FACTORS AFFECTING THE RELIABILITY OF MOTOR COACHES WITHIN METRORAIL IN THE GAUTENG REGION

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DECLARATION

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I understand what plagiarism implies and declares that this mini-dissertation contains my own ideas, words, phrases, arguments, graphics, figures, results and organisation, except where reference is explicitly made to another's work.

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ABSTRACT

In most countries today, railway services form the backbone of the transport system. A passenger train's service is one mode of transport that is widely used in most countries across the world.

Over the past few years, PRASA, one of the passenger railway operators in South Africa has been experiencing a tremendous decline in performance of its rolling stock fleet. The direct impact of this decline in performance has led to a reduction in patronage, loss of revenue and poor company reputation. From the literature reviewed, there is less insufficient evidence regarding the challenges this organisation is facing. The purpose of this study was to explore the factors that affect the reliability of the fleet with the aim of assisting the organisation improving its fleet performance. The class 5M2A motor coaches operating in Gauteng region was used as the population of interest for this research.

In this study, data was collected through mixed method approach in order to assist in answering the research questions and to ensure the research objectives are achieved. The source data used for the study included the failure data for the 5M2A motor coaches operating in Gauteng region and the survey results.

According to failure data results, the following subsystems (windows, line/combination switches, traction motors, exhausters, pantograph, brake system, wheels, compressors, cables, traction controllers, accelerating/braking grids and valves) were responsible for 90% of the fleet failures. The cab equipment, body/underframe and MA/MG were responsible are for 20% of the motor coach failures.

From survey questionnaires, the study revealed that the mostly used maintenance strategies by the organisation were preventative maintenance (95%), corrective maintenance (88%) and reliability centered maintenance (55%). Despite the organisation having a formalised maintenance strategy that is aligned to the corporate plan, the organisation needs focus on upskilling its maintenance personnel, invest more its financial resources on systems, tools and technologies the can assist it to improve the overall performance of its fleet.

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LIST OF ABBREVIATIONS

CMMS	Computerized Maintenance Management System
CBM	Condition-Based maintenance
CM	Corrective Maintenance
DOT	Department of Transport
EMU	Electric Multiple Units
FMMS	Facility Maintenance Management System
FMEA	Failure Mode and Effects Analysis
FRACAS	Failure Reporting and Corrective Action Systems
FTA	Fault Tree Analysis
ICT	Information and Communication Tools
ILS	Integrated Logistics Support .
FIFA	International Federation of Association Football
KPI	Key Performance Indicators
LCC	Life Cycle Cost
MDT	Mean Down Time
MTBF	Mean Time Between Failures
MTTF	Mean Time to Failure
Pd.M	Predictive Maintenance
MA	Motor Alternator
NDP	National Development Plan
NRP	National Rail Plan
PRASA	Passenger Rail Agency of South Africa
PS&C	Passenger Safety and Comport
Pd.M	Predictive Maintenance
PM	Preventative Maintenance
PAM	Proactive Maintenance

RSR.. Railway Safety Regulator
RDB.. Reliability Block Diagram
RCM .... Reliability Centered Maintenance
RIC .... (Russian, Indian and Chinese Railways)
RCA.. Root Cause Analysis
SA .... South Africa
SADC .... Southern African Development Community
SOPs.. Standard Operating Procedures
SOE.. State Owned Enterprise
TM.. Traction Motors
TFR .... Transnet Freight Rail

CHAPTER 1: INTRODUCTION

1.1 Introduction

In most countries today, railway services form the backbone of the transport system. A passenger train's service is one mode of transport that is widely used in most countries across the world. With that said, there is a need to ensure that trains are on time, safe, and reliable to cater for this demand. With increased passenger and freight loads, more mechanisms that are more efficient and effective are required to handle this increase in demand (Nath, 2014). This growing need calls for measures to achieve a high availability of railway services and it requires higher levels of system reliability at the operational level. The reliability and the availability of railway services are critical drivers for the economic performance of a railway system (Tomo, 2010). Railway systems consist of two critical subsystems (i.e. rolling stock and infrastructure). These subsystems can affect the railway system negatively if they are not reliable and safe. Rolling stock means all the rail vehicles that drives on railway tracks, namely, electric multiple units, diesel and electric locomotives, wagons, coaches and railroad cars. The infrastructure system consists of signalling, telecommunication, permanent ways (i.e. railway tracks), overhead lines and traction substations. Railway business is capital intensive in nature, hence it is important to ensure all its systems, be it rolling stock or infrastructure, are kept in good working condition, safe and reliable through regular maintenance (Asekun & Fourie, 2015). Effective and efficient maintenance plays an important role in ensuring that a railway system achieves high levels of availability and reliability. Maintaining an unreliable railway system is expensive, especially when the system experiences unexpected failures that can lead to continuous train delays and cancellations. To minimise such failures, railway operators need to have an efficient and effective maintenance management system (Tomo, 2010).

1.2 Global railway sector

Globally, the railways sector can be divided into three major sectors, namely the North American sector with a total track length of 337 791 km; the RIC (Russian, Indian and Chinese Railways) has a total track length of 268 652 km; the European rail sector with the combined track length of 212 785 km (Ditsele, 2015). According to Transnet group (2016), sub-Saharan Africa has 55 000 km of railways, of which 40% is for the operating network and 70% of this operating network belongs to Transnet freight rail in South Africa. Furthermore, Southern Africa dominates passenger business, carrying more than 70% of the total passenger kilometres, largely because of its extensive passenger services operated by PRASA (Transnet Group, 2016). According to the Department of Transport (2015), the South African rail network is ranked the 11th largest in the world with 22 298 route kilometres, and a total track length of 30 400 km. The Department of Transport (2015) further states that SA rail network is much bigger and longer than its neighbouring countries, such as Botswana (888km), Namibia (2629km), Mozambique (3125 km) and Zimbabwe at (3077 km).

1.3 South African railways

In South Africa, the railways form part of a mode of transport for freight and passengers. The SA railways industry is well established; however, for the past few years it has experienced misfortunes relating to theft, vandalism, arson and system failure due to aging infrastructure and its fleet. However, in 2010, SA railways industry played an important role during FIFA soccer world cup, which had a positive impact on the overall development and the socio-economic impact of SA (Transport, Department of, 2015).

The South African railway is divided into three operating companies, namely Transnet Freight Rail, Passenger Rail Agency of South Africa and Gautrain (Walters, 2014).

1.4 PRASA group structure

PRASA is a state-owned enterprise under legal authority of the Department of Transport through a Board of Control. PRASA was formed in March 2009, as a merger between the South African Rail Commuter Corporation, Shosholoza Meyl, Metrorail, Corporate Real Estate Solutions and its subsidiaries, namely Intersite Investments and Autopax (PRASA, 2020-2022).

The mandate of PRASA rail, particularly Metrorail, is to provide passenger rail services within urban areas and long-distance passenger rail services through Shosholoza Meyl. Autopax provides long distance road based passenger services using City to City and

Translux buses. The sole mandate of Intersite investments to develop and grow assets with the sole purpose of generating income for the PRASA (PRASA, 2020-2022). Another business of PRASA responsible for the management of all buildings (office blocks), stations and depots is PRASA CRES (PRASA, 2020-2022).

1.5 The PRASA strategy

The PRASA long-term strategic plan is to provide a world class, modern, integrated, inter-city and long distance passenger transport system within SA over the next years up to 2050 (PRASA, 2017). The strategic plan builds on the existing National Rail Plan of 2006 and it further widens and includes the functions of other PRASA divisions (PRASA, 2017). The PRASA strategy is aligned to vision outlined in the NDP, which seeks to have a long term, integrated solution for all transport system of the country (Commission, National Planning, 2011). PRASA supports the focus areas and priorities of NDP, through amending the public transport policy issues and fast tracking its modernization program on transport infrastructure to have an effective urban transport system (PRASA, 2017).

1.6 Problem statement

According to Asekun and Fourie (2015), the railway business is capital intensive in nature; hence it is important to ensure all its systems, both rolling stock and infrastructure, are kept in good working condition, and are safe and reliable through regular maintenance. The survival of any business depends on having assets that are operationally fit to perform the required service. Lack of or poor maintenance can lead to asset deterioration, which will in turn lead to asset failure (Asekun & Fourie, 2015). This implies that effective and efficient maintenance should be executed according to a maintenance schedule to ensure the high level of reliability that is required.

There are many reasons why equipment and systems fail in the railway environment. According to Tomo (2010), it is important to know or even predict the potential causes of failures even before they happen. In a passenger rail operating company, equipment failures lead to train delays and cancellations. Most of the time, motor coaches/locomotives would be stopped regularly for repairs, thus affecting negatively on the uptime of the fleet, and resulting in increased maintenance cost and hence reduction in fare revenue. A train break down causes a delay, which led to disrupt of train schedule for that day. It is therefore important to maintain trains regularly, which will ensure that the trains are readily available, fit for purpose when needed and are reliable in service.

PRASA rail is currently experiencing high failure rates on the fleet during operation. These failures result in delayed or cancelled train trips, congestion and high pressure on the railway network, low availability and reliability of the train sets, lower train set productivity and low revenue, passenger frustration resulting in severe vandalism and train burning, which negatively impacts the company reputation. Figure 1 is a summary of the PRASA rail internal monthly report, showing the number of train sets in service, sets required daily for traffic and total train set demand from July 2017 up until July 2019 (Gabryk, 2019). In July 2017, the number of train sets in service was 231. As of July 2019, the number of train sets in service was 165. This sharp decline was due to a number of factors, namely different component and system failures, arson, theft and vandalism. These failures led to non-adherence to regional train set demand and due to this low level of train set availability, the researcher pursued to explore this study. In the Gauteng region, the class 5M2A fleet is used the most for transportation of commuters. Looking at Figure 1, the class 5M2A motor coaches form part of the fleet that has led PRASA to this decline in performance. The class 5M2A fleet is one of the oldest fleets PRASA is currently using for passenger transportation.

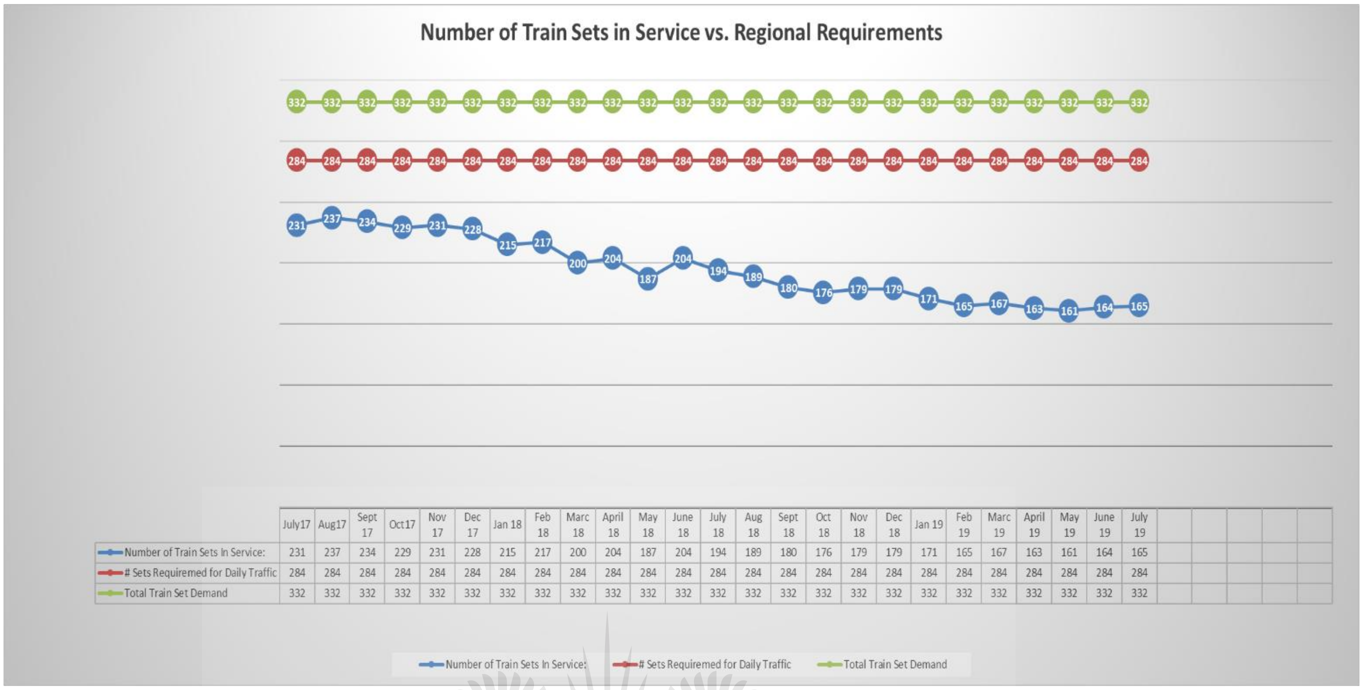

Figure 1: Number of trains in service vs operational demand (Gabryk, 2019)

Over the past few years, PRASA has seen high failures on the class 5M2A due to several reasons. The direct impact of these failures has led to a reduction in patronage, loss of revenue and poor company reputation. Based on the above factors, it was important that a study be conducted to explore factors that led to this state of affairs. The primary objective of this study was to explore factors that affect the reliability of the class 5M2A motor coaches operating in the Gauteng region.

1.7 Research objectives and questions

The main objective of the research was to explore factors affecting the reliability of class 5M2A motor coaches operating in the Gauteng region.

The secondary objective of this research was to assist the maintenance operations managers, engineering managers and system reliability engineers with the relevant tools of maintenance management and reliability engineering to improve the fleet performance, optimise life-cycle cost and sustainability of the fleet over the remaining useful life. In addition, the study will assist maintenance depots management to apply the relevant maintenance and reliability strategies when executing maintenance and dealing with in-service failures.

