull. Transmission links fixed in place on the bogie draw the brake magnet over the top of the rail in the running direction. The braking power is exerted as the moving vehicle's kinetic energy is progressively converted and absorbed by the magnets attached to the rails by the force of the magnetic field. The brake magnets exert an adhesive force of 66 kN ±5%. The magnetic track brake consists of a magnet, cable connection, and a compression spring suspender

2.5 Maintenance

Maintenance can be defined as the combination of all technical and associated administrative actions intended to retain an item in or restore it to, a state in which it can perform its required function. The Maintenance Engineering Society of Australia defined maintenance as the engineering decisions that are associated with actions necessary and sufficient for the optimization of specified capabilities[36] and functions. This definition signifies that the product purpose/function should always be delivered at a high level of performance and reliability. Maintenance is important in railway as it’s aimed at keeping equipment in good condition. Many maintenance policies/techniques have helped to decrease/avoid abrupt failures thus reducing high operational costs such as conventional preventive maintenance.

A Maintenance strategy is a management method used to achieve the target maintenance objectives of an Organization[9]. These objectives are always set by the management and maintenance department and may include; availability of equipment, cost reduction, safety quality service, and environment preservation. The strategy is to give direction to the management and the maintenance department on how to achieve these objectives and this is normally referred to as maintenance management. A maintenance plan specifies which events (for example, failure, the passage of time, or a condition) initiate which sort of maintenance activity (inspection, repair, or replacement)[37]. It depends on several factors, which may include the goals of maintenance, the equipment to be maintained, workflow patterns, and the work environment. Therefore maintenance management is very important to decrease failures and reduce high operational costs and breakdown costs. The success of any service organization is dependent on offering superior customer value accompanied by relatively low operational costs and this can be obtained from ensuring proper train operation with minimum costs of operation. The importance of maintenance has increased greatly today due to its role in improving availability, performance efficiency, quality services, on-time deliveries, the environment, and safety requirements.

2.5.1 Selection of a Maintenance

The selection of a suitable maintenance strategy is very complicated because it requires considering the non-metric variables eg safety, passenger comfort, and metric variables such as maintenance cost. The selection process of an effective maintenance strategy is very crucial towards achieving the highest systems performance and organizational goals. Determining the proper equipment maintenance technique can be a difficult task. There is a narrow line between profitability and reliability, and an organization's strategy generally prioritizes one over the other. Running equipment beyond its intended limitations may result in safety issues, frequent and unexpected interventions/downtime, resulting in labor, material, and lost production expenses. Whenever the maintenance manager opts for over maintenance of equipment, the availability is severely affected and profitability is reduced. It is crucial to identify a perfect balance between the two to provide an acceptable level of maintenance with relevant profitability levels. In this research, we concentrated on the risk associated with the component failure and the maintenance cost due to failure since these two have a direct impact on both the reliability, safety, and profitability of an organization. For this reason that the author proposed a fuzzy logic maintenance selection model that combines the risk posed by the component failure and the maintenance failure cost to provide support for maintenance decisions for the light rail systems.

Dipark et. al[38] created an algorithm based on fuzzy set theory to determine the optimal kind of maintenance, period duration, and replacement policy; however, they did not account for safety in model formulation, which is a critical aspect in rolling stock maintenance. Many authors have suggested models that help in maintenance decisions. Malay and Praveen[39] suggested an approach for finding the suitable maintenance practice with the help of fuzzy logic rule base system on the downtime and frequency of occurrence. George et. al[40], applied a Fuzzy-based FMECA technique to an unloading facility and ranked the RPN number and this was the output of fuzzy inference. This ranking was used as an input to the suggested maintenance model selection after risk assessment. All these proposed models do not involve the maintenance cost to be incurred because of failure which is additionally important during maintenance decisions.

2.5.2 Maintenance cost

Maintenance costs are described as expenses that include missed opportunities in uptime, rate, yield, and quality as a result of no operation or inadequately running equipment, as well as costs associated with equipment-related deterioration of the safety of people, property, and the environment[41]. Niebel et. al[42] and Cavalier et. al[43] classified fundamental costs associated with maintenance more specifically into four areas: direct costs, lost production costs, degradation costs, and standby costs. The direct expenses of maintaining the equipment operational include the expenditures of periodic inspection and preventative maintenance, repair, overhaul, and service. Lost production expenses are connected with lost production because of main equipment failure and the inability to use standby equipment. Degradation costs are connected with a decrease in equipment life because of poor/inadequate maintenance. The expenses of running and maintaining backup equipment are included in standby costs. When either primary facilities are under maintenance or unusable, standby equipment is employed. According to Douglas[44], Maintenance costs may be divided into a series of subcategories, which include direct costs and indirect costs(downtime,). Direct costs comprise labor, material, e.g. spare parts, and overheads, e.g. tools, transportation, training, and methods. Indirect/invisible costs may arise due to planned or unplanned maintenance actions, which may include; low sales due to delays, lost production costs, accidents, etc.

Many maintenance cost estimation models have been suggested in recent years. Ahmed[45] proposed the use of the activity-based costing approach for the estimation of the maintenance cost. Based on the actual preventative maintenance activities done, this maintenance cost model would assist in determining any maintenance work cost with a fair degree of accuracy. Mohammed et. al[46] carried out a study on maintenance cost estimation and mathematical models were derived to predict the accumulated repair and maintenance costs as a percent of the purchase price with accumulated hours of use and age (years) of each tractor make. Five model forms ie linear, logarithmic, polynomial, power, and exponential) were analyzed. Granja et.al [47] suggested a model to calculate the estimated maintenance cost for the software in which consideration of a factor that indicates a measurement of the maintainability of the system was included. This was termed as the 'maintainability index', which was a function of some empirical software measurements. Christer et. al[48] carried out a cost comparison and cost-based analysis between PM and BM on railway infrastructure as the case study. In the analysis, the authors state that to calculate the cost of BM of a system over a given period, important data on costs are considered as a sum of four objects; service/production loss, logistic time, active repair time, and materials. In this study, each component was analyzed independently for its functional failure at a time. The maintenance cost due to component failure (BM) is considered corrective maintenance which cannot be avoided when a random failure of a component occurs[38]. The author opted for Christer's approach for the computation of BM cost for each component failure in this research given by the equation;

$$C_{BM} = \sum_{i=1}^{n}(n_{p,i}Cp\{2t_{LT,i} + t_{RT,i}\} + C_{M,i} + t_{DT,i}C_{DT})$$

Where:

- n is the number of functional failures
- n_P is the number of personnel on the maintenance team;
- t_{LT} is the logistic time (LT) for travelling one way, i.e. travel time [t];
- t_{RT} is the repair time (RT), i.e. active repair [t];
- t_{DT} is the service/production loss time [t];
- C_P is the monetary cost per personnel and unit of time [t^{-1}];
- C_M is the monetary cost of materials (spare parts)
- C_{DT} is the monetary cost of service/production loss [t^{-1}].

2.5.3 Maintenance practices

Four Maintenance practices were considered in this study i.e. total productive maintenance (TPM), breakdown maintenance (BM), condition-based maintenance (CBM), and design upgrade (DU) as explained below;

a) Breakdown maintenance

According to Adolfsson et. al[49], breakdown maintenance also defined as corrective maintenance is performed to return the equipment to its working condition after a breakdown or after perceived deficiencies that are severe enough to necessitate a halt in its operation. It includes repair and replacement of failed parts to create a successful operation again as before failure which makes this maintenance harder to plan and more costly to perform however if utilized correctly, it’s a cost-saver. This method is often used/appropriate when the effect of failure is very little, i.e. when the failure of a piece of equipment may not have a significant influence on an organization's availability or service for productive[9].

b) Condition-based maintenance (CBM)

Condition-based maintenance is a maintenance approach where maintenance operations are carried out based on the existing state of the equipment/component. The state of the equipment can be checked through visual inspections, tests, and performance data that are usually obtained from different sensors and instruments. CBM is a philosophy for maintenance engineering of assets/equipment based on non-intrusive measurement of their condition and maintenance logistics[36]. According to Amanda[50], CBM is a maintenance approach used to actively manage the health condition of equipment to optimize maintenance by performing maintenance only when it is needed/required and during opportune times, thus improving overall system, equipment availability and safety while decreasing operating costs.

Condition monitoring assists in the planning and scheduling process that’s to say it identifies the defects early enough before propagation thus allowing the planning and scheduling process to be done based on facts. It further gives the planner something specific to plan for and also the early detection of the fault implies more inventory may be performed. In addition, Rao[51] states the specific list of benefits of CBM which include; Maintenance costs reduced by 50%, unexpected failures reduced by 55%, repair and overhaul time reduced by 50%, reduction in inventory of spare parts by 30%, an increment in the Mean Time Between Failures by 30% and machinery availability increased by 30%.

c) Total Productive Maintenance (TPM):

The Japanese invented and refined the idea of Total Productive Maintenance (TPM) in 1971. It is a team-based preventive "you operate, I maintain" philosophy[52] and productive maintenance and involves every level, from the top executive to the floor operator[53]. It consists of a variety of methods, which involve maintenance management experience to be effective in improving reliability, quality, and production. TPM is founded on preventive maintenance methods which include planned maintenance, training, quality maintenance, safety, health, and environment. It requires the operators to take participate in maintenance activities e.g. cleaning, lubricating, tightening bolts, adjusting, and reporting their observations on the machine condition[54] to the maintenance experts. The primary objective of TPM is mainly to increase production, increase employee morale, job satisfaction, hold emergency and unscheduled maintenance at a minimum by ensuring that downtime is always set for planned maintenance as an element of the operations. TPM emphasizes maintenance as a critical and required component of the business, rather than just as a non-profit venture.

d) Design upgrade/ Design out Maintenance

Design out Maintenance tries to modify those components of the equipment that require a significant amount of maintenance labor or replacement components, or that have extremely or unacceptably high failure rates[55]. This maintenance strategy targets improvement rather than just conducting maintenance activities to ensure system functionality, and also focuses on improving the system design to reduce the maintenance burden or even eliminating maintenance[56].

2.6 Fuzzy logic maintenance selection model

Fuzzy logic is a mathematical system that helps to reduce the complexity of controlling nonlinear systems[39]. The fuzzy logic system can be implemented by following five major steps which include Fuzzifier (giving inputs and outputs suitable membership functions), Rule base (relating inputs and output), Fuzzy inference engine (iv) Defuzzifier (changing a fuzzification value to a crisp value) and output quantity.