In order to reduce motor coach failures and make them more reliable, it is important that reliability engineering and maintenance management are clearly understood. In addition, it is also necessary to determine whether the different subsystems in the motor coaches will succeed or fail. It is also important to identify early warnings to manage the motor coaches and prevent the occurrence of failure. In order to develop a process that will help the engineering managers to make effective and cost-efficient decisions, it is important to understand the challenges affecting the reliability and availability of the motor coaches. The study aimed at answering the following research questions:

a. Which factors affect the performance of class 5M2A motor coaches operating in the Gauteng region?
b. Which maintenance strategies are used to maintain class 5M2A motor coaches operating in the Gauteng region?
c. What can be done to improve the reliability and the availability of class 5M2A motor coaches operating in the Gauteng region?

From the research questions above, the following research objectives were formulated:

- To examine the factors affecting the reliability of the class 5M2A motor coaches;
- To identify various maintenance strategies used to maintain class 5M2A motor coaches operating in Gauteng regions;
- To determine what can be done to improve performance of the class 5M2A motor coaches.

The study considered the number of failures for each sub-system for the duration of the study, the sources of the failures in relation to maintenance, and what tools are available to develop and plan a proper maintenance strategy. In this study, the utilization of reliability tools such as bathtub, FMECA and Pareto analysis were used to identify the failure modes and defects of each sub sub-system. However the objective of the study was not to develop a full maintenance strategy for the organization using the reliability tools. Rather, the study was used to identify the primary sources of failures which would benefit from a to-be-improved PRASA maintenance strategy.

1.8 Research design and methodology

According to Creswell (2013), mixed methods research is the method and methodology that applies the principles of qualitative and quantitative research to collect, analyse and integrate the research data in one study. He further states that mixed methods research provides a better understanding of the research problem under investigation by doing a comparison of both the qualitative and quantitative data collected.

According to Chaudhary and Lesiek (2016), mixed methods research recognises the principles of both quantitative and qualitative research however; it further provides the third element, which provides the research results that are more informative, balanced, and practical.

According to Cameron (2015), mixed methods research is the exploration of different set of studies through collecting, analysing, and interpreting quantitative and qualitative data for the same underlying problem.

According to Matsapola (2018), the qualitative research method focuses on exploring and experimenting with the goal of achieving a specific result and the process of research involves trials, questions, and data collection. Qualitative research methodology articulates attributes that cannot be explained by numbers, like people’s opinion, feelings, emotions, etc. (Makhanya, 2016).

According to Matsapola (2018), the quantitative research method, also referred to as statistical analysis, is a mathematical operation that deals with numbers to explore variables and an analysis of collected data is provided in a scientific statistical manner for a particular problem. The quantitative research method uses equations, statistical and mathematical formulas for data interpretation (Makhanya, 2016).

In this study, the qualitative method assisted in collecting views and opinions of the participants through survey questionnaires, which could not be clearly justified by the numbers. For interpretation of failure data of the fleet, quantitative method became was utilized.

Figure 2 is the mixed method process used for the purpose of this research:

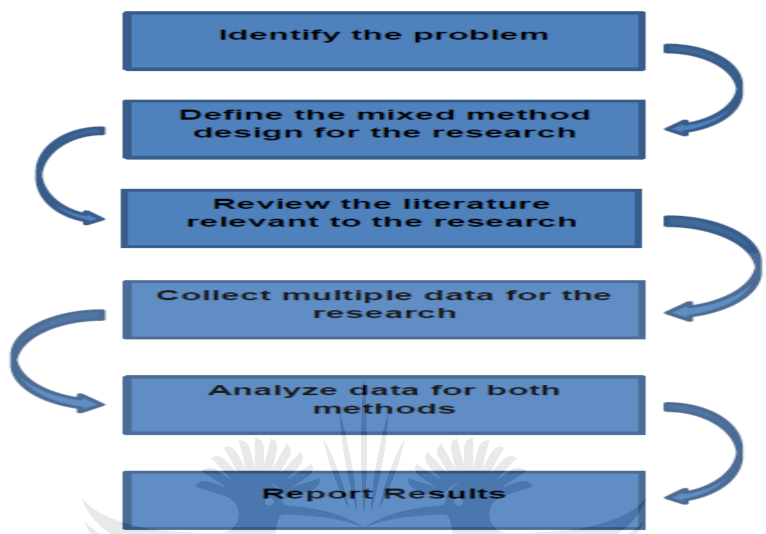

Figure 2 : Process flow for mixed research method

1.9 Assumptions

The study will enhance the existing knowledge within maintenance management and reliability engineering of PRASA personnel. The study received necessary support from PRASA rail maintenance department and the company provided permission for the researcher to look, review the processes and collected the necessary data for the study.

The statistical data used for this research was a true reflection of the PRASA rail asset performance and maintenance policies. The study further considered that the participants had a good understanding of the subject matter of the research, and the participants answered all the questionnaires honestly and truthfully.

1.10 Limitations

The research focused on the factors affecting the reliability of class 5M2A motor coaches operating in Gauteng region. The research was based on the fleet operating in Gauteng; the results could not be generalised for all the fleets of PRASA rail due to the different operational conditions. Another factor that was taken into consideration during the research is the demographics (job title, educational background and experience) of the participants that could negatively affect the outcome of the research.

1.11 Benefits of the research

The purpose of the research is to investigate factors that affect the reliability of motor coaches within Metrorail in the Gauteng region. However, the bi-product of conducting the study will lead to improving the performance of the fleet.

1.12 Report layout

This research report contains five chapters, briefly explained below:

Chapter 1 provides the background, overview and objectives of the research. It also outlines the problem statement and the research purpose. The research objectives, questions and significance were introduced in this chapter. This chapter also highlighted the research method used to collect the data.

Chapter 2 highlights the literature reviewed in order for the researcher to gain more knowledge and understanding in the field of maintenance management, reliability engineering and related topics for this study.

Chapter 3 gives a clear description of the research methodology, and how data was collected and analysed.

Chapter 4 focuses mainly on data presentation and discussion of the results.

Chapter 5 compares the reviewed literature with the research findings, draws conclusions, provides recommendations and suggests the future work to be explored.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter presents a review of the literature and theories that currently exist in the field of reliability engineering, maintenance management and how they are used in the passenger trains sector. In this chapter, the theories relating to maintenance optimisation, maintenance policies and maintenance strategies were discussed. In addition, literature and concepts relating to reliability engineering and reliability techniques were provided.

2.2 The definition of reliability

In this ever-changing world of technology, the systems designed today are costly and very complex in nature. It is of great importance to keep these systems reliable at all times. Reliability has become one of the key performance indicators for any system. It is therefore important that the cost of reliability be specified and accounted for, as it forms part of the product life cycle cost (Tomo, 2010). For example, a passenger train must be available when required for service, and the cost of unavailability, especially if it is unplanned for, can be very high.

According to Pecht (2014), reliability is the product or system's capability to accomplish its intended mission within as specific time.

According to O'Connor and Kleyner (2012), reliability is defined as the likelihood that an item will accomplish its essential task without failure under defined conditions for a specified period. They also argue that reliability is hypothetically defined as the likelihood of failure, the rate of recurrence of failures, or in terms of availability, resulting from consistency and maintainability.

The objectives of reliability engineering as argued by O'Connor and Kleyner (2012) are:

- The utilization of specialized probability techniques and application of engineering knowledge to reduce the reoccurrence of failure;
- Identification and precisely correction of failures regardless of the determinations to inhibit them;

- Regulate method of handling failures transpired, if their cause of origins have not been enhanced;
- Application of approaches for estimating reliability of new designs, and reliability data analysis.

Performing a reliability analysis on any system can provide the following advantages to an organisation (Mbeki, 2017; Pecht, 2014):

- The opportunity to explore the functionality of a system;
- The opportunity to pre-empt system interruptions and the implication thereof; and
- The opportunity to develop and optimise a maintenance policy.

2.3 Reliability elements

Reliability can be defined as the likelihood of an item performing its intended function fully for a defined time under the working conditions it is exposure to (Human, 2012). The definition can be broken down into four basic parts, namely (Human, 2012; Tomo, 2010):

a) Probability
b) Adequate performance
c) Time
d) Operating conditions.

2.3.1 Probability

One could ask why reliability is a probabilistic concept. Probability and reliability are associated because one cannot tell when an element or structure is going to fail. According to Tomo (2010), probability is the main component in the reliability description and is mostly expressed in quantitative terms as representing a portion or a percentage stipulating the amount of times that one can anticipate an event to happen in a total number of trials.

2.3.2 Adequate performance

When a product is purchased, there is an expectation that it will perform as intended (Pecht, 2014). Adequate performance is another important element of reliability, indicating that specific measurable criteria in the form of key performance indicators (KPIs) must be defined that will be measured to determine if the product is providing adequate performance (Human, 2012). A product failure can lead to the system being completely removed from service, or to a catastrophic failure or may eventually be caused by a violation of the required system function (Tomo, 2010). For example, a motor may perform below average capacity (below minimum requirement) although it may still be operating.

2.3.3 Time period

The third element for reliability is time. When a product is bought, the expectation is that it will perform or operate for a specific period without failure. Most products come with a manufacturer's warranty, which states the period of time for which the product should operate without failure, if it does fail, the manufacturer will repair it at no cost or replace it with a new one. It is important to envisage the likelihood of a product enduring (without failure) for a certain interval of time (Tomo, 2010). According to O'Connor & Kleyner, (2012), time is important in reliability conditions and it is usually articulated in terms of MTBF or MTTF.

2.3.4 Specific operating conditions

Reliability of a product is dependent on the utilisation and operating conditions that the product is exposed to. The operating conditions of any product differ according to different applications throughout the product life cycle. The operating conditions may include environmental conditions, fatigue, corrosion, temperature variances, humidity, shock, vibration and so forth (Tomo, 2010). For example, electrical or electronic systems are sensitive to humidity, vibration and temperatures, and on the other side, mechanical systems are sensitive to fatigue, and wear and tear.

2.4 Reliability tools

According to Tomo (2010), understanding reliability tools is very important in the maintenance environment, especially when an organisation wants to improve the performance of its assets. The utilisation of reliability tools can assist in the reduction of the high cost of unreliability, which can eventually improve the entire performance of the product. The evaluation of any system or product from reliability perspective is established from well-defined reliability theories and processes. Accordingly, this section is concerned with the development of selected reliability measures and terms. A basic understanding of these is required before discussing reliability programme functions as related to the system/product design (O'Connor & Kleyner, 2012). The reliability tools that can be used to demonstrate the available techniques are discussed below.

2.4.1 Acquiring reliability data

According to Dibakoane (2013), reliability data collection and storage are vital for making good reliability decisions. Reliability data is the resultant from development tests and operational usage with the objective of monitoring trends, identifying origins of unreliability and measuring reliability (Tomo, 2010). Other sources of reliability data are from historical records, i.e. log books, maintenance work records and test records (Dibakoane, 2013). Failure data is valuable because it is a true reflection of operating practices, maintenance practice and real operating conditions (Tomo, 2010).

According to Jacob and Akers (2011), failure reporting and corrective action systems are a closed loop system used to improve the reliability of a product or service. The "closed loop" in FRACAS (see Figure 3) refers to the well-defined and efficient approach in which every incident or failure is reported and resolved without missing any failure. FRACAS is considered an initial stage for starting improvements by obtaining reliability data appropriately and using it for improvements (Dibakoane, 2013).

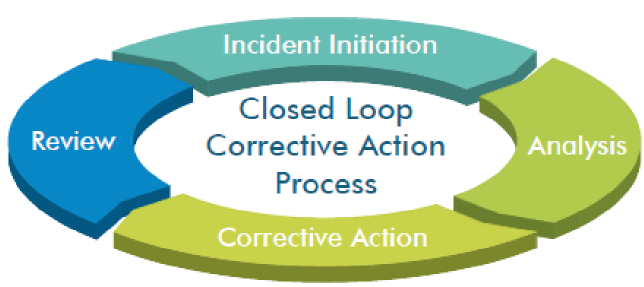

Figure 3 : FRACAS close loop system (Jacob & Akers, 2011)

The implementation of FRACAS can differ from one industry to another or according to a different product or service. However, the following steps can be used as a general guideline for implementation FRACAS (Jacob & Akers, 2011):

- Utilization of database management system to record the failures or incidents and initiation of process to attend failures.
- Utilization of database management system to analyse reported failures or incidents and establishment the root cause of the failure or incident.
- Utilization of database management system to identify the necessary corrective action plans, track its development, implementation, with the objective of reducing or eliminating failure reoccurrence.
- Utilization of database management system to review and verify the corrective action and incident close out as per the system procedure.

2.4.2 Reliability key performance indicators

For reliability data to have meaning and be better understood, it could be converted into simple key performance indicators. Reliability KPIs are necessary for the qualitative characterisation of a system's capability to complete its function (Tomo, 2010). Reliability KPIs are statistical in nature and depend on time (O'Connor & Kleyner, 2012). The availability and use of reliability tools is important and helps to measure and/or reduce the high cost of reliability. This usually results in system improvements.

According to O'Connor (2012), reliability can be defined when MTTF of non-repairable items or MTBF for repairable items is longer compared to the operation time. Smaller values for mean time indices reflect unreliability of the system as compared to the operation time.

Reliability index means that a system on average works T time units before failure. According to O'Connor and Kleyner (2012), reliability indices define mean time to failure as the average time that the system is expected to function effectively before a failure occurs.

According to Stanley (2011), MTTF is the fundamental indication of reliability for non-repairable systems. He further states that, it is mean time expected until the first failure of a piece of equipment. MTTF is used to measure reliability for non-repairable products, while MTBF can be used only for repairable items (Stanley, 2011). According to Pecht (2014), for a given probability density function, the MTTF is the anticipated value for the time to failure and is defined by equation 1:

$$MTTF = \int_0^{\infty} R(t)dt \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (1)$$

When the failure distribution function is specified then MTTF can be used because the value of the reliability function at a given MTTF depends on the probability distribution function used. In addition, for the same MTTF you can have different failure distributions and different reliability functions.

Failures of numerous complex systems are often categorized into soft failure and hard failure caused by degradation and unplanned shocks (Songhua Hao, 2018). To calculate the failure rate of a non-repairable system, one can use both MTTF and MTBF for repairable systems. The reciprocal of both the MTTF (one / MTTF) and MTBF (one / MTBF) will provide what is known as failure rates (Tomo, 2010). According to Pecht (2014), the hazard rate is defined as the speed at which failures happen in a certain time interval for those items that are working at the start of the interval.

According to Tomo (2010), failure rate can be defined using equation 2

$$\lambda = \frac{\text{Number of failures}}{\text{Total operating hours}} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (2)$$

Where the relationship between the failure rate and mean time between failure can be defined as MTBF= $1/\lambda$. It is significant to identify the failure rate in order to decide the corrective maintenance actions and it is important to address all process failures.

2.4.3 Availability concepts

Availability is defined as the likelihood that an item will be available when needed, or as the fraction of entire time that the item is available for use (O'Connor & Kleyner, 2012).

Availability is also defined as the probability that a system will perform its intended function under specified conditions for a duration of time (Blanchard, 2004). When availability values are higher that is a good indication, and lower values are a bad indication.

An elementary measure of reliability for repairable items is a measurement of how frequent downtime occurs, similarly known as the mean time between failures (Tomo, 2010). According to O'Connor (2012), availability for repairable systems can be measured using equations 3:

$$Availability = \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots . (3)$$

Where:

MTBF is the mean time between failures and

MTTR is the mean time to repair as a function of design

Operational availability is defined as the sudden likelihood that a system or component will be available to complete its intentional purpose when called upon to do so at any point in time (Tomo, 2010). Operational availability can be expressed as the ratio between system uptime and system downtime by equation 4 below (Blanchard, 2004):

$$Ao = \frac{MTBM}{MTBM+MDT} \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (4)$$

Where:

MTBM is the mean time between maintenance inclusive of corrective and preventive maintenance and

MDT is the mean downtime inclusive of the actual maintenance time plus the delays from required personnel and spares.

Availability for non-repairable systems can be determined using equation 5 (O'Connor & Kleyner, 2012):

$$A = \frac{MTTF}{MTTF+MTTR} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (5)$$

Where:

A is the availability,

MTTR is the mean time to repair; this is the simplest steady state equation,

MTTF is the mean time to failures for non-repairable systems.

According to O'Connor and Kleyner (2012), operational availability can be measured using uptime and downtime and can be expressed as equation 4 and 6:

$$Ao = \frac{Scheduled\ Production\ Time - Unplanned\ Delays}{Scheduled\ Production\ Time} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots (6)$$

Where *Ao* is the operational availability.

A simple measure of reliability for repairable items is the rate at which downtime occurs usually known as MTBF. According to O'Connor and Kleyner (2012), the reliability of repairable systems can also be characterized by mean time between failures, expressed using equation 7:

$$Reliability(MTBF) = \frac{Total\ Production\ Time}{Number\ of\ Failures} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .. (7)$$

Failure rate is expressed by equation 2, hence MTBF = 1/ λ. However, this assumption is only true under the particular condition of a constant failure rate. Usually this is so for simple equipment but not so for redundant systems.

According to Tomo (2012), maintainability can be expressed by equation 8:

$$Maintainability(MTTR) = \frac{Total\ Downtime\ due\ to\ Failures}{Number\ of\ Failures} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .. (8)$$

Operational availability, as defined by O'Connor and Kleyner (2012), can be expressed as reliability and maintainability, as shown in equation 9:

$$Availability = \frac{MTBF}{MTBF + MDT} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. (9)$$

MTBF: is the reliability measurement of how frequently downtime occurs.

MTTR: is the capacity to conduct maintenance, including the turnaround time of equipment after failure.

MDT is the total downtime from the failure up until the equipment is ready for operation, which includes MTTR and all other time involved with downtime, such as logistics delays. Sometimes MTTR is used in this formula instead of MDT but MTTR may not be the same as MDT because (Blanchard, 2004):

- The failure may not be noticed for some time after it has occurred.
- It may be decided not to repair the equipment immediately.
- The equipment may not be put back in service immediately after the repairs.

2.4.4 Probability plots

A graphical representation of data is vital for engineering personnel for a thorough understanding of the failure patterns. Weibull probability data analysis is possibly the most used technique of processing and interpreting life data. The advantages Weibull distribution is the ability to easily interpret the distribution parameters, their failure rates and bathtub curve (O'Connor & Kleyner, 2012).

Once the life data has been analysed and interpreted, failure patterns are known. The right maintenance strategy will be apply to perform root cause analysis. This will help in solving the true causes of failures rather than working on symptoms of failures.

According to Redling (2004), the purpose of using probability charts is to appreciate the failure rate and try to minimise the cost of failures. The reliability function or the survival function, is found from the likelihood that a system/product will be successful for specified time (t).

The reliability function is determined from the probability that a system will be successful at least for some specified time t. According to Tomo (2012), the reliability function, R (t), is defined as in equation 10:

$$\boldsymbol{R(t) = 1 - F(t)}$$
$$= \boldsymbol{e}^{\left\{-\left(\frac{t}{\eta}\right)p\right\}} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots (\mathbf{10})$$

Where:

F (t) is the probability that the system will fail by time t.

Reliability function used on equation 10 is to demonstrate how to derive the straight equation to use on a 2-parameter Weibull distribution of which the failures in this study were assumed to follow.

Assuming the failure-free time (γ) is 0 for 2- parameters, then Weibull distribution is used

Then

$$\boldsymbol{1 - F\,(t) = e}^{\left\{-\left(\frac{t}{\eta}\right)p\right\}}$$

Taking double logarithms on both side

$$\ln\,(\ln)\,[1 - F\,(t)] = \beta \ln t - \beta \ln \eta$$

This can further be developed to a straight line in a form y = ax + b

In this study the researcher assumed that the failure data for the fleet as per different sub-systems will follow the conditions outlined in all the equations discussed under para 2.4.

2.4.5 Bathtub curve

The bathtub curve has been widely used, among others, to describe a particular type of failure distribution. The bathtub shape is the representative of the failure rate curve of many products and components, including the human body. Graphical representation of lifetime of a population of products by reliability specialist is often called bathtub curve

(Ebeling, 2010). This idea of bathtub curve is expressed as a composite of several failure distributions, and formalises it as a function of piecewise linear and constant failure rates.

Figure 4 shows a curve indicating the relationship between failure rate and time.

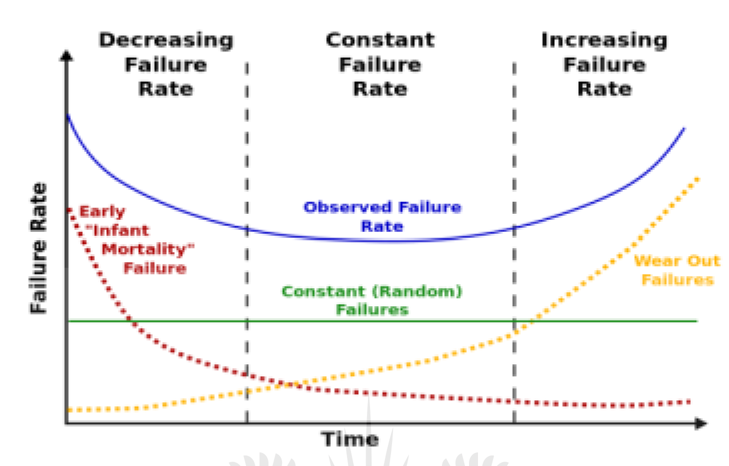

Figure 4 : Typical failure rate curve (Tomo, 2010)

The bathtub curve have three phases: an infant mortality phases with a decreasing failure rate followed by a normal life phases (or useful life) with a low, relatively constant failure rate and concluding with a wear-out phase that shows an increasing failure rate. The classic bathtub curve against time has three different periods. The first period is decreasing failure rate for infant mortality; as the debugging continues, the failure rate decreases, resulting in reliability growth. The second period consists of useful lifetime of the equipment, where the failure rate remains constant and failures vary randomly. The third period represents the wear out or the fatigue phase during which the failure rate increases rapidly with time.

The bathtub and most of other reliability tools used in this study are typically used in the whole maintenance planning, execution and analysis process. This study only identified failures per sub-system and their subsequent root causes, based on the data collected from the maintenance management system. The objective of the study was not to propose a complete analysis and strategy approach for the maintenance of the PRASA assets. Furthermore, a determination regarding the position of each sub-system on the bathtub was not conducted in this study. For the purpose of developing a comprehensive maintenance study for PRASA, further studies should be conducted, firstly to determine where on the bathtub each sub-system (or even the coach) is, and also to assist the organization to develop the maintenance strategies to be applied on each sub-system.

2.4.6 Pareto analysis and critical items list

Pareto principle of the significant few and the insignificant many can be used as the first step in performing analysis data. In most cases, a small number failures causes a large number of failures of a product. Therefore, if we analyse the failure data, we can determine how to solve the largest proportion of the overall reliability problem with the most economical use of resources (Barringer, 2006). Pareto analysis is a statistical technique in decision making that is used for the selection of a limited number of tasks that produce significant overall effect.

According to Chopra (2017), the Pareto Principle (also known as 80/20 Rule) suggest the idea that by doing 20% of the work you can generate 80% of the benefit of doing the whole job. From quality perspective, Pareto says that majority of most problems (80%) are caused by few cause (20%) (O'Connor & Kleyner, 2012).

2.4.7 Reliability block diagrams

According to O'Connor (2012), the failure logic of a system can be broken down into reliability block diagram (RBD), which illustrates the logical links between components of a system. He further states that RDB does not presents the block functional layout of the system. RDBs depict the functional relationships between components comprising a system and are popular in reliability theory (Debarun Bhattacharjya, 2012).

An RBD is a diagram and analytical tool utilized to model complex systems (O'Connor & Kleyner, 2012). An RBD is a chain of blocks demonstrating different quotas of a system. When the blocks are appropriately configured and block information is provided, MTBF, failure rate, reliability, and availability of the system can be calculated (O'Connor & Kleyner, 2012). The calculation results of RBD are dependent on the configuration of the block diagrams.

Network relationships of large and complex systems can be shown through block diagrams of RBDs and also the system reliability and availability analyses can be calculated (Milosevic, 2016). The organisation of the RBD describes the analytical interface of failures within a system that are required to sustain the system.

2.4.7.1 Series network

The simplest arrangement of a system for reliability analysis is one where the components are connected in series. In a series configuration, a failure of any element results in the entire system failure. At their basic subsystem level, most complete systems are configured in series reliability-wise (O'Connor & Kleyner, 2012).

For example, a motor coach may consist of four basic subsystems: the traction system, the pneumatic system, the propulsion system and the control system. These systems are configured in series reliability-wise, hence a failure of one of these subsystems will cause the entire system failure. In a nutshell, this means all of the components should be connected in series for the system to succeed. For example, in Figure 5, consider the motor coach, comprising four traction motors; the reliability of the entire TMs will be expressed as the product of the reliability of the individual TMs as shown by Equation 11.

Figure 5: Series RBD network for traction motors (O'Connor & Kleyner, 2012)

The total reliability of Figure 5 can be calculated using equation 11:

$$R\ (Total) = [R\ (TM1) X\ R\ (TM2) X\ R\ (TM3) X\ R\ (TM4)] \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots \dots (11)$$

2.4.7.2 Parallel network

For as system to succeed in a simple parallel system, at least one of its units must succeed. In a parallel system, units which are parallel are also called redundant units. In system design and reliability, redundancy is a very special method used to improve the system reliability. Redundancy is mostly used in aerospace industry and also in most mission critical systems. This network can be applied on the motor coach, for example, in a bogie where two traction motors are connected in parallel to one another. In this network, which is made up of two independent TMs with reliabilities R (TM1) and R (TM2), successful operation is achieved if one or both parts functions. Therefore, the reliability of the system, R, is equal to the probability of TM1 or TM2 surviving. Figure 6 below shows the RBD parallel connection of the traction motors (O'Connor & Kleyner, 2012).

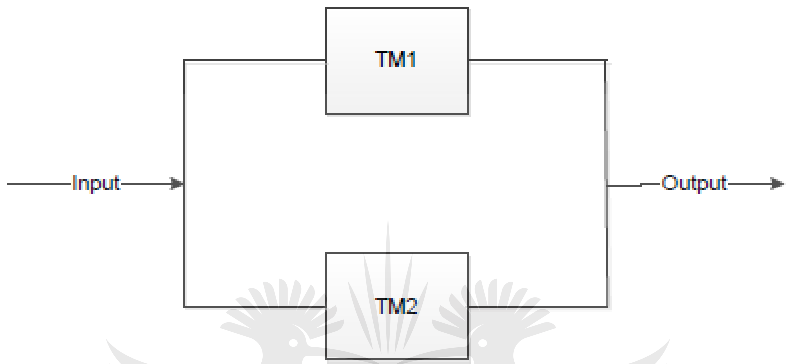

Figure 6: Parallel RDB diagram for traction motors (O'Connor & Kleyner, 2012)

The reliability of this network shown in Figure 6 can be expressed using equation 12:

$$R = R\,(TM1) + R(TM2) - [R(TM1)\ x\ R(TM2)] \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(12)$$

2.4.7.3 Series parallel network

Series parallel systems is shown in Figure 7, consisting of a mixture of series and parallel elements or subsystems, which are mostly deeply studied subject in the system reliability research. Most current studies pays attention on exceptional categories of the series parallel systems, where a number of purely parallel subsystems are connected in series or a number of purely series subsystems are connected in parallel (Levitin, et al., 2017).