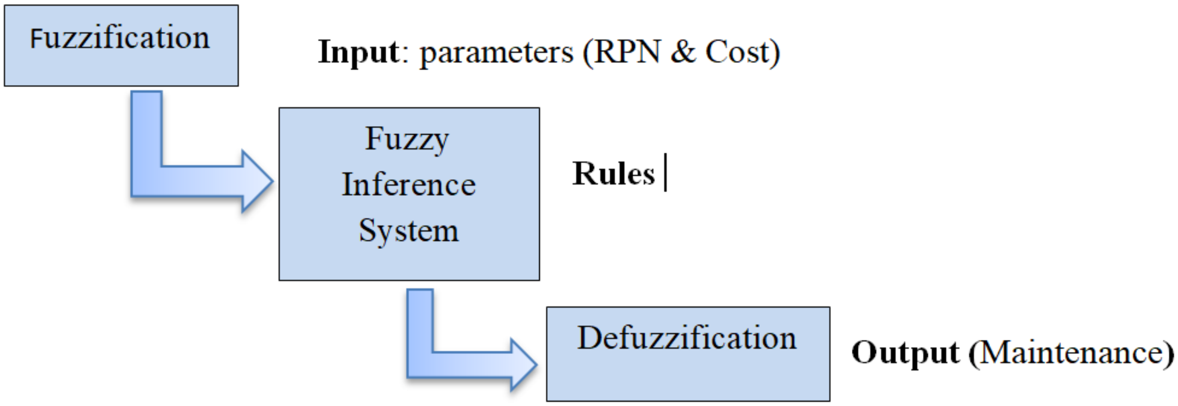
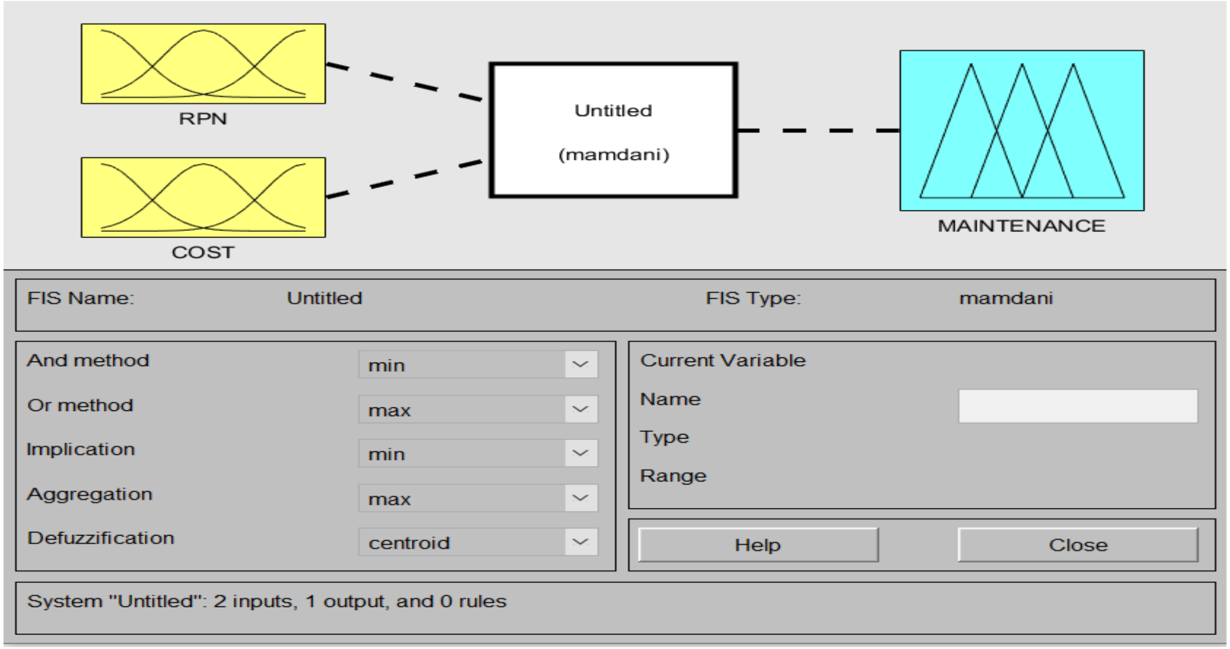


Figure 7: Fuzzy Logic Maintenance Selection Model

In this research, the Fuzzy logic as shown in Fig.7 Mat lab tool was used to enable us to find a maintenance strategy/practice after a risk assessment, and two important factors as inputs in regards to maintenance were considered as shown in Fig.8 i.e. the risk (RPN) associated with the system and the cost as a result of a failure of the components of the system/repair cost as inputs and the maintenance method as the output.



FIS Name: Untitled

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: centroid

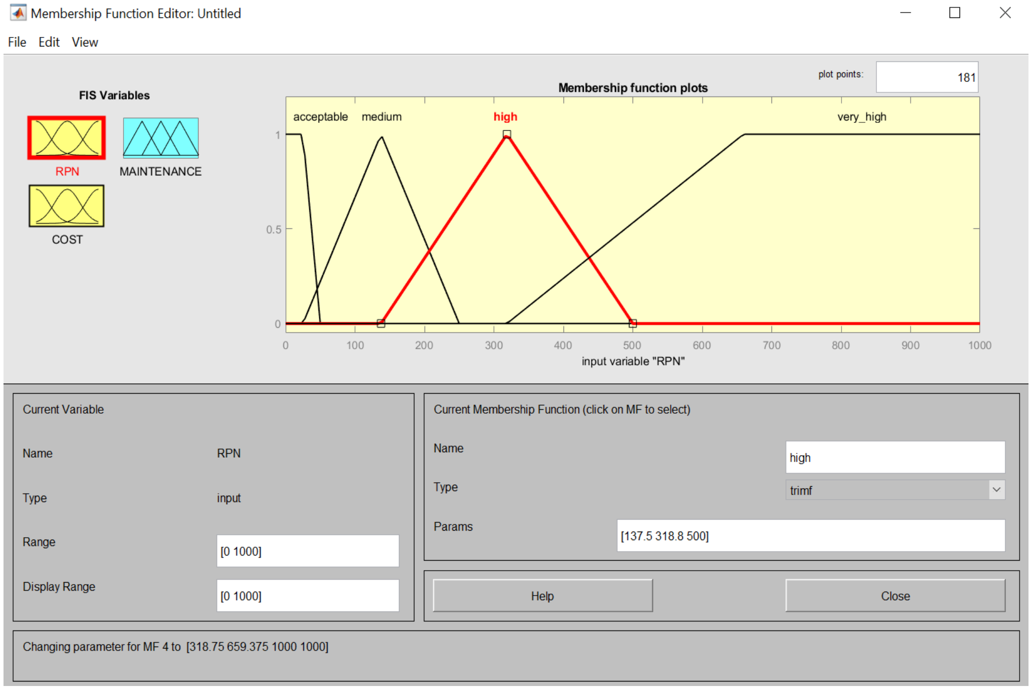
System "Untitled": 2 inputs, 1 output, and 0 rules

Figure 8: Fuzzy Interference System

A fuzzy toolbox in MATLAB software was used to perform the fuzzification process. As the review shows, triangular membership function was used as it was found to be superior to all the other membership functions and advisable to be used with 50% overlap [57],[58]. The RPN set the priority for maintenance based on the evaluated risk and in this case, regarding George et. al[40] the RPN, in this case, was represented as a set of four qualitative linguistic values namely; “acceptable”, “Medium”, “High” and “Very high” with respective ranges of numerical values as shown in Tab.4. This implies that if the RPN is between 0-50, the risk is considered acceptable. Fig.9 shows the membership function of the RPN in fuzzy format.

Table 4: RPN Fuzzy Set

SET	VARIABLE	RANGE
1	Acceptable	0 - 50
2	Medium	25 - 250
3	High	137.5 - 500
4	Very high	318.75 - 1000



Current Variable

Name RPN

Type input

Range [0 1000]

Display Range [0 1000]

Current Membership Function (click on MF to select)

Name high

Type trimf

Params [137.5 318.8 500]

Changing parameter for MF 4 to [318.75 659.375 1000 1000]

Figure 9: RPN Membership Functions

The repair cost was categorized in terms of “Low”, “Medium”, “High” and “very high” as shown in Tab.5 and its membership function in fuzzy format represented in Fig.10 in this case the cost between “0-12500” is considered low and the cost between “23437.5-42500” USD is considered very high.

Table 5: Maintenance Cost Fuzzy Set

SET	VARIABLE	RANGE
1	Low	0 – 12500
2	Medium	6250 – 22500
3	High	14375 – 32500
4	Very high	23437.5 – 42500

Current Variable

Name COST

Type input

Range [0 4.25e+04]

Display Range [0 4.25e+04]

Current Membership Function (click on MF to select)

Name medium

Type trimf

Params [6250 1.438e+04 2.25e+04]

Changing parameter for MF 4 to [23437.5 32968.75 42500 42500]

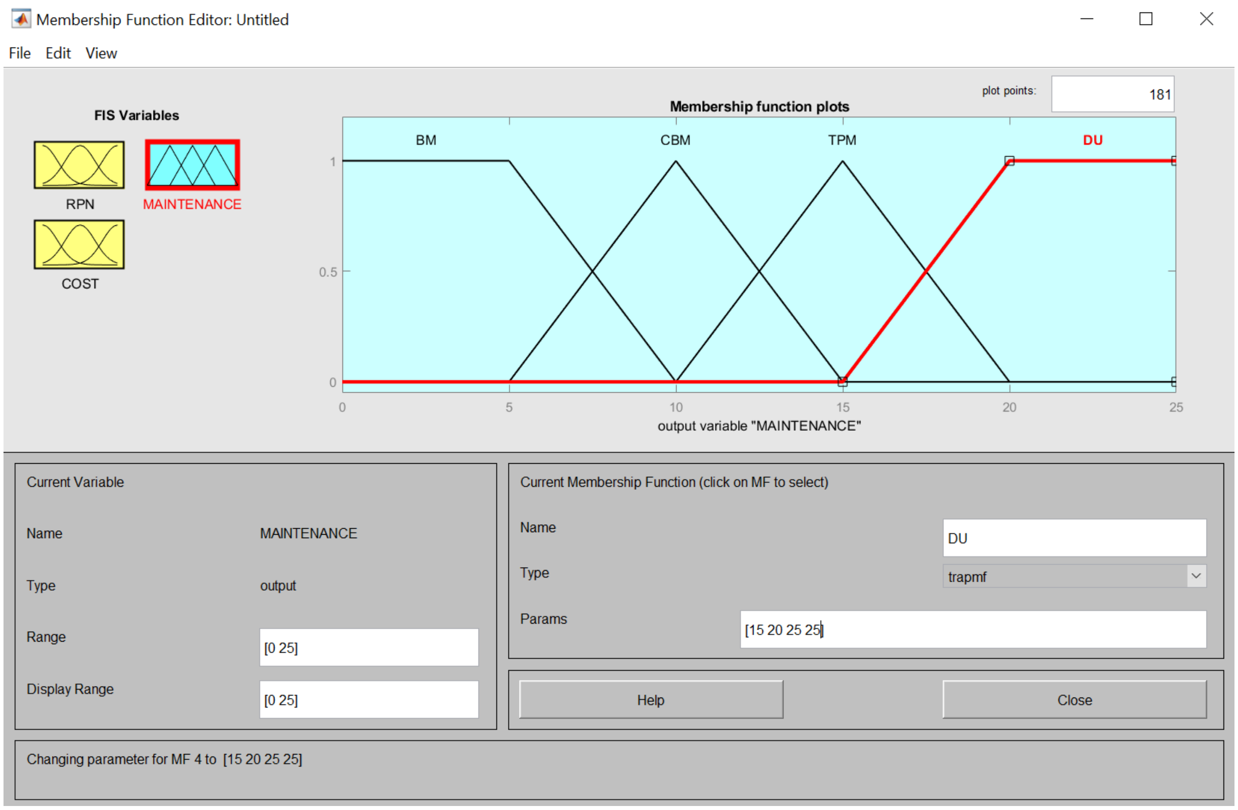
Figure 10: Maintenance Cost Membership Function

Maintenance practice

Regarding Niraj and Kumar maintenance selection in fuzzy logic whose ranking was based on the frequency and downtime,[39], In this case, we considered four maintenance practices i.e. Breakdown Maintenance/run to failure (BM), Condition Based Maintenance (CBM), Total Productivity Maintenance (TPM,), and Design upgrade. Tab.6 shows the output range for the maintenance practice and this was based on repair on the requirement. Fig.11 represents the maintenance fuzzy format.