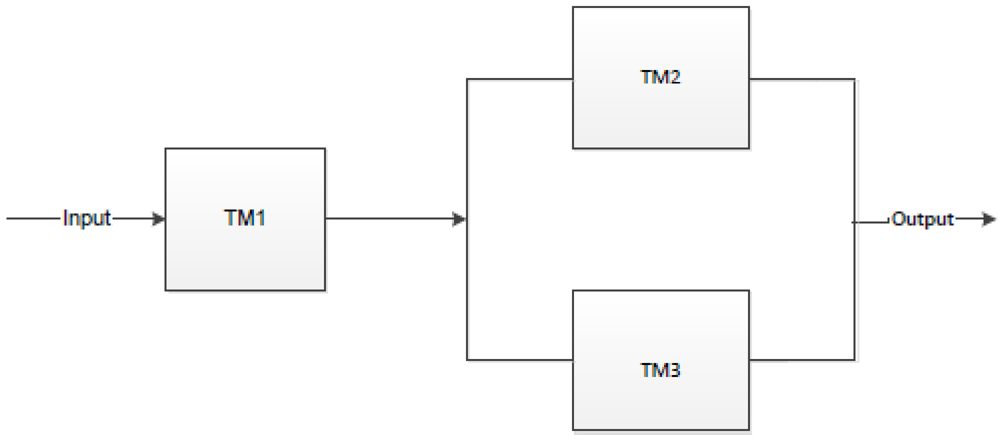

Figure 7: Series-parallel RDB diagram (O'Connor & Kleyner, 2012)

The reliability of the network in Figure 7 can be expressed as equation 13:

$$R = \{R\ (TM1)\ x\ [\ R(TM2) + R(TM3) - R(TM2)\ x\ R\ (TM3)]\} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots ..13)$$

It is important that redundancy be provided for, especially for critical equipment just in case of failure.

2.4.8 Failure system analysis

According to Oster (2017), failure analysis is the systematic gathering and study of data to find the root causes of a specific failure and the development and reporting of recommendations to prevent the failure reoccurrence. There are two methods that are commonly used for failure analysis, namely failure mode and effects analysis and fault tree analysis (Peeters, et al., 2017).

Furthermore, Peeters et al. (2017) state that FMEA is a bottom-up technique, starting at the component level utilized to discovery failure modes and draw their effects. By including criticality analysis, the qualitative FMEA can be stretched to a quantitative method.

According to O'Connor (2012), the most utilized and effective design reliability analysis technique is FMECA. He further states that the principle of FMECA considers every mode of failure of all component of a system and to determine the effects on system operation of each failure mode in turn. In FMECA, failure modes are categorized in relation to the severity of the effects.

According EN 60812 standard, the extension of FMEA also known as FMECA represents an effective support technique to semi-quantitatively quantity the criticality of system failure modes. The criticality of each failure mode is calculated by merging the risk parameters S, O and D. For each failure mode, the product of parameters O, S, and D lead to the risk priority number shown in equation 14 below (Carpitella, et al., 2017):

$$RPN = S * O * D \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (14)$$

Where:

S is an estimate of how strongly the failure mode will affect the system,

O is the frequency of occurrence of the failure mode within a predefined period time and

D represents the likelihood of detecting the failure.

The RPN value defines very clearly the degree of the risk based on which particular safety and preventive measures are introduced (Bonato, et al., n.d.). The traditional FMEA uses the scale from one to 10 when measuring, for example, the failure severity. The greater the value of the RPN, the more important is the risk over the failure mode and frequency of failure occurrence.

According to Barringer (2006), FMECA is an analysis technique applied for evaluating reliability by investigating the projected failure modes in order to discovery the effects of failure on the equipment. FMECA focuses on possible failures and how these failures can disturb the performance of the equipment. The key application of FMECA is to help in the following (Barringer, 2006):

- Identification of failures that have detrimental or substantial effects; to find the failure modes that may extremely affect the expected or required quality.
- Identification of safety hazard and liability problem zones, or non-adherence with regulations.
- Identification of control areas where inspection and maintenance of product or process can be done.
- Provision of organized and vigorous analysis of the product, process and its environment aimed at enhancing the knowledge how of the product or process might fail.
- Support the need for a standby or alternative process/product.
- Identification of training deficiencies for operator and supervisor.

According to Peeters et al. (2017), FTA is a top-down technique used to draw the interactions between events subsystem failures and their causes. A fault tree is a logic diagram that characterizes the interactions between an event (subsystem failure) and the causes of the event (component failures).

2.5 Maintenance management

2.5.1 Overview

Maintenance refers to all events and actions that are directly performed on a component, which return it to its proper operation after it was interrupted by failure or some abnormality (Tomo, 2010). According to Campbell and Picknell (2016), maintenance is a function that ensures that an asset is kept operating at a standard that is required to ensure that the business objectives are met. Most engineered systems are faced with many challenges that result in degradation of systems performance, which is costly due to maintenance activities that should be done to recover them (Rhayma, et al., 2013). The simplicity with which repairs and other maintenance work can be done defines system's maintainability. Maintenance management deals with the tactical planning, organisation, directing and use of the resources necessary to keep the asset running well and contributing to customers and business success (Campbell & Picknell, 2016). These activities comprise removal and replacement of failed components, repair of failed components, servicing and lubrication and calibrations. Other supporting activities and resources are needed to support maintenance. These resources include spares, labour, facilities, training and procedures. These activities and resources usually form part of integrated logistics support.

According Blanchard (2004), ILS is a combination of all deliberations essential to guarantee the efficient and cost-effective support of a system or equipment at all levels of maintenance for its entire life cycle.

2.5.2 Personnel and training

Another critical element of maintenance is to provide training to maintenance personnel. For the organisation to achieve high levels of system reliability and availability, training should be provided to machine operators and people who are executing maintenance. According to Campbell and Picknell (2016), as shown in Figure 8, training can be provided to all levels in the organisation, ranging from basic literacy to the latest methods of managing technical people.

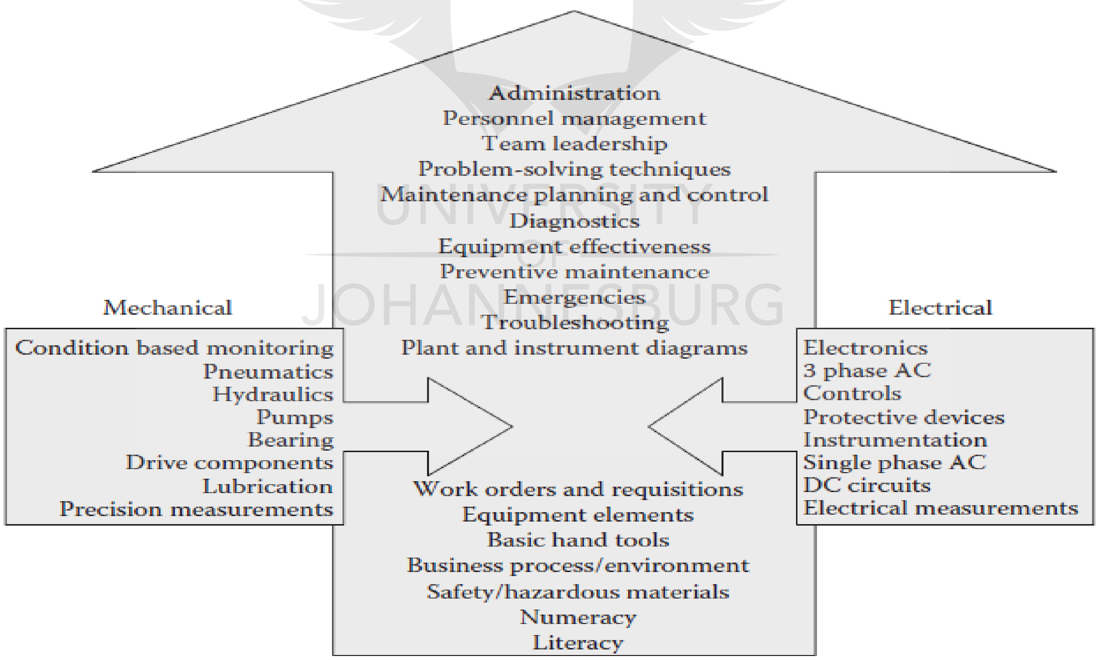

Figure 8: Scope of training requirements (Campbell & Picknell, 2016)

According to Alastair (2010), organisations need to develop training plans for operator and maintenance personnel, which entail the followings factors:

- System requirements training for operator;
- System requirements training for maintenance personnel;
- Resource or specialised equipment to facilitate training needs;
- Operators and maintenance personnel training schedules.

In addition to the above-mentioned factors, Tomo (2010) emphasises that an organisation should have a good maintenance team, which has the following features:

- Well trained maintenance personnel
- Sufficient resources
- Authority and know how to do material planning
- Ability to develop a repair plan and prioritise it
- Skills to identify the cause of breakdowns
- The skills and ability to extend the MTBF.

2.5.3 Maintenance planning

Maintenance planning is a fundamental decision-making characteristic for maintenance engineers, needing support from modern practices, data analysis techniques, and information and communication tools (Gopalakrishnan, et al., 2015). To ensure that maintenance is executed easily and on time, there should be a maintenance schedule that guides the maintenance planning team. To ensure that maximum yield is reached in terms of maintenance execution, the required stock of material and equipment needed for maintenance execution should be planned for in line with the maintenance schedule (Tomo, 2010). Furthermore, Tomo (2010) states that the following aspects should be considered when implementing the maintenance plan:

- Defined the activity and tasks with the maintenance plan;
- The importance of each initiative, in comparative to others;
- The expected resources and level of requirement;
- Set the start and end date of each milestone, and milestones should be set;
- How the success completion will be measured.

2.5.4 Maintenance strategies

According to Gandhare & Akarte (2012), the main aim of maintenance is to warrant system functionality, system life and system safety with minimum energy consumption. Gandhare and Akarte (2012) furthermore state that maintenance strategy is a well-organized techniques to maintenance the facilities, equipment, and it differ vary from industry to industry.

Choosing the best maintenance strategy depends on numerous factors, such as the objectives of maintenance, the type of the facility or the equipment to be maintained, work flow designs, and the work atmosphere. A number of well-known maintenance strategies can be applied to achieve the objectives set for the maintenance department. These strategies are corrective maintenance, preventative maintenance, predictive maintenance, proactive maintenance and reliability centred maintenance. These strategies are fully discussed in the section that follows.

2.5.4.1 Corrective maintenance

Corrective maintenance is the maintenance strategy that is applied to the equipment or system after the failure has already occurred. This type of strategy is referred to as run-to-failure maintenance and it comes to play due to unscheduled breakdowns or unforeseen circumstances (Mbeki, 2017; Alastair, 2010). According to Fang and Zhaodong (2015), there are numerous corrective maintenance influence factors, which can comprise one or all of the following events, namely breakdown location, breakdown isolation, corrosion, exchange, re-install, modification, confirmation and fix the broken parts. Because this kind of maintenance is unplanned, its impact has serious financial implications, which will see an increase in overall maintenance cost.

2.5.4.2 Preventative maintenance

PM is a technique used to ensure that equipment failures are mitigated before they occur (Nyathi, 2015). According to Alastair (2010), preventative maintenance is the execution of maintenance activities in a systematic method with the objective of returning the system to its required performance level. The execution of maintenance activities is done by using a maintenance schedule. Alastair (2010) further states that the maintenance intervals required and the exact tasks to be executed are well defined within the maintenance schedule.

According to Mbeki (2017), the following proactive tasks, among others, can be executed in preventative maintenance while the system is operational:

- Inspections
- Condition monitoring
- Lubricating
- Testing
- Service
- Equipment restoration.

The main objective of preventative maintenance is to ensure reduction in wear and tear, aging and prevention of possible failures (Mbeki, 2017). The disadvantage of a PM strategy is that in some instances some equipment can be under-maintained whereas others can be over-maintained (Alastair, 2010). To manage these scenarios, the PM strategy should be implemented in a coordinated manner alongside corrective maintenance and predictive maintenance (Tomo, 2010).

According to O'Connor and Kleyner (2012), the efficiency and cost effectiveness of PM can be exploited by factoring the time-to-failure distributions of the maintained equipment and of the failure rate trend of system. O'Connor and Kleyner (2012) further state that the impact of failures, both in terms of impact on system and costs of lost time and repair, must also be measured.

2.5.4.3 Predictive maintenance

According to Alastair (2010), Pd.M. refers to the sequence of maintenance activities that are executed in an effort to obtain an understanding of current existing equipment conditions. Alastair (2010) further states that the objective of Pd.M. is to determine the exact maintenance tasks that need to be executed. According to Nyathi (2015), Pd.M. is a maintenance technique that is designed to find the state of the equipment in operation with the aim of predicting failures before they occur.

The execution of the Pd.M. strategy involves the utilisation of planned maintenance activities in the same way as the PM strategy. To effectively apply the Pd.M. strategy, the utilisation of reliability engineering tools is beneficial in the execution of predictive maintenance (Tomo, 2010). The vibration analysis and lubricant analysis are basic methods that can be applied to demonstrate Pd.M. Condition monitoring is a technique that commonly uses the Pd.M. strategy used by industries today (Alastair, 2010). While setting up the Pd.M. strategy, the cost of buying condition-monitoring equipment and training costs will increase the maintenance budget; however, in the end, the Pd.M. strategy will offer the following benefits in the overall organisation (Nyathi, 2015):

- Reduce equipment downtime due to predictive maintenance;
- Improve equipment life, reliability, availability, operability, safety;
- Energy saving.

2.5.4.4 Proactive maintenance

PAM strategies combine elements of the previous tactics to maintenance by concentrating on root causes that lead to equipment wear and failure (Feit, 2017). According to Feit (2017), this method lengthens the lifetime of equipment while also inhibits redundancy in repairs for things that do not need it. PAM is the ideal strategy to implement when equipment continues to demonstrate a lack of reliable operation or if there is a re-occurring failure within the equipment (Alastair, 2010). According to Tomo (2010), PAM can be used to identify the enhancement of both predictive and preventative maintenance strategies. Owing to the cost associated with PAM, the strategy should be used only in extreme or special circumstances (Alastair, 2010).

2.5.4.5 Reliability centred maintenance

According to Campbell and Picknell (2016), RCM is a technique for determining the utmost suitable maintenance policy for any particular asset in its current operating perspective. RCM offers an organized and practical method for arriving at a suitable maintenance strategy for each component of a particular system (Gupta, et al., 2016). The RCM methodology is built on the system functional failure analysis using characteristics such as FMEA and FTA. RCM is usually used to accomplish enhancements in fields such as the creation of safe minimum levels of maintenance, alterations to operating procedures and strategies and the creation of capital maintenance regimes and plans (Tomo, 2010). RCM is another form of maintenance that can lead to cost effectiveness and an increased understanding of the level of risk of equipment (Mbeki, 2017).

To perform RCM on a system, the following basics steps can be followed (Gupta, et al., 2016):

- Select system and data collection;
- Divide the system and classify the functionality significant item;
- Perform FMEA;
- Do criticality analysis;
- Perform RCM logic decision;
- Select maintenance strategy.

2.5.5 Maintenance optimisation

With the dynamic modern technology developments, the need for optimising maintenance becomes of utmost importance for organisations to ensure improved overall asset performance. According to Alastair (2010), there is a need to have a balanced combination of different maintenance strategies in order to improve performance of the asset in a cost-effective way by moving from a reactive maintenance strategy to more proactive and preventative maintenance strategies.

An organisation can optimise its maintenance by combining the above discussed maintenance strategies. Maintenance optimisation plays an important role in ensuring that the system functions at lower cost, failing to do so will increase the cost of operating the system (Canh Vu, et al., 2018).

2.5.6 Adopted maintenance strategies for class 5M2A motor coaches at PRASA

PRASA has adopted diverse type of maintenance strategies for the maintenance of class 5M2A motor coaches, ranging from PM and CM. The principle applied to execute maintenance is centred on the condition-based maintenance principle. There are four types of maintenance intervals done for preventative maintenance. These intervals are named in line with the scope of work to be executed on the motor coaches, namely passenger safety and comport, Intermediate Shedding, and full shedding and general overall. The duration of each maintenance interval is as follows:

- Passenger safety and comfort – happens every two weeks through scheduled maintenance;
- Intermediate – happens every four weeks through scheduled maintenance;
- Full shed – happens every eight weeks through scheduled maintenance;
- General overhaul – happens between nine to twelve years; this activity is outsourced to external service providers through a formal contract.

These maintenance intervals are planned through the planning department within the depots. Planning utilises the computerised maintenance management system known as the facility maintenance management system. Through FMMS, job cards are generated by using each maintenance activity to be executed on motor coaches. Job cards are assigned to different maintenance personnel according to the type of skill needed to perform these activities, namely:

- Electrical fitters
- Carriage and wagon fitters
- Vehicle builders
- Examiner/underframe builder
- Trade hand.

The typical maintenance intervals of different components or systems of class 5M2A motor coach are shown in Table 1:

Table 1: Example of typical maintenance on class 5M2A motor coach

Description	Inspection interval
Lubricants	14-60 days
Brushes	30-60 days

Description	Inspection interval
Brake blocks	30-60 days
Exhauster oil	14-30 days
Pantographs	30-60 days
Compressor oil	90 days
Minor brake overhaul	2 years
Minor traction motor overhaul	2 years
Minor motor coach overhaul	6 years
Major motor coach overhaul	9-12 years

Table 2 shows the typical example of condition-based maintenance on class 5M2A motor coaches.

Table 2: Example of condition based maintenance on class 5M2A motor coaches

Description	Measuring tool	Condemning limits	Corrective action
Wheels	Mini proof	Motor coach = (984 – 1054) mm Trailer coach = (800 – 863) mm	Replace the worn out part or scrap
Pantograph	Ruler stop watch	Strip thickness = min 2 mm Raise time = 10-20 sec Lowering time < 6 sec	Replace the strip Calibrate the springs
Traction motor insulation resistance test	5000V Insulation resistance tester	< 2 mega ohms per traction motor	Send for rewinding
Brake Test	Brake Test	Fail on procedure	Repair before release back into service
Transformer	Oil analysis	>100 ppm impurities/wetness	Purify or change oil

Description	Measuring tool	Condemning limits	Corrective action
Motor Alternator (MA) Set	Fein Pruff	> 80 microns	Grind to less than 10 microns
Brushes	Ruler	< 8mm wear line	Replace the brush

2.5.7 Summary

This chapter presented a review of the literature and theories that currently exist in the field of reliability engineering, maintenance management and how they are used in the passenger train sector. In this chapter, the theories relating to maintenance optimisation, maintenance policies and maintenance strategies were discussed. In addition, literature and concepts relating to reliability engineering and reliability techniques were also discussed in this chapter. The maintenance strategies adopted by PRASA to execute maintenance of a class 5M2A were explained in this chapter.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

The main objective of this chapter is to develop a methodology that can be used to determine and model the factors that affect the reliability of the class 5M2A motor coaches operating in the Gauteng region. The methodology used for this study is the mixed method in a railways environment for passenger trains. In addition, the purpose of this chapter is to further explain the methodology followed to complete this research, taking into consideration the literature reviewed in Chapter 2. The methodology used also affords the researcher the opportunity to explore the research question outlined in Chapter 1 and further explains how the data is going to be collected for this study.

3.2 Purpose of research inquiry

There are different ways of conducting a research inquiry, taking into account what the objective of the research is, namely exploratory research, descriptive research and explanatory research.

3.2.1 Exploratory research

According to De Langhe and Schliesser (2017), exploratory research is a type of research aimed at carving out a new niche or entirely new puzzle. To support this definition, Makhanya (2016) defines exploratory research as a type of investigation that aims at creating new ideas and it is a useful approach if there is any ambiguity of the problem. This research method is useful for this study, as it will assist to explore the factors that affect the reliability of the class 5M2A motor coaches operating in Gauteng.

3.2.2 Descriptive research

According to Purdy and Popan (2018), descriptive research is a research methodology that can be either qualitative or quantitative to describe the events, situations, behaviours and results. They further state that descriptive research can be conducted through surveys, observations and through case studies.

Descriptive research is very important for this study, as it will assist in analysing the survey questionnaires and the failure trends of the different class 5M2A motor coach systems, subsystems and components that have failed for the past 24 months.

3.2.3 Explanatory research

According to Makhanya (2016), explanatory research, also referred to as causal research, is the type of research that provides the relation between the cause and the effects of the variables. The process for this type of research is sophisticated in nature and allows for the adaptation of an exhaustive list of causes influencing changes to other variables.

3.3 Research approach

Research can be classified as either applied or fundamental (Walliman, 2011). Applied research is used for this study because already known principles and theories are utilized to answer the set out research questions. According to Makhanya (2016), applied research uses already defined principles and policies, whereas fundamental research creates new ideas regarding the problem or subject of the research.

The following research techniques, namely deductive and inductive techniques, are of outmost importance for this study:

- The deductive technique starts from having a theory followed by deriving the hypothesis, testing of the hypothesis and revising the theory (Woiceshyn & Daellenbach, 2018). According to Makhanya (2016), the deductive approach starts by evaluating the data available, then develops propositions based on the known philosophies and finally the hypothesis can be accepted or rejected as a conclusion through arguments.
- The inductive technique is when creating empirical remarks about some phenomenon of interest and establishing ideas and principles based on them (Woiceshyn & Daellenbach, 2018). According to Makhanya (2016), the inductive approach starts by focusing on the research objectives and applies the known research theories to produce beliefs. He further states that the inductive approach is a theory building approach instead of hypothesis testing. This approach is the preferred method to be used in order to explore the objectives of this study.

According to Creswell (2013), research designs are categorised according to three methods, namely qualitative, quantitative and mixed methods. Qualitative research uses a naturalistic methodology that seeks to understand phenomena in context-specific settings, such as real world setting, where the researcher does not attempt to influence the phenomena of interest (Golafshani, 2003). According to Ferreira et al. (2016), qualitative research encompasses gathering and evaluating a heterogeneous set of empirical resources recorded in different media, such as audio, video, images, texts, diagrams, interactive and visual materials, and software artefacts. This data may characterize diverse instants and circumstances, including observations, interviews, and interaction with artefacts, case studies, personal experiences, introspections, descriptive narratives, history and others.

3.4 Unit of analysis

In this study, the statistical failures data of class 5M2A motor coaches operating in Gauteng region were used as the unit of analysis.

3.5 Study population and sample

According to Williamson (2018), population refers to a full set of all those elements, either people or institutions that have at least one characteristic in common. In this study, the population consists of 673 class 5M2A motor coaches, which were operating in Gauteng. Furthermore, data was collected through the opinions of the Metrorail maintenance personnel who were involved in the maintenance of the units under this investigation.

A sample is a selection of elements from the population nominated to represent the total population under investigation (Williamson, 2018). In this study, two types of sampling techniques were used, namely probability and non-probability sampling techniques (Makhanya, 2016). Even though all the elements of the population were taken into consideration for this study, some criteria had to be developed to ensure consistency in the results. The following elements were to be achieved as criteria for all the elements of the population to be used in this study:

- The motor coach should not have been out of service for the past 12 month (June 2018 to May 2019) for a period of 30 days.
- The motor coach had been operating in Gauteng for the past 12 months.
- The motor coach had at least 12 months' failure records.

For participants to take part in the survey developed for the study, the criteria below were to be met:

- The participant should be working in the maintenance of class 5M2A motor coaches;
- The participant should be a Metrorail employee;
- The participant should be eager to partake in the survey;
- The participant should have access to a computer with internet and email.

3.6 Data collection and analysis

There are different data collection strategies utilised when conducting research (Boieje & Hox, 2005). According to Makhanya (2016), there are two types of data that can be used in research, namely primary and secondary data. Secondary data analysis is analysis of data that had been composed by someone for alternative primary purpose (Johnston, 2017). To further support this definition, Makhanya (2016) defines secondary data analysis as the collection of records from other sources for other purposes rather than of those of the research. According to Sreejesh et al. (2014), primary data is collected for a unique research project straight from respondents by means of data collection methods like experiments, questionnaires and direct observations.

In this research, primary data was collected through research questionnaires consisting of closed-ended questions, for ease of analysis organized in a manner that data can be analysed qualitatively. The survey was distributed throughout PRASA rail maintenance depots and PRASA technical engineering services, especially those involved in maintenance execution, ranging from artisans, technicians, engineers, maintenance managers to engineering managers. The respondents were given a duration of 15 days to complete the survey. The Likert scale was provided inside the survey for the participants to rate the questions using strongly agree, agree, neutral, disagree and strongly disagree and provision for comments by the participants was also provided at the end of the survey (Makhanya, 2016).

In addition, another source of primary data was collected through PRASA maintenance databases for analysing the failure data of the class 5M2A motor coaches as outlined in the criteria stipulated in Section 3.5 of Chapter 3. This data was analysed using Microsoft Excel and Pareto Chart and the results were presented in different formats, such as tables, bar charts and histograms.

Secondary data was collected by downloading relevant existing literature from sources, such as the university of Johannesburg databases, google scholar, PRASA databases,and department of transport and railway safety regulator website to support and achieve the objectives of the research.

3.7 Reliability and validity

Reliability is the degree to which results are reliable over time. An precise demonstration of the total population under study is referred to as reliability and if the results of a study can be replicated under a similar approach, then the research instrument is considered to be reliable (Golofshani, 2003). According to Makhanya (2016), reliability is sensitive to errors of the participants and their bias, as well as the state of the observer.

According to Sreejesh et al. (2014), validity is the capability of a scale or a measuring instrument to quantity what it is anticipated to measure. According to Matsapola (2018), validity has three measurement approaches, namely construct, content and criterion as discussed below:

- Construct validity – the utilisation of a specific tool to reach a conclusion while collecting data from different sources;
- Content validity – the utilisation of a construct to provide sufficient details and representation of all participants that might measure the construct of interest;
- Criterion validity – is the comparison of the results of the new measure against the measures of the same construct.

The questionnaires were reviewed by the supersivor to ensure data quality and validity before implementation of the survey.

3.8 Limitation

The data collected in this research was only limited to the class 5M2A motor coaches and people working in the Gauteng region hence the outcome of the researcher is only limited to the Gauteng region. Other regions, like Western Cape and Kwazulu-Natal, where class 5M2A motor coaches are operated, can use the outcomes of this study as reference.

3.9 Conclusion

In this chapter, the methodology used to collect the data for this research was explained and the researcher provided the reasons why this method was preferred to warrant that all the research questions are answered and the research objectives are achieved.

This chapter also discussed the study population and how the population elements were selected in line with specified criteria.

The failure data of the class 5M2A motor coaches and the survey questionnaires were chosen to complement each other to answer the research questions.

The survey questionnaires were reviewed by the supersivor to ensure the data quality and the validity before implementation of the survey.

CHAPTER 4: DATA PRESENTATION AND ANALYSIS

4.1 Introduction

The purpose of this study was to address the challenges faced by the South African railway company (PRASA rail). The company has to keep its fleet in operation despite the high failure rates of this fleet, which has a direct impact on availability, reliability and related maintenance costs. The study focused on the class 5M2A motor coaches operating in Gauteng region as a unit of the research.

The primary objective of this study was to explore the factors that affect the reliability and availability of class 5M2A motor coaches operating in the Gauteng region with the intention of improving the fleet performance and hence optimising the associated maintenance cost. In addition, the secondary objectives were to:

- Identify various maintenance strategies used by PRASA rail maintenance depot;
- Evaluate the nature and causes of failures through failure mode analysis;
- Provide recommendations on how to enhance the reliability and the availability of the motor coaches.

In order to achieve the objectives, the evidence in the form of statistical failure data from the maintenance management system was used together with feedback provided through the questionnaire surveys. The results of both the failure data and questionnaires survey were analysed and presented in this chapter.