Table 6: Fuzzy Set for Maintenance Selection

SET	VARIABLE	RANGE
1	BM	0 - 10
2	CBM	5 - 15
3	TPM	10 - 20
4	DU	15 - 25



Current Variable

Name: MAINTENANCE

Type: output

Range: [0 25]

Display Range: [0 25]

Current Membership Function (click on MF to select)

Name: DU

Type: trapmf

Params: [15 20 25 25]

Changing parameter for MF 4 to [15 20 25 25]

Figure 11: Membership Function for Maintenance Practices

Rule evaluation

The rule evaluation in fuzzy logic implies relating the fuzzy inputs to the output. These are set using expert knowledge and in this case, it is to be obtained from the maintenance department of AALRT to set the fuzzy rules base on the risk and repair cost per component to suggest a maintenance practice. These fuzzy rules are based on logic statements of “If-Then”. As seen from our Fuzzifier, each of our inputs has four subdivisions thus to set the rules we have a set of 16 rules for our fuzzy system

Defuzzification

This is the output of the fuzzy system using the rule viewer, we draw a relationship between our two input variables of RPN and cost, and the output is calculated as a point that can be translated into linguistic form.

CHAPTER 3

3.0 MODEL FORMULATION AND DATA COLLECTION

3.1 Introduction

To achieve a safe train with less system failure, maintenance has to be at its best and this is through effective maintenance practices. A well-designed maintenance strategy must ensure the safety, reliability, and availability of the system by minimizing the risk of failure to the system. A risk assessment helps understand to set priority for maintenance ie it identifies the most critical component whose failure might be hazardous and costly to the organization. It further checks the effectiveness of the current maintenance strategies based on the failure rate and the operation environment. The objectives of this research include analysis of the past failure records of the light rail systems and identify the system with passenger safety-related issues, what are the major components of the identified system? What is the purpose of each sub-component to the system? What are the common/potential causes of failures associated with the system and their effects? What is the cause of every identified potential failure mode and how often does this happen? How, when, and where can we detect this cause? What are the most risky components of the system? What maintenance practice is suitable to minimize/eliminate the risk?

According to a 2009 survey of Swedish companies, 81 percent of the enterprises that choose their Maintenance Strategy relied on the knowledge and experience gained within the organization[59]. In this research mostly primary data was used which includes data from the maintenance department concerning records of past failures of the light rail systems; interviews and a questionnaire were also prepared and given to the experienced personnel in the maintenance department for any other possible failures in the selected system. This research intends to introduce a model to assist in maintenance decision-making for light rail system components based on the risk priority number (FMECA) and the cost of maintenance due to failure/repair cost through the use of the fuzzy logic Mat lab tool to select a maintenance method.

3.2 Methodology

A model was developed for risk assessment of light rail train systems based on the FMECA, with the ability to assist in maintenance selection decisions for the respective risk components. In this study, the light rail system of AALRT was used as a case study for risk assessment. The model consists mainly of the following aspects. First, a light rail system is selected for the risk assessment based on the accumulated component failures and safety aspects of passenger transportation. The selected system is analyzed per component using the FMECA to obtain the components that require more attention with respect to safety and this is through the RPN evaluation. A fuzzy logic maintenance selection model is used to suggest an appropriate maintenance practice. In this model, the RPN is coupled with the failure maintenance cost/repair cost as an economic index towards maintenance decisions. The detailed analysis of the methodology is shown in fig.12

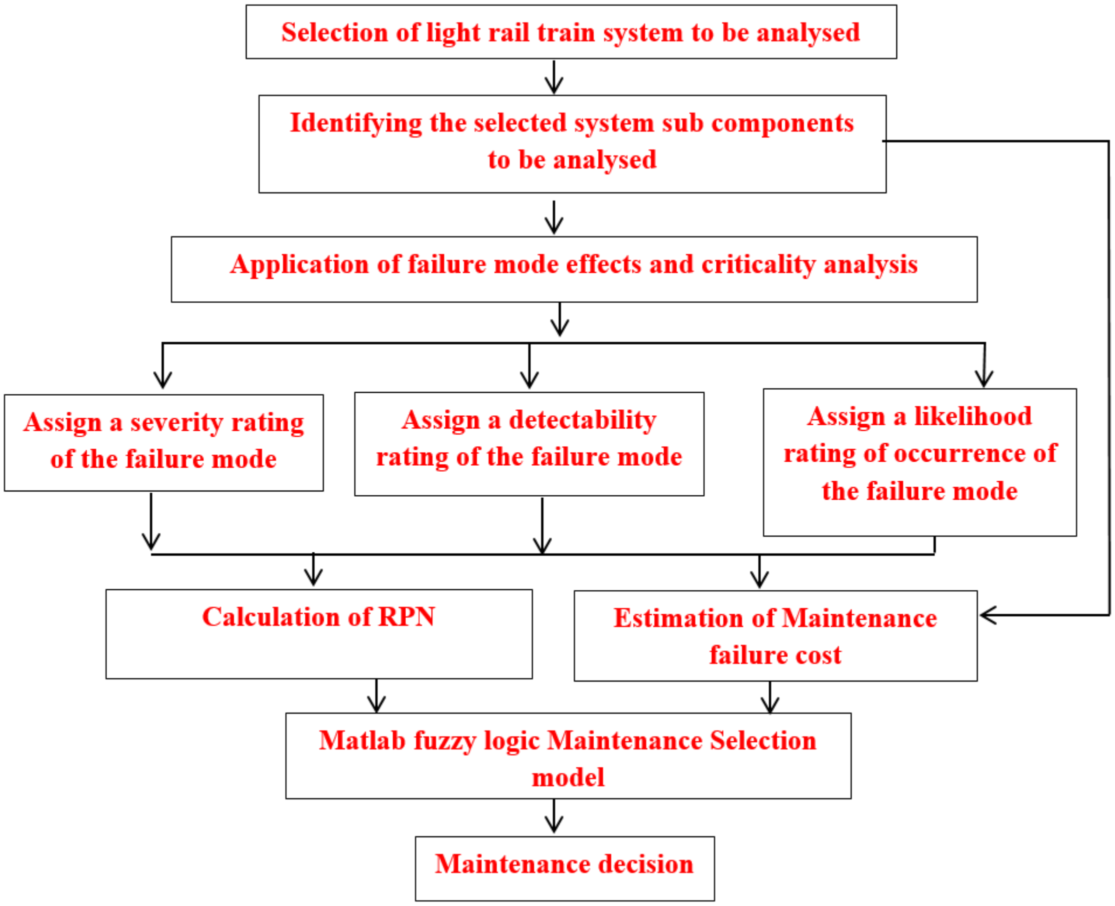


Figure 12: Research Methodology

3.3 Data Collection

Data collection for the assessment of the light rail train braking system using FMECA required expert opinion from the maintenance department of the AALRT. The data collection phase was divided into 3ways ie

(i) Raw data (design manual of the train braking system and past failure records)
(ii) Interviews (a total of 10 maintenance experts were interviewed Tab.1)
(iii) Questionnaire(10 maintenance personnel took part in the survey)

Table 7: Selected Maintenance Experts for Interview

No	DEPARTMENT	Education	Age group	Workplace
1	Inspection and maintenance	M.Sc.	25 - 34	Kaliti Transit
2	Inspection and maintenance	M.Sc.	25 - 34	Kaliti Transit
3	Rolling stock equipment	B.Sc.	25 - 34	Kaliti Transit
4	Safety and planning	M.Sc.	25 - 34	Kaliti Transit
5	Inspection and maintenance	M.Sc.	25 - 34	Kaliti Transit
6	Safety and planning	M.Sc.	25 - 34	Ayat transit
7	Rolling stock equipment	M.Sc.	25 - 34	Ayat transit
8	Inspection and maintenance	M.Sc.	25 - 34	Ayat transit
9	Inspection and maintenance	M.Sc.	25 - 34	Ayat transit
10	Safety and planning	M.Sc.	25 - 34	Ayat transit

3.3.1 Questionnaire design

The FMECA application required a comprehensive understanding of the train braking system type used on the Addis Ababa light rail train, identifying the key components, potential failures, their root causes, effects and quantifying the qualitative data to quantitative data thus besides the interview, a questionnaire was prepared. AALRT maintenance department has an estimated number of 25 maintenance personnel. The benefit of quantitative approaches is their capacity to make conclusions about bigger groups of individuals using smaller groups of people.

In a survey with a large sample size, respondents may be prone to providing arbitrary responses, resulting in a significant degree of inconsistency [60][9]. The Quota sampling approach was employed in this study, in which the sample is chosen based on people we believe are most likely to have experience with, knowledge about, or insights into the research issue[61]. During the questionnaire preparation, we needed to obtain an expert opinion on relating the risk with the maintenance cost due to failure and 10 maintenance experts participated in the general survey and shared their opinions by answering our questionnaire.

3.2.2 Selection of light rail system

The selection of the light rail system to be analyzed was carried out by analyzing the past failure records of the Addis Ababa light rail system vehicles for five years. The Addis Ababa light rail train was opened on 20 September 2015, with 41 vehicles running at a maximum speed of 70 km/hr. The results of the past-recorded failure data showed that the braking system required more attention due to its accumulated failures and its crucial role in human mass transportation as shown in Tab.8. It showed be noted that the AALRT has so far recorded only minor failures since the start of its operation.

Table 8 : AALRT Past Failure Records

SYSTEM	**2016**	**2017**	**2018**	**2019**	**2020**	**TOTAL**
TCMS	25	1	12	3	3	**44**
PIS	59	52	62	17	78	**268**
Main circuit	0	3	1	1	2	**7**
Auxiliary	5	2	25	11	30	**73**
Traction	43	49	108	20	40	**260**
Air conditioning	35	57	182	77	90	**441**
Door	33	25	156	8	16	**238**
Bogie	44	41	18	3	6	**112**
Brake	40	64	52	58	62	**276**
Lighting	10	4	2	0	0	**16**
Car body & gang way	6	12	17	21	22	**78**
Cab	32	70	65	17	81	**265**
Coupler	4	2	0	0	0	**6**

AALRT BRAKING SYSTEM FMECA SHEET

After the collection of data, a FMECA sheet was constructed and the RPN was calculated for the respective components as shown in tab.6. The quantitative data from the questionnaires followed an average number of all respondents.

Table 9: AALRT Braking System FMECA Sheet

Class 2	Class 3	Failure mode	Failure cause	Local effect	End effect	S	O	D	RPN
HCM	**Circuit board**	Fault signals	Unit defective	Required pressure not generated	Low braking force	8	2	1	**16**
		no signals generated	Unit not being electronically activated	HU not activated	No EH braking in motor cars	8	2	1	**16**
BCU	**Circuit board**	Fault signals	Unit defective	Required pressure not generated	Low braking force	8	2	1	**16**
		no signals generated	Unit not being electronically activated	HU not activated	No EH braking in the trailer car	8	3	1	**24**
HU		Oil leakage from a hydraulic port	Connection leakage/ loose fitting	Reduction in oil pressure and levels	Unnecessary braking	4	7	3	**84**
			Over tightening						
	Oil tank	Oil level too low	Unit leaking	Reduction in oil pressure and levels	Uncontrolled braking	4	8	3	**96**
			Oil drain plug leaking						

			Unit leaking						
		Fluid running out of the hose connection	Hose connection lose	Reduction in oil pressure and levels	Uncontrolled braking	4	7	3	**84**
			Over tightening						
		Traces of fluid on the tank	Tank damaged or cracked	Reduction in oil pressure and levels	Uncontrolled braking	4	2	3	**42**
		Unit operating incorrectly	Wrong or no electric control over the unit	Undesired opening and closing of valves	insufficient/ No hydraulic braking	9	6	4	**216**
			Wrong or no electric control over some of its units						
		Failing entirely	Unit defective	Valves not opening	No EH braking	9	8	6	**432**
	Oil filter	No oil filtration	Dirt accumulation	Blockage of hydraulic flow	No hydraulic release/no braking	6	3	3	**54**
	Pressure sensor	Fault or no signal	Unit defective	Insufficient/more hydraulic oil pressure	Insufficient braking	7	2	5	**70**
			Unit not connected electrically						
	valves	Valve not opening/ closing	Unit defective		No hydraulic braking	9	3	5	**135**
			Failure in coil						

			Bad de-Energized position	Failure to operate security and parking brakes					
Diaphragm Accumulator		The motor pump of the related hydraulic unit starts very often and stops after running briefly	Fault in the hydraulic system	Decrease brake pressure	Reduced braking force/release	7	2	3	**42**
			Diaphragm defective						
			Diaphragm accumulator leaking						
		Unacceptably high loss of gas pressure	Diaphragm defective	Decrease brake pressure	Reduced braking force/release				
			Diaphragm accumulator leaking	Brake not released					
Pump control module		Pump motor not starting	Electronic unit not being powered sufficiently (fault signal)	No hydraulic flow to the accumulator	unnecessary partial brake application	6	3	1	**24**
			Motor not being powered up						
			False control signals						
			Electronic unit defective						

			Under voltage						
		Pump motor operating incorrectly or not switching off	Overcurrent (fault signal)	Reduced hydraulic brake line pressure	Brakes will not be released fully	6	3	1	**24**
			Electronic unit overheating (fault signal)						
		No Output	Electronic Unit defective	The pump will not run	Brakes will not be released after parking	4	3	1	**12**
			False control signals						
Brake caliper	**Automatic slack adjuster**	Inadequate brake pad clearance	Slack adjuster not entirely reset	Reduced actuator pressure	Reduced/no hydraulic braking	9	6	5	**270**
		Excessive brake pad clearance	Slack adjustment incomplete or slack adjuster defective	brake pads not reaching the brake disc					
		Loud knocking noise during brake application.	The slack adjuster trying to adjust although the clearance is still insufficient.						
		Fluid leakage	Connection leaking	reduced hydraulic pressure	Unexpected/ partial brake release	7	8	6	**336**
			Seals defective						
			Cracks						

		The mechanical emergency release gear is stuck.	Slack adjuster stiff to move because the wear is too slight	no manual release	no brake release	5	5	2	**50**
Brake pads		Thinning	Worn or defective brake pads.	Reduced contact between the disc and the pad	Insufficient braking/No hydraulic braking	10	10	6	**600**
		Unfamiliar smell							
Brake discs		bolts fracturing	Wear and stress	loss of contact between the disc and the pad	Reduced or no hydraulic braking	7	8	5	**280**
		cracks	Friction	brake pad wear					
		scorch marks	thermal stresses						
		Chattering during brake application	Brake pads are severely worn irregularly						
		The friction ring is loosening	The amounts of wobble/parallel misalignment exceed the installation specified values						
		High temperatures	Bolt pre-tensioning force is possibly lost						

		The surface of the friction ring damaged							
Speed Sensor		False or no speed signal	Unit not being activated electrically	Poor braking pressure applied due to lack of running speed.	untimely stops	6	2	5	**60**
			Spacing between the speed sensor and rotating gear is out of specification		poor braking pressures				
			Unit defective						
Fittings		cracking	high pressure	Reduced hydraulic pressure and oil	Loss of line pressure	4	1	5	**20**
HU	**Magnetic valves**	Not opening	Unit not powered electrically	No hydraulic flow	No braking	9	3	5	**135**
			Unit defective						
	Motor/pump	No response	Not connected electrically	Low hydraulic pressure	Wheel disc wear due to slight brake application	8	3	3	**72**
			The defective pump control module						
			Fault motor						
Relay switch		No response	Defective unit	Pump not switched on/off	No hydraulic in the accumulator	6	4	1	**24**

Hosepipe		leakage	damaged pipe over tightening	loss of hydraulic pressure and oil	Uncalled brake application	4	4	4	**64**
Electromagnet		Unit not being lowered	Unit not powered	Magnetic field not generated	No magnetic braking	10	1	2	**20**
		Required contact pressure not being reached	Unit defective	Magnetic field not generated	No magnetic braking	7	1	3	**21**
Load sensor		False or no speed signal	Unit not being activated electrically	Poor braking pressure amount signals	untimely stops & Less release pressure	6	2	5	**60**
TCU board		no power supply	short circuit	No regeneration	No dynamic braking	9	2	1	**18**

In this study, 42 failure modes were discovered from 17 major brake components and 18 sub-components, and these were analyzed quantitatively using our research questionnaire and interview to determine the RPN via the severity, frequency of occurrence, and the degree of detectability of the failure. Out of the 42 failure modes, 20 major events (reduce brake adhesion) were discovered for example failure of the brake pads through thinning will increase the clearance between the train brake pad and the brake disc thus little or no contact will happen to lead to no braking in the ED brakes. On the other hand, 22 minor events (do not reduce adhesion) were discovered

To ensure a safer train, all the high risky components must be subjected to maintenance to minimize/avoid failure. In this research, we suggested a new model for maintenance selection that related the RPN and the repair maintenance cost due to failure using the Matlab fuzzy logic tool.

3.2.3 Maintenance Cost Analysis

The maintenance cost used in the study was the breakdown /corrective maintenance cost of a given brake system component at a given point in time. The calculated corrective maintenance cost is the cost incurred every time a respective component of the AALRT completely fails. The author opted for Christer's approach for the computation of BM cost for each component failure. Due to the presence of a redundant train at the station, the logistic time (LT) for traveling one-way, service/production loss time, and the monetary cost of service/production loss were not considered in the cost analysis per component failure. Thus the estimated corrective/repair cost per component failure, C_{BM} *equation is now given by;*

$$C_{BM} = \{n_p * Cp * t_{RT}\} + C_M$$

- n_P is the average number of personnel on the Repair Maintenance team;
- t_{RT} is the average repair time (RT), i.e. active repair [t];
- C_P is the monetary cost per personnel and unit of time [t^{-1}];
- C_M is the monetary cost of materials (spare parts)

Obtained maintenance repair cost data for AALRT

$n_P = 4$ people, $t_{RT} = 3$ hours

Average monthly salary/personnel = 10000 Birr/ 218 USD

Average Active working days per month = 20 days

Active hours per day = 8 hours

Total active hours per month = 160 hours

Thus $C_P = 1.4$ USD/hr

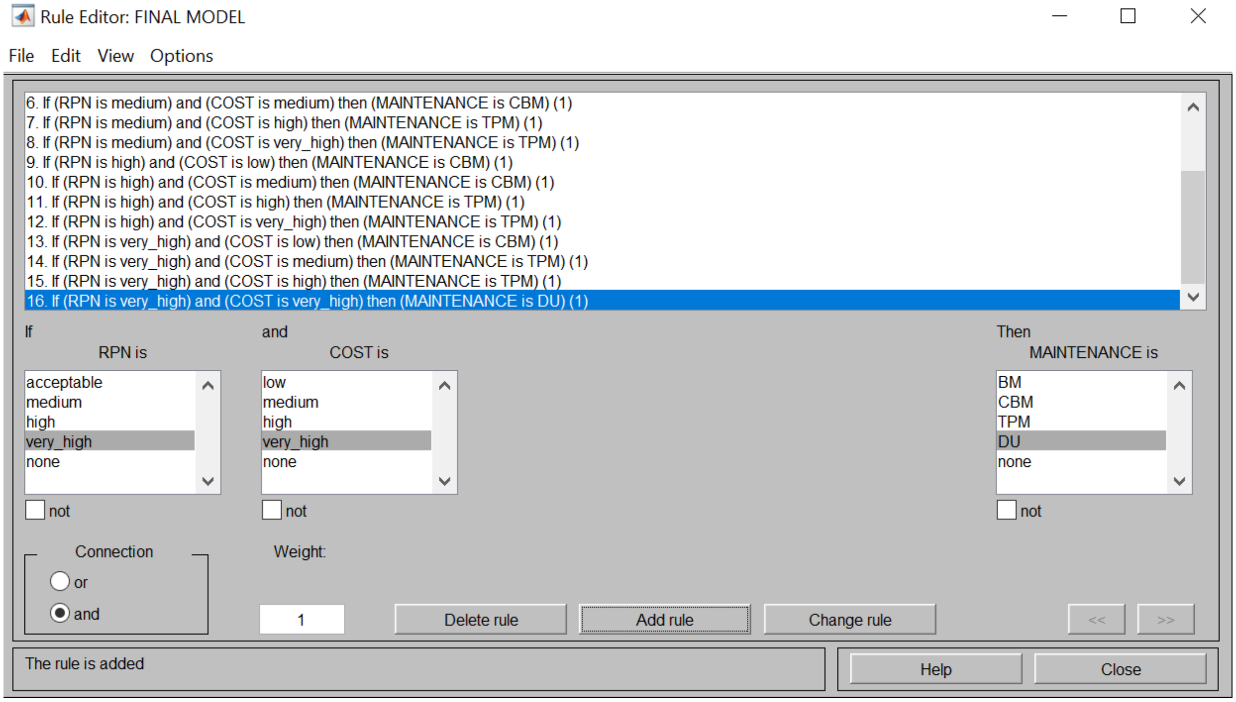
$$C_{BM} = \{4 * 1.4 * 3\} + C_M$$

Table 10: Estimated Maintenance Cost Analysis

Item	C_M (USD)	C_{BM}
BCU	14800	14817
HU(motor car)	33700	33717
HU(trailer car)	29500	29517
HCM	5200	5217
Diaphragm Accumulator	4350	4367
PSM (pump control module)	3000	3017
Rubber Hose	185	202
Relay switch	46	63
Fittings (average price)	115	132
Electromagnet rail brake unit	7000	7017
Speed sensor	3500	3517
Load sensor	3500	3517
Oil tank	24	41
Brake caliper	22600	22617
TCU circuit board	27500	27517
Magnetic valves	7800	7817
Pump/motor	3500	3517
Pressure switch/Sensor	2300	2317
Filter element	24	41
Brake pads	267	284
Brake discs	1049	1066