There were 673 motor coaches operating in Gauteng that comprised the population of the study. However due to the criteria that were developed for this study, only 273 motor coaches passed the criteria and hence the 273 that passed the criteria formed the sample for the study.

4.2 Failure data presentation

4.2.1 Motor coach subsystem failures

Table 3 shows the motor coach subsystem failures over the period of the study. The pattern of the subsystems failures differs from one another. The line/combination switches accounted for the highest (16.84%) of the motor coaches failures. The windows accounted for 16.10% of the fleet failures, which is not far from the line/combination switches. Traction motors and exhausters also formed part of subsystems, which dominated the fleet failure with 9.1% and 7.93%, respectively. Other subsystems that contributed to the fleet failures were wheels and brake system with 6.97% and 5.87%, respectively. The bulk of the motor coach failures were due to pantographs, accelerating/braking grids, compressors, cables, valves, traction controller, body/underframe, MA/MG, and cab equipment, amounting to 34.86% of the fleet failures.

Table 3: Motor coach subsystem failure: June 2018-May 2019

Motor coach subsystem failure: June 2018-May 2019			
Subsystems	**Total**	**Percentage relative**	**Cumulative relative %**
Traction motors	673	9.10%	9.10%
MA/MG	193	2.61%	11.71%
Compressor	354	4.79%	16.49%
Exhauster	587	7.93%	24.43%
Wheels	516	6.97%	31.40%
Traction controller	257	3.47%	34.87%
Line/combination switches	1 246	16.84%	51.72%
Windows	1 191	16.10%	67.82%
Valves	286	3.87%	71.68%
Cab equipment driving end	192	2.60%	74.28%
Cables	304	4.11%	78.39%
Brake system	434	5.87%	84.25%
Accelerating/Braking Grids	370	5.00%	89.25%
Body/underframe	205	2.77%	92.02%
Others	173	2.34%	94.36%
Pantographs	417	5.64%	100.00%
Total	7 398	100.00%	

4.2.2 Pareto chart of subsystem failures

Figure 9 presents the motor coach subsystems failures for the duration of the study. The chart indicates the top 20% subsystems failures that caused 90% of the motor coach failures. The following subsystems (windows, line/combination switches, traction motors, exhausters, pantograph, brake system, wheels, compressors, cables, traction controllers, accelerating/braking grids and valves) are in the top 20% subsystems causing 90% of the fleet failures. The cab equipment, body/underframe and MA/MG are the bottom 90% systems causing 20% of the motor coach failures.

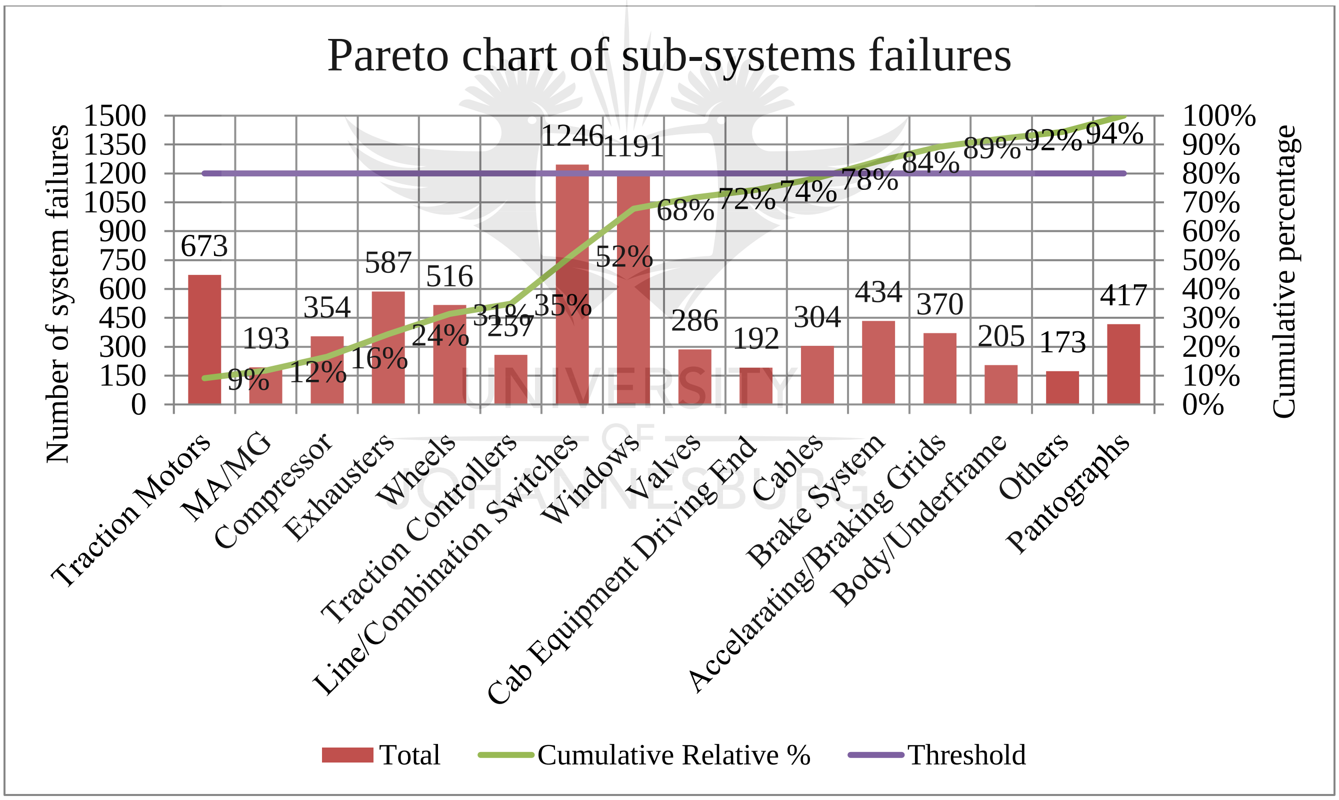

Figure 9: Motor coach subsystem failures

The following section discusses the failure modes, failure mode and criticality analysis for the top 20% subsystems that caused the 90% of the motor coach failures. Furthermore, the top 10 locomotives affected by these subsystems are discussed below.

4.2.3 Failure mode and effects: windows

Table 4 presents the failure modes of the windows. The most reported failure (56.93%) was due to missing windows. The other main failure mode for the windows was worn/damaged windows at 30.73%. At the bottom of window failure modes (12.34%) were not operating windows and others.

Table 4: Failure mode and effects: windows

Failure mode and effect windows			
Failure mode	**Total effects (No # of faults)**	**Contribution percentage**	**Cumulative percentage**
Worn/damaged	366	30.73%	30.73%
Missing	678	56.93%	87.66%
Not operating	103	8.65%	96.31%
Others	44	3.69%	100.00%
Total	1 191	100.00%	

4.2.4 Failure mode and effects analysis: windows

Table 5 shows the top 20% reasons for windows failure modes. The highest failure mode (64%) was due to theft. The second highest failure mode (25%) was due to mechanical failure related to aperture being broken. The rest of the failure modes, amounting to 11%, was due to wear and tear, broken windowpanes and unknown.

Table 5: Failure mode and effect analysis: windows

Failure mode and effect analysis: windows				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effects per cause (No. of faults)**	**Percentage**
Worn/ damaged	Operational conditions	Wear and tear	43	4%
	Mechanical damage	Aperture broken	298	25%
Missing	Stolen	Theft	763	64%
	Operational conditions	Unknown	17	1%
Not operating	Mechanical damage	Window pane broken	63	5%
	Operational conditions	Unknown	7	1%
			1 191	100%

4.2.5 Top 10 motor coaches affected by windows

Figure 10 shows the top ten motor coaches affected by windows. Motor Coach 5M29051 was the most affected with 38 failures. The next motor coach on top 10 list was 5M29058 with 36 failures, followed by 5M29274 and 5M9278 with 35 failures. The 33 failures on the top 10 list were motor coach 5M29345, 5M213557 and 5M213424. The following motor coaches 5M29170, 5M213110 and 5M213041 were on the bottom of the top 10 list with 32 failures.

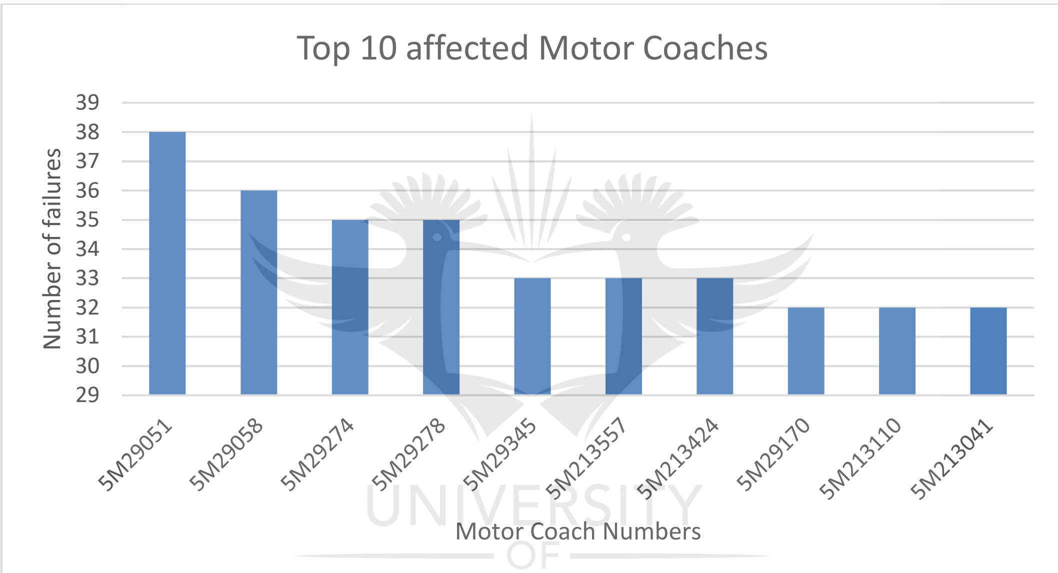

Figure 10: Top 10 motor coaches affected by windows

4.2.6 Failure mode and effects: line/combination switches

Table 6 highlights the failure mode of the line/combination switches. Sixty-two per cent of the line/combination switches failure mode was due to burns. The most significant failure of the switches is the flashes. Twelve per cent (12%) of the switches failure modes were due to the air leaks switches being defective and not operating. About 4% of the failure mode for the switches was due to damage, incorrect operation and switches being broken.

Table 6: Failure mode and effect : line/combination switches

Failure mode and effect: line/combination switches			
Failure mode	**Total effects (No # of faults)**	**Contribution percentage**	**Cumulative percentage**
Flashed	252	20%	20%
Burnt	773	62%	82%
Leaking air	49	4%	86%
Defective	64	5%	91%
Not operating	42	3%	95%
Broken	17	1%	96%
Damaged	18	1%	98%
Incorrect operation	19	2%	99%
Others	12	1%	100%
	1 246		

4.2.7 Failure mode and effects analysis: line/combination switches

Table 7 shows the top 20% reasons for each failure mode. The highest 20% reasons for the flashes were due to dirtiness of the system, contributing 54% of the total failures. The other reason for flashes was tracking, contributing 29% of the failures.

The other highest contributing failure mode on the list for the line/combination switches was due to system burn. The top 20% reason, burnt arc chute and sticky contact tips contributed 63% and 11%, respectively. Other contributing factors for the flashes were due to overvoltage (7%) and dirtiness (4%) in the system. Leaking air in the system was due to defective magnet valves (67%). Most defects were due to burns (45%) and not operating (55%) due to failures, with no reasons reported. The other failure for the line/combination switches was broken, of which 20% of the reasons were due to mechanical damage (53%) and operating conditions (41%). Damages in the systems also contributed to the failures of the system, of which 2% of the failures were due to mechanical damages (50%) and operating conditions (39%). Incorrect operation also caused switches failures and the contributing factors for incorrect operation were due to out of calibration (58%), mechanical damages (26%) and operating conditions (11%). The next section presents the top 10 motor coaches affected by line/combination switches.

Table 7: Failure mode and effect analysis of line/combination switches

Failure mode and effect analysis: line/combination switches				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effect per cause (No. of faults)**	**Percentage**
Flashed	252	Dirty	137	54%
		Tracking	73	29%
Burnt	773	Burnt arc chute	489	63%
		Dirty	34	4%
		Overvoltage	57	7%
		Sticky contact tips	83	11%
Leaking air	49	Defective magnet valve	33	67%
Defective	64	Burnt	29	45%
Not operating	42	Reason not reported	23	55%
Broken	17	mechanical damage	9	53%
		Operating conditions	7	41%
Damaged	18	Mechanical damage	9	50%
		Operating conditions	7	39%
Incorrect operation	19	Out of calibration	11	58%
		Mechanical damage	5	26%
		Operating conditions	2	11%

The next section presents the top 10 motor coaches affected by line/combination switches.

4.2.8 Top 10 motor coaches affected by line/combination switches

Figure 11 shows the top 10 motor coaches affected by line/combination switches. On top of the list, motor coach 5M29052 and 5M29062 had 45 failures each. The other motor coaches affected by switches failures were 5M29276, 5M29280 and 5M29347 with 43 failures each. Motor coaches 5M213559 and 5M213426 were also on the top 10 list with 41 failures each. Motor coaches 5M29172 and 5M213112 were also on the top 10 list with both having 39 failures. The last three motor coaches (5M213043, 5M213061 and 5M213065) on the top 10 list had 37 failures each.