3.2.4 Fuzzy Rule Evaluation

This is the obtained relationship between the risk and component failure cost and as advised by maintenance experts the risk was given a higher priority as compared to the cost during the process of setting the rules as shown in fig.13 and fig.14. the rule viewer as shown in fig.15 is used for defuzzification



6. If (RPN is medium) and (COST is medium) then (MAINTENANCE is CBM) (1)
7. If (RPN is medium) and (COST is high) then (MAINTENANCE is TPM) (1)
8. If (RPN is medium) and (COST is very_high) then (MAINTENANCE is TPM) (1)
9. If (RPN is high) and (COST is low) then (MAINTENANCE is CBM) (1)
10. If (RPN is high) and (COST is medium) then (MAINTENANCE is CBM) (1)
11. If (RPN is high) and (COST is high) then (MAINTENANCE is TPM) (1)
12. If (RPN is high) and (COST is very_high) then (MAINTENANCE is TPM) (1)
13. If (RPN is very_high) and (COST is low) then (MAINTENANCE is CBM) (1)
14. If (RPN is very_high) and (COST is medium) then (MAINTENANCE is TPM) (1)
15. If (RPN is very_high) and (COST is high) then (MAINTENANCE is TPM) (1)
16. If (RPN is very_high) and (COST is very_high) then (MAINTENANCE is DU) (1)

RPN is: acceptable, medium, high, **very_high**, none ☐ not

COST is: low, medium, high, **very_high**, none ☐ not

MAINTENANCE is: BM, CBM, TPM, **DU**, none ☐ not

Connection: ○ or ● and

Weight: 1

The rule is added

Figure 13: Fuzzy Rule Editor

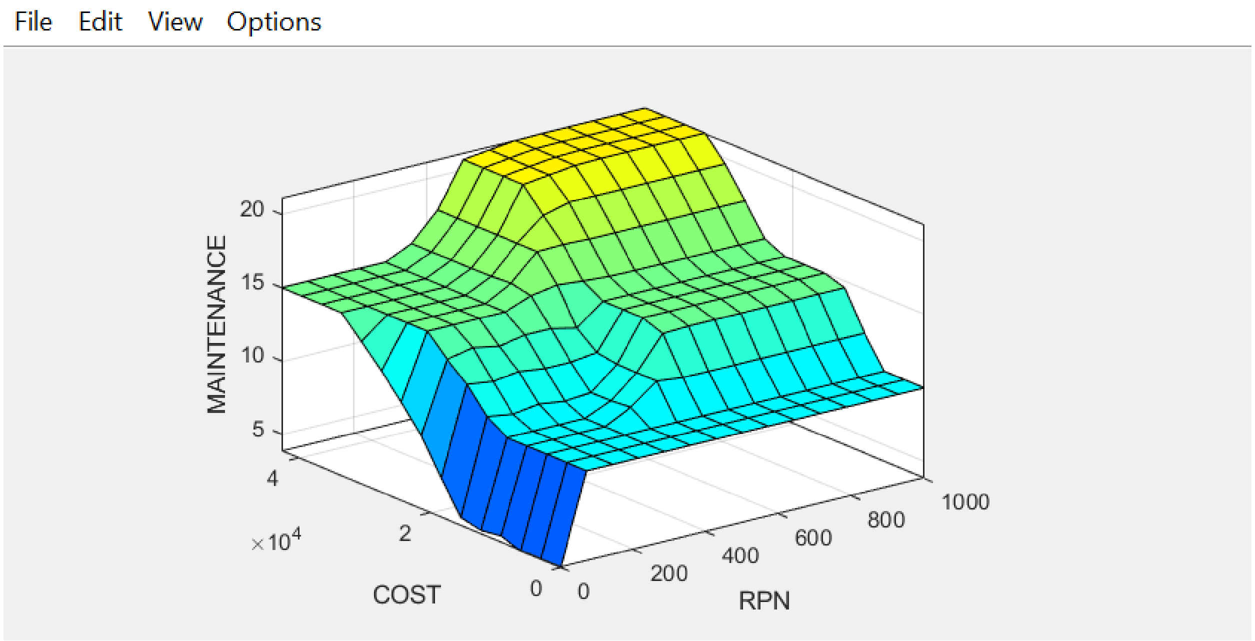
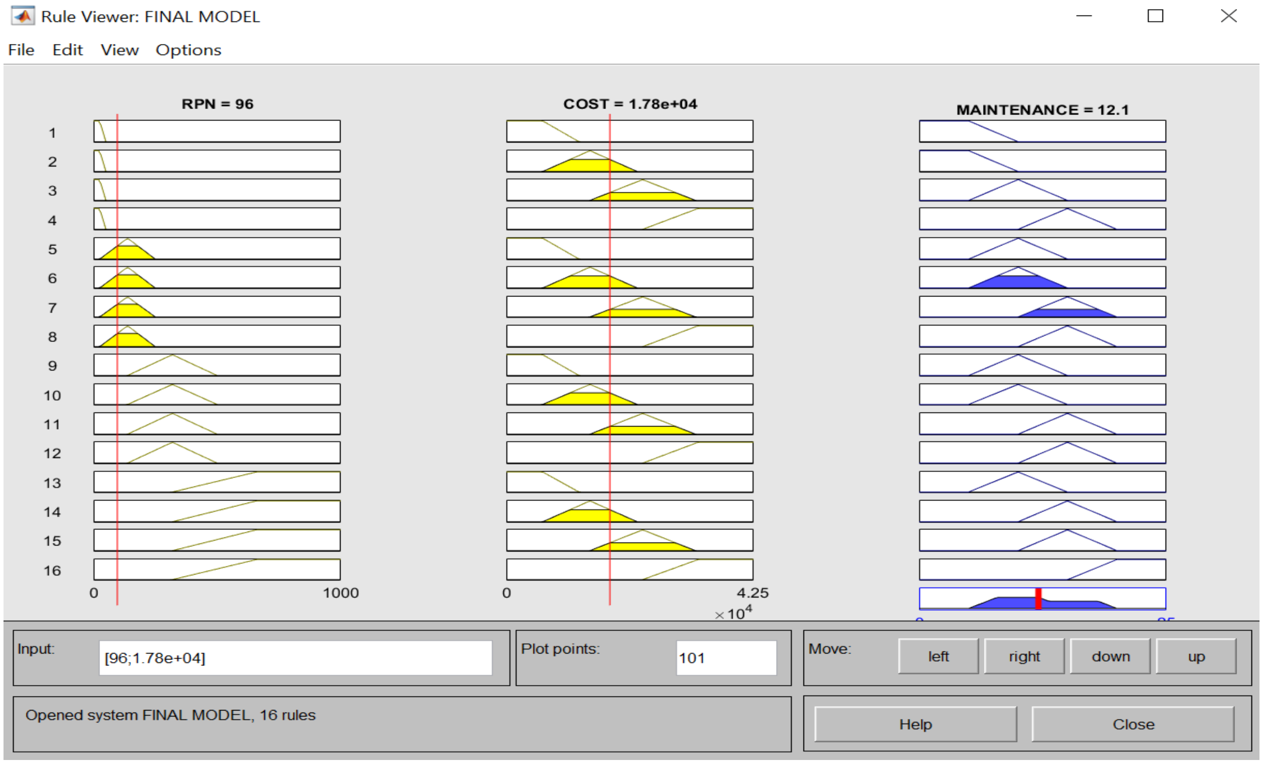


Figure 14: Fuzzy Rule Surface View



Input: [96;1.78e+04]

Plot points: 101

Opened system FINAL MODEL, 16 rules

Figure 15: Rule viewer

CHAPTER 4

4.0 Results and discussion

4.1 Results

After the data collection, the AALRT braking system risk assessment was carried out by FMECA and the RPN obtained. The AALRT braking system is made up of three different systems ie ED, EH, and MB. From the risk assessment using the FMECA on the AALRT, we discovered 42 failure modes with 20 major events and 22 minor events. The minor errors would trigger the fail-safe mode of the braking system whereas the major errors would cause insufficient or no braking even with the application of the safety brake and emergency brakes. The complete failure of the electronic circuit boards for BCU and HCM was taken as a major event since their failure would reduce the braking force although the application of the safety brake would ensure full braking. In the minor events, we also encountered some human errors and these were quantified as a function of the level of training, motivation, stress, and the support provided to the employees by their supervisors. We discovered a common regular event of leakage, which was due to both system component failure, and human errors ie oil leakage due to over-tightening of joint fittings and this calls for training of maintenance personnel to avoid such failures. All the major events were encountered on the moving components such as brake pads. The priority for maintenance based on the RPN was as shown in tab.11 and the brake pads had the highest RPN implying the need for more attention on the component.

Table11: Component Priority for Maintenance based on RPN

COMPONENT	RPN
Brake pad	600
HU (trailer car)	432
HU (motor car)	432
Brake caliper	336
Brake disc	280
Magnetic valves	135
Oil tank	96
Motor/pump	72

Pressure sensor	70
Hosepipe	64
Speed sensor	60
Load sensor	60
Oil filter	54
Diaphragm accumulator	42
BCU	24
Relay switch	24
Electro magnet	21
Fitting	20
TCU board	18
HCM	16

The maintenance cost of failure due to failure was integrated to ensure that we strike a balance between the safety of the train system and the failure maintenance cost within the maintenance decision. As shown in fig.16, we see that some components like fittings have a low risk and low cost due to failure occurrence implying the need for a relatively low-cost maintenance method. The quantitative value of each component in terms of maintenance cost and RPN was input to the fuzzy system and output was obtained as a crispy value for a maintenance practice It should also be noted that the electronic circuits of the BCU, HCM, and TCU are not affected by mechanical wear and therefore do not need any maintenance. Proper operation of the circuit boards is tested continuously during normal running. Any errors detected will be displayed. The results as shown in tab.11 showed that moving components required more attention as they are more susceptible to wear and to do this the results showed that CBM, TPM, and BM can be employed for the respective components.