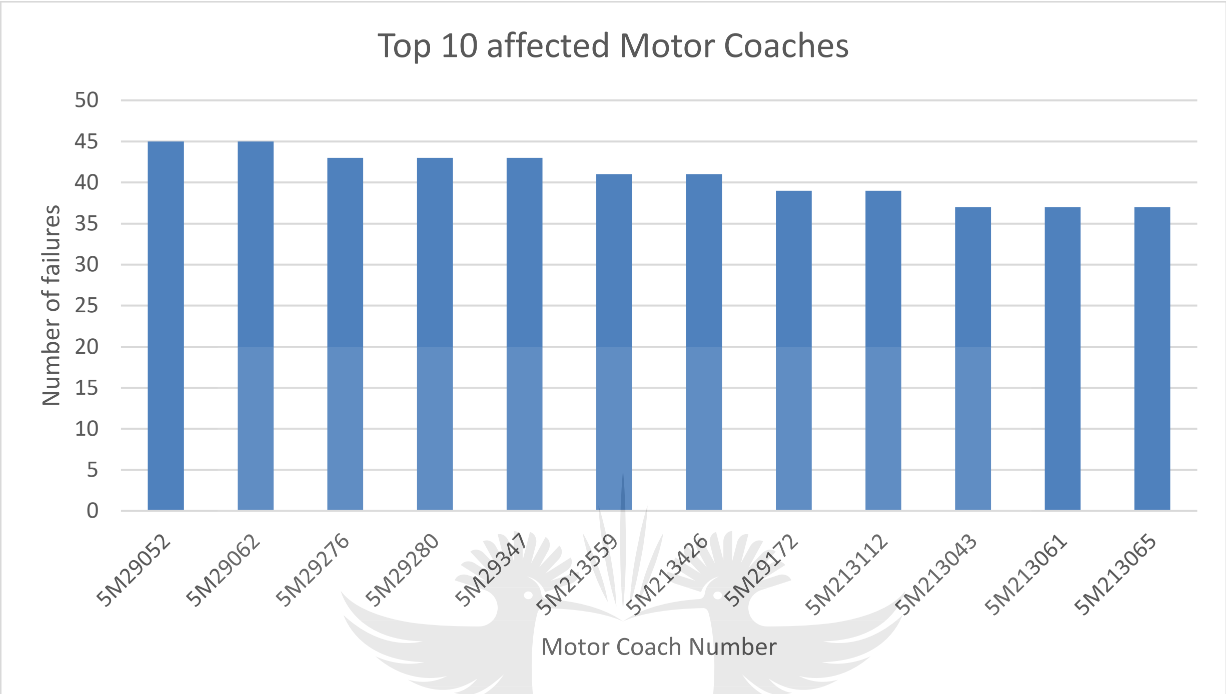

Figure 11: Top 10 motor coaches affected by windows

4.2.9 Failure mode and effect: traction motors

Table 8 presents the failure modes of the subsystem traction motors. The highest failure mode of the traction motors was due to flashes (46%). The other cause of traction motors was due to burns contributing 23% of the subsystem failure. Leaking oil and failures due defects were also factors that caused subsystem failure with 8% and 6%, respectively. The other factors that caused traction motor failures, contributing 14%, were not operating, broken, damaged and incorrect operation.

Table 8: Failure mode and effects: traction motor

Failure mode and effects: traction motors			
Failure mode	**Total effects (No. of faults)**	**Contribution percentage**	**Cumulative percentage**
Flashed	312	46%	46%
Burnt	153	23%	69%
Leaking oil	53	8%	77%
Defective	42	6%	83%
Not operating	21	3%	86%
Broken	35	5%	92%
Damaged	29	4%	96%
Incorrect operation	17	3%	98%
Others	11	2%	100%
	673		

4.2.10 Failure mode and effect analysis of traction motors

Table 9 presents the top 20% reasons of the failure of subsystem traction motors. The highest top 20% failures of the traction motors were due to flashes. The 62% of the flashes were due to dirtiness of the system and overvoltage, which contributed 14% of the flashes. The burns caused traction motor failures, with 63% being inter pole coils, followed by the main pole (14%) and the armature coils (11%). Brush box burns contributed 7% to the traction motors failures.

Leaking oil also contributed to the top 20% failures of the traction motors, with leaks caused by mechanical damage (23%) and broken gear case (55%). Defectives also contributed to 20% of the subsystem failures. Short brushes accounted for 55% of the defects. Low megger reading contributed 26% of the defects.

Two other factors that caused the defects of traction motors were burns (10%) and bearing seizure (5%). Not operating also contributed 20% failures of the traction motors in the subsystem with the main cause being broken armatures (33%).

Breakages of the subsystem also contributed to the 20% failures of which the following factors were the cause: broken pinion (26%) and operating conditions (20%).

Mechanical damage contributed 59% and operating conditions (17%) of the damages in the top 20% failures of the traction motors. Incorrect operation also contributed to the top

20% of the subsystem failures, of which polarity swap (65%), mechanical damage (6%) and operating conditions (12%) were the cause of the failures. The next section discusses the failure mode and the effect of the exhauster.

Table 9: Failure mode and effects: traction motor

Failure mode and effect analysis: traction motor				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effect per cause (No. of faults)**	**Percentage**
Flashed	312	Dirty	192	62%
		Over voltage	43	14%
Burnt	153	Burnt main pole coils	21	14%
		Burnt inter-pole coils	97	63%
		Burnt armature coils	17	11%
		Burnt brush box	11	7%
Leaking oil	53	Mechanical damage	12	23%
		Gear-case broken	29	55%
Defective	42	Burnt	4	10%
		Bearing seized	2	5%
		Short brushes	23	55%
		Low megger reading	11	26%
Not operating	21	Armature broken	7	33%
Broken	35	Pinion broken	9	26%
		Operating conditions	7	20%
Damaged	29	Mechanical damage	17	59%
		Operating conditions	5	17%
Incorrect operation	17	Polarity swap	11	65%
		Mechanical damage	1	6%
		Operating conditions	2	12%

4.2.11 Failure mode and effect: exhauster

Table 10 presents the failure modes of the subsystem exhauster. The main contributor to the subsystem was due to electrical failure with 47%. The mechanical failure was the second contributor with 19%. Damages caused 12% of the subsystem failures, followed by leaking air at 11%. The following factors contributed 10% of the subsystem failure, defective, incorrect setting and incorrect operation.

Table 10: Failure mode and effects: exhauster

Failure mode and effect: exhauster			
Failure Mode	**Total effects (No. of faults)**	**Contribution percentage**	**Cumulative percentage**
Damaged	73	12%	12%
Leaking air	67	11%	24%
Incorrect setting	18	3%	27%
Incorrect operation	12	2%	29%
Defective	29	5%	34%
Electrical failure	277	47%	81%
Mechanical failure	111	19%	100%
	587		

4.2.12 Failure mode and effects analysis: exhauster

Wear and tear contributed to 78% and operating conditions 10% of the damages of the exhauster failures. Another factor that contributes to the exhauster top 20% failure is the air leaks with 76%. Incorrect setting was part of the top 20% failures of the subsystem, with failure caused by out of calibration (56%) and operating conditions (22%). Incorrect operation contributed 67% of the subsystem failure due to out of calibration. Operating conditions accounted for 45% and damage by foreign object (31%) failure for the defects.

Electrical failures also formed part of the 20% failures of the subsystem. These failures consist of 59% burnt inter-pole coils, 22% motor overload, 7% burnt armature coils and 4% burnt main pole coils. The main contributor for the exhauster top 20% failures was due to mechanical failures. Broken gasket was the highest, accounting for 47%, followed by wear and tear at 24%. The rest of the mechanical failure was due to operating conditions (22%) and seized bearings (4%).

Table 11: Failure mode and effect analysis: exhauster

Failure mode and effect analysis: exhauster				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effect per cause (No. of faults)**	**Percentage**
Damaged	73	Wear and tear	57	78%
		Operating conditions	7	10%
Leaking air	67	Operating conditions	51	76%
Incorrect setting	18	Out of calibration	10	56%
		Operating conditions	4	22%
Incorrect operation	12	Out of calibration	8	67%
Defective	29	Operating conditions	13	45%
		Damage: foreign object	9	31%
Electrical failure	277	Motor overload	61	22%
		Burnt armature coils	19	7%
		Burnt main pole coils	12	4%
		Burnt inter-pole coils	163	59%
Mechanical failure	111	Wear and tear	27	24%
		Operating conditions	24	22%
		Gasket broken	52	47%
		Bearing seized	4	4%

The next section presents the top 10 motor coaches affected by exhauster failures.

4.2.13 Top 10 motor coaches affected by exhauster failures

Figure 12 presents the top 10 motor coaches affected by exhauster failures. The motor coach with the highest failures was 5M29141 with 45 failures. Motor coaches 5M29316, 5M29023 and 5M29026 were the second highest with 44 failures. The following motor coaches 5M29065 and 5M29058 both had 43 failures. With 41 failures were motor coaches 5M29059, 5M29171 and 5M29221. The last motor coaches on the top 10 list were 5M29253 and 5M29254 with 39 failures each.

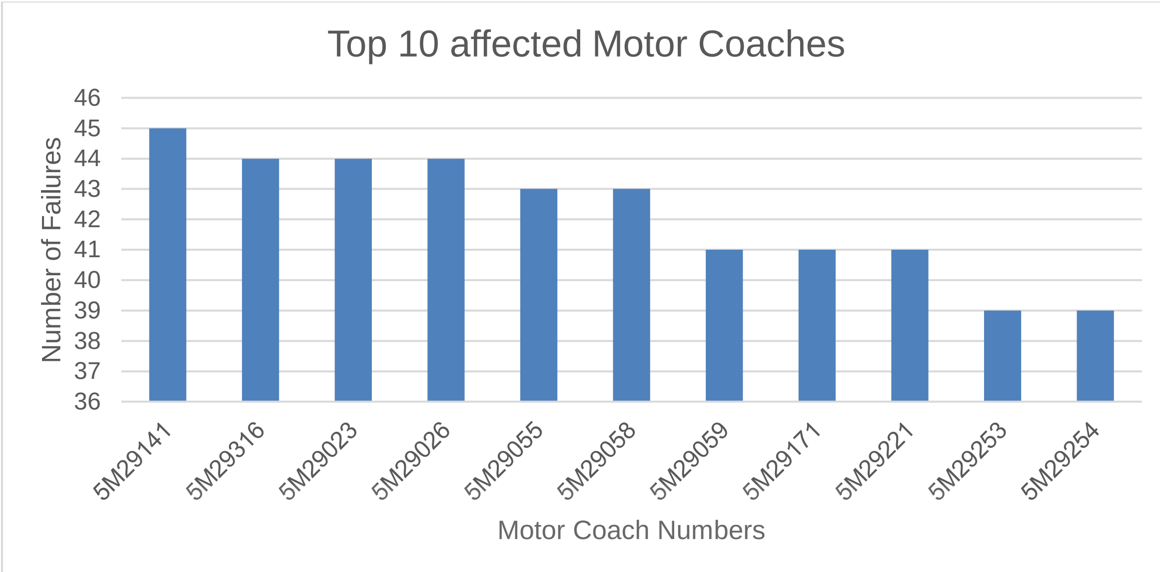

Figure 12: Top 10 motor coaches affected by exhauster

The following section presents the failure mode and effects of the pantographs.

4.2.14 Failure mode and effect of pantographs

Table 12 shows the failure mode of the subsystem pantograph for the duration of the study. The highest failure mode of pantographs is due to the worn out copper strips contributing 39% of the failures. The second highest failure mode is the damaged copper strips (18%), followed by leaking cylinders, accounting for 11% of the failures. Nine per cent (9%) of the failures were due bents. The other factors that contributed to 12% of subsystem failures were due to broken pantographs (6%) and not rising (6%). The remainder of the pantographs failures, amounting to 9%, were due to insufficient contact (4%), missing (4%) and sticky (2%).

Table 12: Failure mode and effects pantograph

Failure mode and effect: pantograph			
Failure mode	**Total effects (No. of faults)**	**Contribution percentage**	**Cumulative percentage**
Damaged copper strip	73	18%	18%
Worn copper strip	161	39%	56%
Bent	37	9%	65%
Broken	23	6%	71%
Not rising	27	6%	77%
Leaking cylinder	47	11%	88%
Sticky	9	2%	90%
Missing	13	3%	94%
Insufficient contact	16	4%	97%
Other	11	3%	100%
	417		

4.2.15 Failure mode and effect analysis of pantograph

Table 13 presents the causes of the top 20% failures of the pantograph. Ninety-five per cent (95%) of damaged copper strips were caused by wear and tear. Worn out copper strips were mostly due to wear and tear (94%). The following factors contributed to the pantographs that have bent, panto hook-up contributed (76%) and damaged by foreign objects (24%). For about 91% of the pantographs that were broken, the main cause was the panto hook-up. The cause of pantographs not rising was due to no upper pressure (93%). Defective cylinders had led to 91% of the leaking cylinders. Seventy-eight per cent (78%) of sticky pantograph was due to insufficient lubrication. Insufficient contact was caused by wear and tear (69%) and defective suspension springs (31%).

Table 13: Failure mode and effects analysis pantograph

Failure mode and effect analysis: pantograph				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effect per cause (No. of faults)**	**Percentage**
Damaged copper strip	73	Wear and tear	69	95%
Worn copper strip	161	Wear and tear	151	94%
Bent	37	Panto hook-up	28	76%
		Damaged: foreign object	9	24%
Broken	23	Panto hook-up	21	91%
Not rising	27	No upper pressure	25	93%
Leaking cylinder	47	Defective cylinder	43	91%
Sticky	9	Insufficient lubrication	7	78%
Missing	13	Insufficient lubrication	11	85%
Insufficient contact	16	Wear and tear	11	69%
		Defective suspension	5	31%

4.2.16 Top 10 motor coach affected by pantographs

At the bottom of the top 10 list were motor coaches 5M213017 and 5M213033 with 33 failures each. The following motor coaches, 5M29275, 5M29172 and 5M29346, had 35 failures each. Motor coach 5M213558 and 5M213425 had 37 failures each. At the top of the list, with 38 failures were motor coaches 5M29055, 5M29053, 5M313444 and 5M213457.