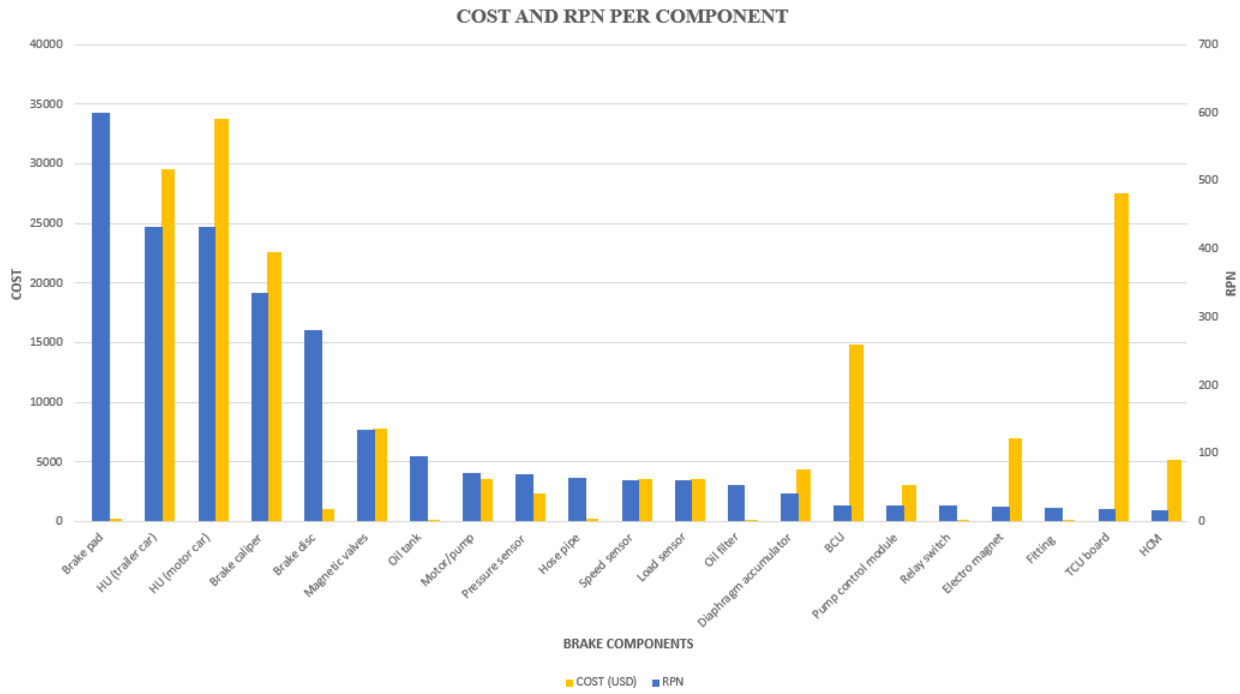


Figure 16: Risk and Cost per Component

As shown in fig.16, the RPN does not depend on the cost of maintenance due to failure that's to say a high risk does not necessarily mean a high cost of maintenance e.g. the brake pad failure has the highest threat to passenger and train safety but a relatively low maintenance cost. This implies that a balance has to be made between the risk and the cost with the risk having the higher priority with respect to the cost during maintenance decision making. The best way to strike the balance is by reducing the rate of occurrence of the failure modes. When we reduce the occurrence rate, the cost of maintenance due to failure will also reduce automatically. The two inputs were run into the proposed fuzzy logic maintenance selection model and the suggested maintenance practices were as shown in Tab.12.

Table 12: Maintenance Model Results

COMPONENT	RPN	COST	MAINTENANCE SCALE	MAINTENANCE PRACTICE
HU	432	29517	17.8	TPM
		33717		
Oil tank	96	41	4.62	BM

Oil filter	54	41	4.2	BM
Pressure sensor	70	2317	4.46	BM
Diaphragm accumulator	42	4367	5.55	BM
Magnetic valves	135	7817	5.14	BM
Brake caliper	336	22617	17	TPM
Brake pad	600	284	10	CBM
Brake disc	280	1066	10	CBM
Speed sensor	60	3514	4.56	BM
Fitting	20	132	3.82	BM
Motor/pump	72	3517	4.43	BM
Relay switch	24	63	3.82	BM
Hosepipe	64	202	4.52	BM
Electro magnet	21	7017	3.94	BM
Load sensor	60	3517	4.56	BM

4.2 Discussion

This research was aimed at identifying the risk components of the light rail train and propose a means of minimizing the risks through maintenance to ensure the safety of the passengers, railway infrastructure, and the environment. The braking system was selected due to its accumulated failures and its crucial role in the safety of human mass transportation. This research proposed a fuzzy logic maintenance selection model that related the risk and the failure cost as a means of improving maintenance decisions for light rail trains. The fuzzy logic model used both the RPN and cost as inputs and the output to be the maintenance strategy. The model was created on expert opinion that risk is given more priority as compared to the cost during selecting a maintenance strategy. However, the maintenance experts also acknowledged that the failure cost is very important in selecting an effective maintenance strategy so as to achieve the overall objectives of the organization. It was also realized that a modern braking system is not only made up of mechanical components but also other elements which may include electronic, hydraulic, electromechanical elements, software, and human beings. All these elements can contribute to system failure. The new model can still be implemented at a full system-level e.g. the whole rolling stock vehicle and different systems are considered. As we all know that the accuracy of maintenance selection depends on the data analyzed this model ensures accuracy of the selection since different systems are looked at in detail and understood in terms of risk. As shown in tab.13 there is a slight variation in the recommended maintenance practice by the manufacturer of the light rail trains eg the hydraulic unit is repaired after a failure signal and the model results called for a TPM. This is reflected by the relative importance and risk of this component and its high maintenance cost. The manufacturer recommended that the lifetime of the hydraulic unit is about ten years subject to a 5-year overhaul however there has been a failed hydraulic unit within the 5-years of operation. This is due to several reasons that include maintenance and human maintenance errors. Out of the 16 components that underwent assessment, three components had a different maintenance practice as opposed to the model results. This further indicated that the proposed maintenance selection model proved realistic and reliable for maintenance decision-making because of a slight variation in the maintenance practices proposed by the manufacturer's maintenance manual. The overall results suggest that CBM and TPM are suitable for the light rail braking system.

Table 13: Current vs Suggested Maintenance

COMPONENT	**CURRENT MAINTENANCE**	**SUGGESTED MAINTENANCE**
HU	BM	TPM
Oil tank	BM	BM
Oil filter	BM	BM
Pressure sensor	BM	BM
Diaphragm accumulator	BM	BM
Magnetic valves	BM	BM
Brake caliper	TPM	TPM
Brake pad	CBM	CBM
Brake disc	CBM	CBM
Speed sensor	BM	BM
Fitting	BM	BM
Motor/pump	BM	BM

Relay switch	BM	BM
Hosepipe	TPM	BM
Electromagnet	TPM	BM
Load sensor	BM	BM

4.2.1 Validation of the model

The validation step seeks to validate the technique used and the maintenance selection model used to perform the benchmark and prediction analyses. As mentioned in the literature, the Unit Cost per maintenance is subject to change, therefore while the approach can be validated, the maintenance cost as a result of failure is expected to increase accordingly. The validation process was based on Jianqiang et. al[62] who proposed a model for determining the key components in automobile braking systems that were based on FMECA and ABC classification. The model was calibrated by using case data from a bus braking system, and the components of the braking system were compared and analyzed. This method is aimed at attaining efficient maintenance work, identifying the most critical components in addition to reducing the organization's administrative costs. During the model application, the RPN value was initially derived using FMECA, which reflected the safety and reliability of the system component. As an economic indicator, this was then combined with the cost of upkeep. The authors used ABC classification on the parts and relied on Pareto's law to categorize the parts ie: parts that need close monitoring as Class A, parts that need regular review as Class B, and parts that need less attention as Class C. To validate the suggested model in this study, the input data (RPN and cost) of the ABC classification was used the suggested fuzzy logic maintenance selection model and in this case, the output was represented as; class A as CBM, class B as TPM and class C as BM. As shown in tab.14, we related the results of both models with the same inputs and there was a slight variation in the maintenance practices proposed. Out of the 17 components, 11 matched the proposed practices by the authors, 5 components (Brake pipe, Gas reservoir, Rear wheel brake cylinder, Hand brake valve, and Front tire) called for more attention, and one component (Air compressor) called for less attention as opposed to the authors of the ABC classification. The variation in the results is reflected in the fact that as mentioned earlier that in the fuzzy logic model, the RPN was given higher priority as compared to the maintenance cost eg the results for the gas reservoir as per the fuzzy model, the component moved from class B to class A and this can be explained by the high/very high RPN and relatively low/medium cost. On the other hand, the air compressor shifted from class B to class C due to a low RPN and low cost.

Table 14: Fuzzy Logic vs ABC classification

COMPONENT	**RPN**	**COST**		**MAINTENANCE**			
		YUAN	**USD**	**Fuzzy Model results**			**ABC model Results**
Brake pipe	72	150,700	23614.69	15	TPM	B	C
Front brake	192	32,100	5030.07	6.17	BM	C	C
Gas reservoir	256	12,780	2002.63	10	CBM	A	B
Rear wheel brake cylinder	96	207,900	32577.93	15	TPM	B	C
Hand brake valve	144	100,000	15670	15	TPM	B	C
Rear brake	192	20,100	3149.67	6.17	BM	C	C
Air compressor	88	21,546	3376.26	4.27	BM	C	B
Quick-release valve	96	5145	806.22	4.2	BM	C	C
Check valve	144	2400	376.08	4.08	BM	C	C
Brake master cylinder	80	39600	6205.32	4.35	BM	C	C
Four-wheel brake adjustment	96	1920	300.86	4.2	BM	C	C
Hand brake two-way flow valve	144	10625	1664.94	4.08	BM	C	C
Hand brake adjustment	48	10000	1567	4.69	BM	C	C
Pressure-regulating valve	32	315	49.36	4.1	BM	C	C
Front tire	288	64800	10154.16	10	CBM	A	B
Rear cover tire	192	112000	17550.4	12.1	CBM	A	A
Rear inner tube	480	136200	21342.54	14	TPM	B	A

Chapter 5

5.0 Conclusions, recommendations & future work

5.1 Conclusions

As the train, operating speed continues to improve in railway transportation, the effectiveness, reliability, and availability of the train systems is key to the safety of the passengers, railway infrastructure, and avoid costs incurred due to the occurrence of a hazard. To ensure this, understanding the risks connected with the light rail train systems is essential, and the first way to minimize these risks is through effective maintenance. System failures are normally related to maintenance methods and implementation by an organization. These system failures can prove to be costly and have very high safety-related consequences that may lead to catastrophic events such as loss of lives. The majority of the challenges in the field of maintenance are associated with failures and their prevention. Understanding why, when, and how components fail should therefore play an important role in many aspects of maintenance management and engineering. Increasing safety and efficiency of systems can be obtained through the optimization of maintenance tasks. In this research, the risk assessment aimed at identifying the most risky components of the light rail systems in terms of safety and suggested a maintenance selection model assist in maintenance decisions of light railway systems. The assessment was carried out on the train braking system was selected due to its accumulated failures and its crucial role in the safety of human mass transportation. Based on the FMECA analysis, 42 failure modes were discovered with 20 major events and 22 minor events concerning the light rail train. Four key components affecting the safety of the braking system of the light rail were presented i.e. Brake pads, hydraulic units, Brake caliper, and the Brake disc evidenced by a high RPN. The proposed fuzzy logic maintenance selection model compared the RPN and the maintenance failure cost per component to select an appropriate maintenance practice. The research outcomes proved realistic as the mechanical components such as brake pads, discs, and caliper called for more attention than the other components in terms of maintenance as suggested by the manufacturer’s maintenance manual. Concerning safety, the overall results showed that CBM and TPM are suitable for the light rail trains. Adoption of this model in the light rail train maintenance will help improve general maintenance planning and decision making as it gives a maintenance strategy based on the critical/high-risk systems and the cost to be lost internally due to failure.

5.2 Recommendations

Every system has an early infant mortality phase defined by a high failure rate followed by a period of diminishing failure. The infant mortality period is generally followed by a functional life with a steady failure rate. Then comes the wear-out stage, which is distinguished by a rapidly increasing failure rate over time. When carrying out the assessment, the maintenance personnel should put into consideration these periods. Similarly, following the recent trends, new maintenance strategy changes are always introduced with new options and practices developed and this is due to the changes in operational requirements and technology with cost-effectiveness. Therefore, for both safety and cost-effectiveness, the LRT maintenance management should also be adaptive to the dynamics of maintenance and safety. Additionally, an automatic diagnostic system should be adopted to easily identify possible root causes of recorded faults

Implementation of maintenance practices

Regarding the AALRT manufacturer's maintenance manual, one identified high-risk component ie the hydraulic unit had a different maintenance practice related to the proposed practices in this research and this is may be attributed to the work environment to non-anticipated failures.

Table 15: Proposed Maintenance Practices

Component	Manufacturer	Proposed maintenance
Hydraulic unit	Break down maintenance and subject to 5-year overhaul. Inspection; not specified	Yearly inspection to sight check for unnecessary leakages and wear since the hydraulic brake system can only be guaranteed to function well if the oil level in the brake system complies with the recommended levels.

5.3 Future work

- Assess the effectiveness of the risk assessment and maintenance selection model.
- Application of the method to other systems and generate an overall maintenance plan for the whole system.
- Use of another risk assessment method e.g. fault tree analysis and make a comparison with the FMECA on the same system
- Addition of more parameters in the model such as the value-added by the maintenance practice.

Reference

[1] N. H. B. Nordin, M. I. H. Mohd Masirin, M. I. Bin Ghazali, and M. I. Bin Azis, "Appraisal on Rail Transit Development: A Review on Train Services and Safety," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 226, no. 1, 2017, doi: 10.1088/1757-899X/226/1/012034.

[2] "Malaysia's Light Rail Transit Train Doors Stay Open While Moving, Just Two Months After Collision Incident - AUTOMOLOGY: automotive + logy (the study of)." https://www.automology.com/malaysias-light-rail-transit-trains-door-stays-open-with-train-moving-just-months-after-collision-incident/ (accessed Aug. 03, 2021).

[3] "1 Killed, 2 Hurt In St. Paul Light Rail Crash – WCCO | CBS Minnesota." https://minnesota.cbslocal.com/2021/07/04/1-killed-1-hurt-in-st-paul-light-rail-crash/ (accessed Aug. 03, 2021).

[4] S. Kumar, "Study of Rail Breaks : Associated Risks and Maintenance Strategies Study of Rail Breaks : Associated Risks and Maintenance Strategies," p. 33, 2006.

[5] F. Dinmohammadi, B. Alkali, M. Shafiee, C. Bérenguer, and A. Labib, "Risk Evaluation of Railway Rolling Stock Failures Using FMECA Technique: A Case Study of Passenger Door System," *Urban Rail Transit*, vol. 2, no. 3–4, pp. 128–145, 2016, doi: 10.1007/s40864-016-0043-z.

[6] A. W. Siddiqui and M. Ben-Daya, "Reliability centered maintenance," *Handb. Maint. Manag. Eng.*, pp. 397–415, 2009, doi: 10.1007/978-1-84882-472-0_16.

[7] G. Cai, Y. Wang, Q. Song, and C. Yang, "RAMS analysis of train air braking system based on Go-Bayes method and big data platform," *Complexity*, vol. 2018, p. 4, 2018, doi: 10.1155/2018/5851491.

[8] M. An, Y. Chen, and C. J. Baker, "A fuzzy reasoning and fuzzy-analytical hierarchy process based approach to the process of railway risk information: A railway risk management system," *Inf. Sci. (Ny).*, vol. 181, no. 18, pp. 3946–3966, 2011, doi: 10.1016/j.ins.2011.04.051.

[9] A. T. D. Muluken, "'Selection of Maintenance Strategy by AHP Algorithm for Light Rail Transit System,'" pp. 10–17, 2017, [Online]. Available: www.esme-ethiopia.org.

[10] R. I. Muttram, "Railway safety's safety risk model," *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit*, vol. 216, no. 2, pp. 71–79, 2002, doi: 10.1243/09544090260082317.

[11] J. Sekulová and E. Nedeliaková, "Risks Assessment in Railway Passenger Transport in Relation To Cutomers," pp. 79–89, 2015.

[12] W. Górka, "Cloud decision support system for risk management in railway transportation," *ICSOFT 2019 - Proc. 14th Int. Conf. Softw. Technol.*, no. Icsoft, pp. 475–482, 2019, doi: 10.5220/0007837904750482.

[13] G. Purdy, "ISO 31000:2009 - Setting a new standard for risk management: Perspective," *Risk Anal.*, vol. 30, no. 6, pp. 881–886, 2010, doi: 10.1111/j.1539-6924.2010.01442.x.

[14] L. Sultan and J. Haq, "Risk analysis method: FMEA/FMECA in the organizations," *Int. J. Basic Appl. Sci. IJBAS-IJENS*, vol. 11, no. 05, pp. 74–82, 2011.

[15] B. T. McKinney, "FMECA, the right way," *Proc. Annu. Reliab. Maintainab. Symp.*, pp. 253–259, 1991, doi: 10.1109/arms.1991.154444.

[16] L. Ciani, G. Guidi, and G. Patrizi, "A Critical Comparison of Alternative Risk Priority Numbers in Failure Modes, Effects, and Criticality Analysis," *IEEE Access*, vol. 7, no. D, pp. 92398–92409, 2019, doi: 10.1109/ACCESS.2019.2928120.

[17] M. Rausand, "Fmeca.Pdf," pp. 1–46, 2005.

[18] Y. Chen, C. Ye, B. Liu, and R. Kang, "Status of FMECA research and engineering application," *Proc. IEEE 2012 Progn. Syst. Heal. Manag. Conf. PHM-2012*, pp. 1–9, 2012, doi: 10.1109/PHM.2012.6228914.

[19] Agency of the Government of Ontario "Metrolinx FMECA (Failure Modes , Effects , and Criticality Analysis)," 2020.

[20] J. Kim and H. Y. Jeong, "Evaluation of the adequacy of maintenance tasks using the failure consequences of railroad vehicles," *Reliab. Eng. Syst. Saf.*, vol. 117, pp. 30–39, 2013, doi: 10.1016/j.ress.2013.03.008.

[21] B. Lu, P. Hua, Z. Fu, and F. Gao, "Case study on FMECA and risk assessment for the door system in high speed train," *Adv. Mater. Res.*, vol. 655–657, pp. 2335–2339, 2013, doi: 10.4028/www.scientific.net/AMR.655-657.2335.

[22] P. Liu, X. Cheng, Y. Qin, Y. Zhang, and Z. Xing, "Reliability analysis of metro door system based on fuzzy reasoning petri net," *Lect. Notes Electr. Eng.*, vol. 288 LNEE, no. VOL. 2, pp. 283–291, 2014, doi: 10.1007/978-3-642-53751-6_29.

[23] D. Vernez and F. Vuille, "Method to assess and optimise dependability of complex macro-systems: Application to a railway signalling system," *Saf. Sci.*, vol. 47, no. 3, pp. 382–394, 2009, doi: 10.1016/j.ssci.2008.05.007.

[24] Y. H. Li, Y. D. Wang, and W. Z. Zhao, "Bogie failure mode analysis for railway freight car based on FMECA," *Proc. 2009 8th Int. Conf. Reliab. Maintainab. Safety, ICRMS 2009*, pp. 5–8, 2009, doi: 10.1109/ICRMS.2009.5270253.

[25] C. S. Carlson, "Failure Mode and Effects Analysis (FMEA) UNDERSTANDING THE FUNDAMENTAL DEFINITIONS AND," *John Wiley Sons*, 2012.

[26] M. Rausand, "Chapter 3 System Analysis Event Tree Analysis," *October*, pp. 1–28, 2005.

[27] W. A. Wolfe, "Fault Tree Analysis.," *At. Energy Canada Limited, AECL*, no. 6172, pp. 1–18, 1978, doi: 10.1177/1062860615614944.

[28] W. Ming-Yan, W. Hong, and Z.-G. Liu, "Reach on Fault Tree Analysis of Train Derailment in Urban Rail Transit," *Int. J. Bus. Soc. Sci.*, vol. 5, no. 8, pp. 128–135, 2014.

[29] PQRI, "Hazard & Operability Analysis (HAZOP)," *Risk Manag. Train. Guid.*, pp. 1–9,

2014.

[30] AcuTech, “The HAZOP (Hazard and Operability) Method,” pp. 1–7, 2012, [Online]. Available: http://158.132.155.107/posh97/private/accident-prevention/HAZOP_Technique.pdf.

[31] J. Hwang, “Risk Analysis Method Applied to Train Control Systems for Safety Assurance,” no. January 2007, 2015.

[32] L. O. A. Affonso, *Machinery Failure Analysis Handbook: Sustain Your Operations and Maximize Uptime*, First Edit., vol. 1. Gulf Publishing Company, 2007.

[33] Y. Wang, U. A. Weidmann, and H. Wang, “Using catastrophe theory to describe railway system safety and discuss system risk concept,” *Saf. Sci.*, vol. 91, pp. 269–285, 2017, doi: 10.1016/j.ssci.2016.08.026.

[34] R. C. Sharma, M. Dhingra, and R. K. Pathak, “Braking systems in railway vehicles,” *Int. J. Eng. Res. Technol.*, vol. 4, no. 1, pp. 206–211, 2015.

[35] C. G. Kang, “Analysis of the braking system of the Korean high-speed train using real-time simulations,” *J. Mech. Sci. Technol.*, vol. 21, no. 7, pp. 1048–1057, 2007, doi: 10.1007/BF03027654.

[36] F. Ng, J. A. Harding, and J. Glass, “Improving hydraulic excavator performance through in line hydraulic oil contamination monitoring,” *Mech. Syst. Signal Process.*, vol. 83, pp. 176–193, 2017, doi: 10.1016/j.ymssp.2016.06.006.

[37] I. Alsyouf, “The role of maintenance in improving companies’ productivity and profitability,” *Int. J. Prod. Econ.*, vol. 105, no. 1, pp. 70–78, 2007, doi: 10.1016/j.ijpe.2004.06.057.

[38] B. Santoso, “王丽丽 1 贾丽娜 2 罗跃嘉 3 (1,” *J. EECCIS*, vol. 3, no. 2, pp. 1–6, 2018, [Online]. Available: https://www.sparkfun.com/datasheets/Components/SMD/ATMega328.pdf%0Ahttps://journal.uinsgd.ac.id/index.php/istek/article/view/1476%0Ahttps://ejournal.unib.ac.id/index.php/jurnalenggano/article/download/1357/1132%0Ahttp://jurnal.polines.ac.id/jurnal/index.p.

[39] M. Niraj and P. Kumar, “Selection of Maintenance Practice through Fuzzy Logic Based Simulation in TPM,” *Int. J. Sci. Eng. Res. Vol.*, vol. 2, no. 8, pp. 1–5, 2011.

[40] J. J. George, V. R. Renjith, P. George, and A. S. George, “Application of fuzzy failure mode effect and criticality analysis on unloading facility of LNG terminal,” *J. Loss Prev. Process Ind.*, vol. 61, pp. 104–113, 2019, doi: 10.1016/j.jlp.2019.06.009.

[41] B. S. Dhillon, *Engineering maintenance: A modern approach*. 2002.

[42] B. W. Niebel, *Engineering Maintenance Management*. 1994.

[43] M. P. Cavalier and G. M. Knapp, “Reducing preventive maintenance cost error caused by uncertainty,” *J. Qual. Maint. Eng.*, vol. 2, no. 3, pp. 21–36, 1996, doi:

10.1108/13552519610130422.

[44] D. S. Thomas and D. S. Thomas, “The Costs and Benefits of Advanced Maintenance in Manufacturing NIST AMS 100-18.”

[45] Haroun, Ahmed E. “Maintenance cost estimation: application of activity-based costing as a fair estimate method,” *Journal of Quality in Maintenance Engineering*, vol. 21, no. 3. pp. 258–270, doi: 10.1108/JQME-04-2015-0015.

[46] A. N. O. kheiry Mohamed Hassan Dahab, Awad omer mohamed, “Repair and Maintenance Costs Estimation as Affected by Hours of Use and Age of Agricultural Tractor in New Halfa Area - Sudan,” vol. 4, no. 5, pp. 824–830, 2016.

[47] J. C. Granja-Alvarez and M. J. Barranco-García, “A method for estimating maintenance cost in a software project: A case study,” *J. Softw. Maint. Evol.*, vol. 9, no. 3, pp. 161–175, 1997, doi: 10.1002/(sici)1096-908x(199705)9:3<161::aid-smr148>3.0.co;2-8.

[48] C. Stenström, P. Norrbin, A. Parida, and U. Kumar, “Preventive and corrective maintenance – cost comparison and cost–benefit analysis,” *Struct. Infrastruct. Eng.*, vol. 12, no. 5, pp. 603–617, 2016, doi: 10.1080/15732479.2015.1032983.

[49] E. Adolfsson and T. Dahlström, “Efficiency in corrective maintenance - a case study at SKF Gothenburg,” p. 59, 2011.

[50] A. Gillespie, “Condition Based Maintenance : Theory , Methodology , & Application Amanda Gillespie Table of Contents,” *Reliab. Maintainab. Symp. Tarpon Springs, FL*, no. September, 2015, [Online]. Available: https://www.researchgate.net/publication/271643051_Condition_Based_Maintenance_Theory_Methodology_Application.

[51] B. V. A. Rao, “Condition Monitoring - Condition Based Maintenance.,” *J. Inst. Eng. Mech. Eng. Div.*, vol. 66, no. pt 5, pp. 123–129, 1986.

[52] A.- Ama, “Implementation of Total Productive Maintenance (TPM) In Nigerian Manufacturing Industries (Brewery),” vol. 9, no. 6, pp. 29–41, 2020, doi: 10.35629/6734-0906012941.

[53] S. G. Katkamwar, S. K. Wadatkar, and R. V Paropate, “Study of Total Productive Maintenance & Its Implementing Approach in Spinning Industries,” *Int. J. Eng. Trends Technol.*, vol. 4, no. 5, pp. 1750–1754, 2013.

[54] I. Alsyouf, *Cost effective maintenance for competitve advantages*. 2004.

[55] A. K. Jain, “Influence of Modification of Design out Maintenance & Design Out Information System For Maintenance Cost Control & A Lucrative Business (With Case Study). ISSN : 2231-5381 ISSN : 2231-5381,” vol. 4, pp. 1–9, 2013.

[56] P. Muganyi, C. Mbohwa, and I. Madanhire, “Design-Out Maintenance as a crucial maintenance facet,” *Proc. Int. Conf. Ind. Eng. Oper. Manag.*, vol. 2018-March, pp. 3406–3416, 2018.

[57] A. Sadollah, “Introductory Chapter: Which Membership Function is Appropriate in Fuzzy System?,” *Fuzzy Log. Based Optim. Methods Control Syst. its Appl.*, pp. 3–6, 2018, doi: 10.5772/intechopen.79552.

[58] J. Zhao and B. K. Bose, “Evaluation of membership functions for fuzzy logic controlled induction motor drive,” *IECON Proc. (Industrial Electron. Conf.*, vol. 1, pp. 229–234, 2002, doi: 10.1109/iecon.2002.1187512.

[59] K. Rashidpour, “Using Improved AHP Method in Maintenance Approach selection,” p. 77, 2013.

[60] J. E. Bartlett II, J. W. Kotrlik, and C. C. Higgins, “Determing appropriate sample size in survey research,” *Inf. Technol. Learn. Perform. J.*, vol. 19, no. 1, pp. 43–50, 2001, [Online]. Available: https://www.opalco.com/wp-content/uploads/2014/10/Reading-Sample-Size1.pdf.

[61] Glenn.D, University of Florida, IFAS Extension, *Methods*, vol. 36, no. 10. 1989.

[62] J. Gong, Y. Luo, Z. Qiu, and X. Wang, “ScienceDirect Determination of key components in automobile braking systems based on ABC classification and FMECA,” *J. Traffic Transp. Eng. (English Ed.*, no. xxx, pp. 1–9, 2020, doi: 10.1016/j.jtte.2019.01.008.

APPENDIX

Appendix I Questionnaire Personal Profile

a) Name of respondent: ______________________________

b) Address: Email…………………………….. Telephone…………………………….

c) Gender: Male ☐ Female ☐

d) Age group: Below 25 ☐ 25 to 34 ☐ 35 to 44 ☐ 45 and above ☐

e) Title/ work type:_______________________________

f) Year of experience: :_______________________________

g) What is your highest attainment in education?

High school graduate ☐ Diploma Bachelor degree ☐

Master's Degree ☐ Doctorate degree ☐

Other(s), please specify: ____________________

h) Have you ever participated in any maintenance-related activity particularly rolling stock?

YES ☐ NO ☐

i) If your answer to the above question is yes, what role do (did) you play in the maintenance department?

____

j) Would you like to participate in our second stage questionnaire survey concerning the train brake system failure?

YES ☐ NO ☐

Thank you so much for your kind participation in this survey.

Appendix II Questionnaire Train braking system

Risk assessment questionnaire explanation

This research study intends to assess the risks associated with the light rail transit braking system so as to recommend the best maintenance strategy for the braking system. In this research, we intend to use the past failure records and expert opinions on the related failure of the train braking system components/modes. The expert opinion is to help us understand the failure modes of different components, the causes, and the effects of these failures in regards to the safety of passengers.

Your inputs are tremendously valuable and we do hope that you can participate in this survey. It would be much appreciated if you could spend around 45 minutes to complete and return the completed questionnaire in person. Should you have any queries, please feel free to contact Mr. Mpiima Isaac by email address mpiimaisaac95@gmail.com or phone +251987006845 / +256774649523. Thank you for your time and efforts on this research.

Instructions

- Please read each question carefully before giving your opinions/answers in both section A and B
- Each section in this survey consists of several question sets.
- section A consists of structured questions that may require simple answers and section B consists of rating questions in which you are required to use a scale rating of 1-10 to give a quantitative view of your opinion and answer according to the following rating criteria:

Thank you so much for your kind participation in this survey.

Section A

This section requires short and precise answers

a. What is the importance of the braking system to the train?

____
____

b. List some of the most important components of the braking system?

____
____
____

c. What do you think are the possible causes of train brake failure?

____
____
____
____

d. What are the possible effects/consequences of the braking system failure?

____
____
____
____

e. What methods have been put in place to detect a failure in any component of the braking system?

____
____
____
____

f. Suggest any methods to reduce brake failures

____
____
____
____

g. Do you think that maintenance can help to prevent brake failures?

YES ☐ NO ☐

h. Name the maintenance methods currently used at your cooperation.

____

____

____

____

i. Considering the risks below, what maintenance method would you recommend for this risk to ensure train safety

Very high risk: ____

High risk: ____

Medium risk: ____

Low risk: ____

Very low risk: ____

j. While selecting a maintenance strategy, do you think the cost of maintenance incurred as a result of a component failure should be put into consideration?

YES ☐ NO ☐

k. If yes, why would you consider this cost during the selection of the maintenance strategy

____

____

l. Considering the cost of maintenance, which maintenance strategy would you suggest for the following;

Very high cost: ____

High cost: ____

Medium cost: ____

Low cost: ____

Very low cost: ____

Thank you so much for your kind participation in this survey.

Section B

In this section, you are required to use the following ranking criteria to answer the questions that follow

Criteria for severity/ consequences of failure

Criteria for ranking severity	**effect**	**rank**
Failure occurs without warning	Deadly	10
Failures occur with a warning	Hazardous	9
System inoperable, with loss of function	Very serious	8
System operable but with loss of performance	Serious	7
System operable but with loss of performance	Moderate	6
System operable but with low effect on performance	Low	5
Noticeable effect on the operation	Very low	4
Noticeable effect on the operation	Minor	3
Noticeable effect on the operation	Very minor	2
No effect on the operation	none	1

Criteria for detection

Chances of detection of failure mode	**Rank**
No known controls are available	10
Very remote chances of detection	9
Remote chances of detection	8
Very low chances of detection	7
Low chances of detection	6
Moderate chances of detection	5
Moderately high chances of detection	4
High chances of detection	3
Very high chances of detection	2
Almost certain to detect	1

What are the consequences/severity/effects of the component failure?										
Component	**Ranking**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Brake control unit (BCU)										
Hydraulic unit										
Hose pipes										
Speed sensors										
Diaphragm Accumulator										
Brake caliper										
Brake pad										
Brake disk										
Oil pump										
Pressure switch										
Oil filter										
Magnetic valve										
Relay switch										
Other components										

Thank you so much for your kind participation in this survey.

What are the chances of detection of failure mode of the component?										
Component	**Ranking**									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Brake control unit (BCU)										
Hydraulic unit (HCU)										
Hose pipes										
Speed sensors										
Diaphragm Accumulator										
Brake caliper										
Brake pad										
Brake disk										
Oil pump										
Pressure switch										
Oil filter										
Magnetic valve										
Relay switch										
Other components										

Thank you so much for your kind participation in this survey.