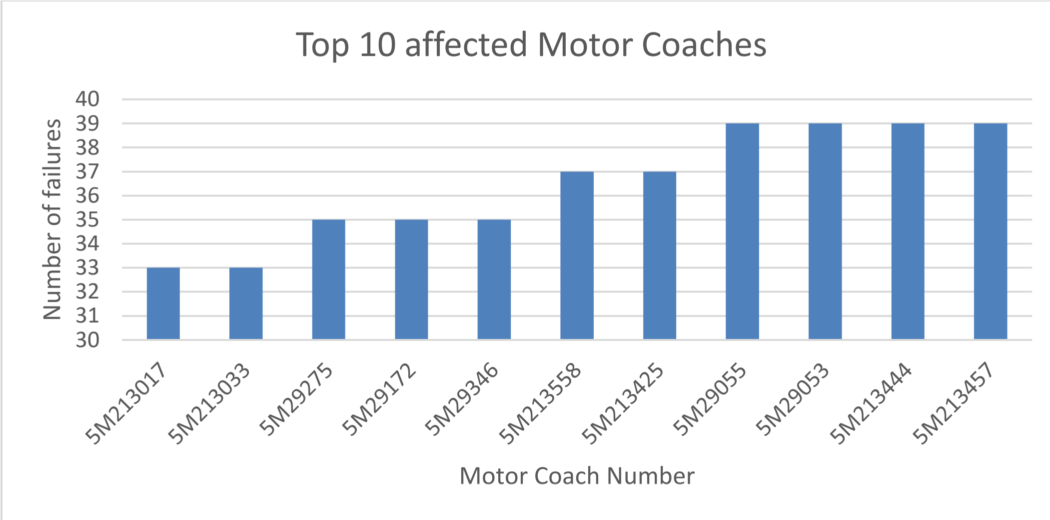

Figure 13: Top 10 motor coaches affected by pantographs

The following section presents the failure mode and effect of the brake system.

4.2.17 Failure mode and effects of brakes system

Table 14 presents the failure modes of the brakes subsystem. The major contributor of brake system failure was due to incorrect operation at 53%. The following factor that contributed 24% of the brake systems failure was air leaks. Ten per cent (10%) of the brake failures were due to damages. The following factors contributed 10% of the brakes system failures, broken off (4%), incorrect setting (3%) and dirtiness (3%).

Table 14: Failure mode and effects brake system

Failure mode and effect: brake system			
Failure mode	**Total effects (No. of faults)**	**Contribution percentage**	**Cumulative percentage**
Damaged	43	10%	10%
Leaking	103	24%	34%
Incorrect setting	15	3%	37%
Incorrect operation	231	53%	90%
Broken off	18	4%	94%
Dirty	13	3%	97%
Others	11	3%	100%
	434		

4.2.18 Failure mode and effects analysis of brakes system

Table 15 presents the top 20% reasons that caused the brake system failures. Eighty six per cent (86%) of damages were due to operating conditions. About 84% of the brake leaks were due to operating conditions. Incorrect settings were due to out of calibration (73%) and operating conditions (27%). Operating conditions (56%) and damaged by foreign object (33%) caused the brake system to break off. Dirtiness was also a contributing factor caused by unknown cause (77%) and out of calibration (23%). The next section presents the top 10 motor coaches affected by brake system failures.

Table 15: Failure mode and effects analysis brake system

Failure Mode and effect analysis: brake system				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effect per cause (No. of faults)**	**Percentage**
Damaged	43	Operating conditions	37	86%
Leaking	103	Operating conditions	87	84%
Incorrect setting	15	Out of calibration	11	73%
		Operating conditions	4	27%
Incorrect operation	231	Out of calibration	211	91%
Broken off	18	Operating conditions	10	56%
		Damage: foreign object	6	33%
Dirty	13	Unknown cause	10	77%
		Out of calibration	3	23%

The next section presents the top 10 motor coaches affected by brake system failures.

4.2.19 Top 10 motor coaches affected by brake system failures

Figure 10 presents the top 10 motor coaches affected by brake system failures. On top of the list was motor coach 5M29041 with 29 failures. The following motor coaches (5M29046, 5M29279 and 5M29173) had 27 failures each. Motor coaches 5M21355 and 5M213423 were also on the top 10 list with 25 failures each. The following motor coaches (5M21311, 5M213042 and 5M213427) were affected by brake failures, with 23 failures each. At the bottom of the top 10 list was motor coach 5M213039 with 21 failures.

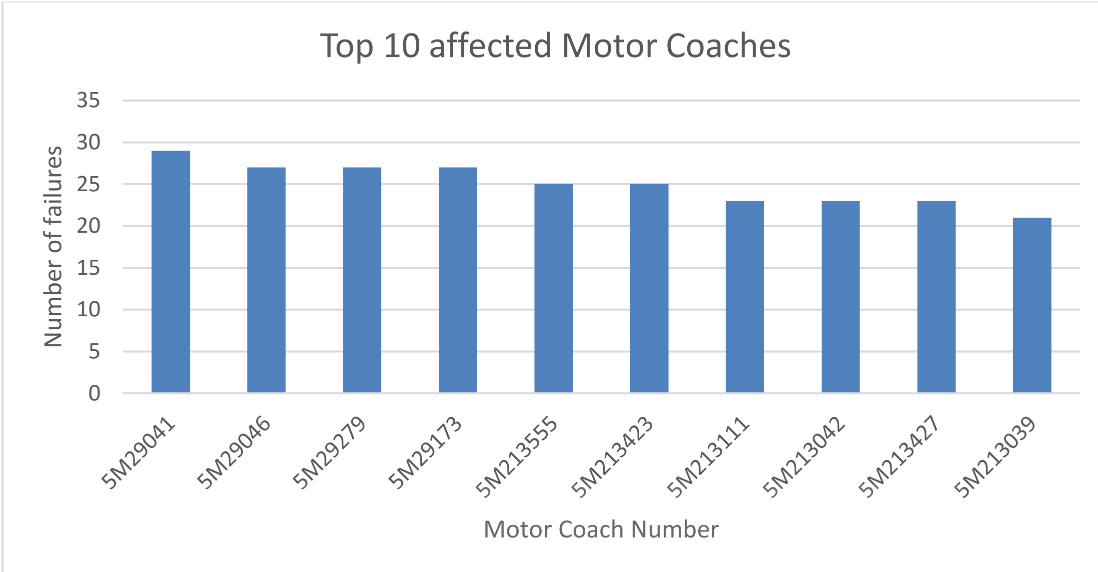

Figure 14: Top 10 motor coaches affected by brakes

The next section will present the failure mode and effects of the wheels.

4.2.20 Failure mode and effects of wheels

Table 16 presents the failure mode of the wheels subsystem. The most contributing failure mode for wheels was defects, accounting for 71% of wheel failures. The second failure mode of wheels was out of the limit, accounting for 22% of the wheel failures.

Table 16: Failure mode and effects wheels

Failure mode and effect : wheels			
Failure mode	**Total effects (No. of faults)**	**Contribution percentage**	**Cumulative percentage**
Defective	367	71%	71%
Out of limit	112	22%	93%
Other	37	7%	100%
	516		

4.2.21 Failure mode and effects analysis of wheels

Table 17 presents the reasons for the 20% failures of the subsystem wheels. The high factor that contributed to defective wheels was sharp flange with 73%. Another factor that contributed to 12% for defective wheels was high flange. Skidded wheels contributed 7%

for defective wheels. The other factors that contributed 9% for the defective wheels were faulty wheel gear (2%) and hollow wear (4%).

The highest cause of wheels being out of limit was due to sharp flange (50%). The following factor that caused wheels to be out of limit was high flange (17%). Hollow wear contributed 15% to the wheels being out of limit. Ten per cent (10%) of wheels that were out of limit had skid marks. Three per cent (3%) of wheels that were out of limit were due to faulty wheel gear. The next section presents the top 10 motor coaches affected by wheels.

Table 17: Failure mode and effect analysis: wheels

Failure mode and effect analysis: wheels				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effect per cause (No. of faults)**	**Percentage**
Defective	367	Sharp flange	268	73%
		High flange	43	12%
		Skidded wheel	27	7%
		Fault wheel gear	9	2%
		Hollow wear	13	4%
		Unknown	7	2%
Out of limit	112	Sharp flange	56	50%
		High flange	19	17%
		Skidded wheel	11	10%
		Fault wheel gear	3	3%
		Hollow wear	17	15%
		Worn	6	5%

The next section presents the top 10 motor coaches affected by wheels.

4.2.22 Top 10 motor coaches affected by wheels

Figure 11 presents the top 10 motor coaches affected by wheels. Motor coach 5M29014 was on top of the list with 49 failures. The following motor coaches (5M29044, 5M29269 and 5M29171) had 47 failures each.

The other motor coaches that were on the top 10 list were 5M213037, 5M213108 and 5M213038 with 45 failures each. At the bottom of the top 10 list was motor coaches 5M213429, 5M213038 and 5M213032 with 42 failures each.

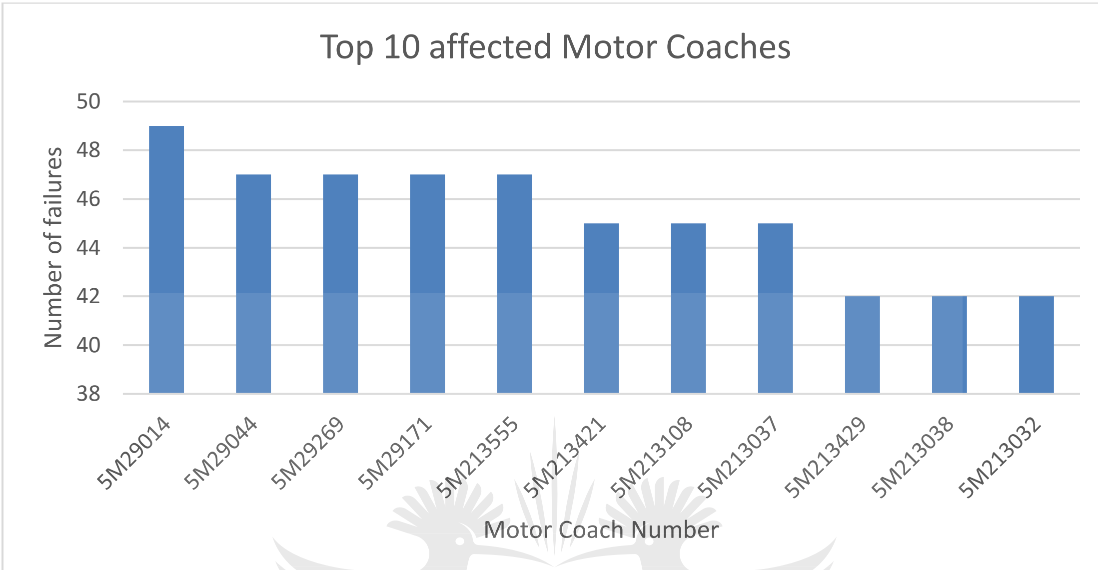

Figure 15: Top 10 affected motor coaches by wheels

4.2.23 Failure mode and effects of compressor

Table 18 presents the failure mode of the compressor subsystem. Most of the compressor failures were due to electrical failures (54%). The second highest failure mode of the compressor was due to mechanical failure (19%). Eight per cent (8 %) of the compressor failures were due to leaking air in the system. About 11% of the compressor failures were due to incorrect operation (5%) and damages (6%). The following factors also contributed to compressor failures: incorrect setting (4%) and defective (4%).

Table 18: Failure mode and effects compressor

Failure mode and effect: compressor			
Failure mode	**Total effects (No. of faults)**	**Contribution percentage**	**Cumulative percentage**
Damaged	22	6%	6%
Leaking air	27	8%	14%
Incorrect setting	15	4%	18%
Incorrect operation	17	5%	23%
Defective	13	4%	27%
Electrical failure	191	54%	81%

Failure mode and effect: compressor			
Failure mode	**Total effects (No. of faults)**	**Contribution percentage**	**Cumulative percentage**
Mechanical Failure	69	19%	100%
	354		

4.2.24 Failure mode and effect analysis of compressor

Table 19 presents the causes for the top 20% failures that caused the compressor to fail. Seventy-seven per cent (77%) of the damaged compressors were due to operating conditions. Operating conditions caused 70% of the air leaks in the subsystem. Incorrect setting failures were because of operating conditions (20%) and out of calibration (60%). Sixty-five per cent (65%) of incorrect operation was due to out of calibration. Defective compressors were because of operating conditions (62%) and damage by foreign objects (23%). The following factors caused electrical failures: burnt inter-pole coils (40%), motor overload (33%), burnt armature coils (16%) and burnt main pole coils (6%). Mechanical failure was caused by wrong vanes (44%), broken gasket (28%), bearing seized (18%) and operating conditions (8%).

Table 19: Failure mode and effect analysis compressor

Failure mode and effect analysis: compressor				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effect per cause (No. of faults)**	**Percentage**
Damaged	22	Operating conditions	17	77%
Leaking air	27	Operating conditions	19	70%
Incorrect setting	15	Out of calibration	9	60%
		Operating conditions	3	20%
Incorrect operation	17	Out of calibration	11	65%
Defective	13	Operating conditions	8	62%
		Damage: foreign object	3	23%
Electrical failure	191	Motor overload	63	33%
		Burnt armature coils	31	16%

Failure mode and effect analysis: compressor				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effect per cause (No. of faults)**	**Percentage**
		Burnt main pole coils	12	6%
		Burnt inter-pole coils	76	40%
Mechanical failure	61	Wrong vanes	27	44%
		Operating conditions	5	8%
		Gasket broken	17	28%
		Bearing seized	11	18%

The top 10 motor coaches affected by the compressor are presented in the following section.

4.2.25 Top 10 affected motor coaches by compressor

The motor coaches with the lowest failures (24) on the top 10 list were 5M213470 and 5M213561. The set of motor coaches with 25 failures were 5M213563, 5M213609 and 5M213611. With 27 failures, each on the top 10 list were motor coaches 5M213612, 5M217563 and 5M217515. The motor coaches with the highest compressor failures (31) were 5M217530 and 5M217524.

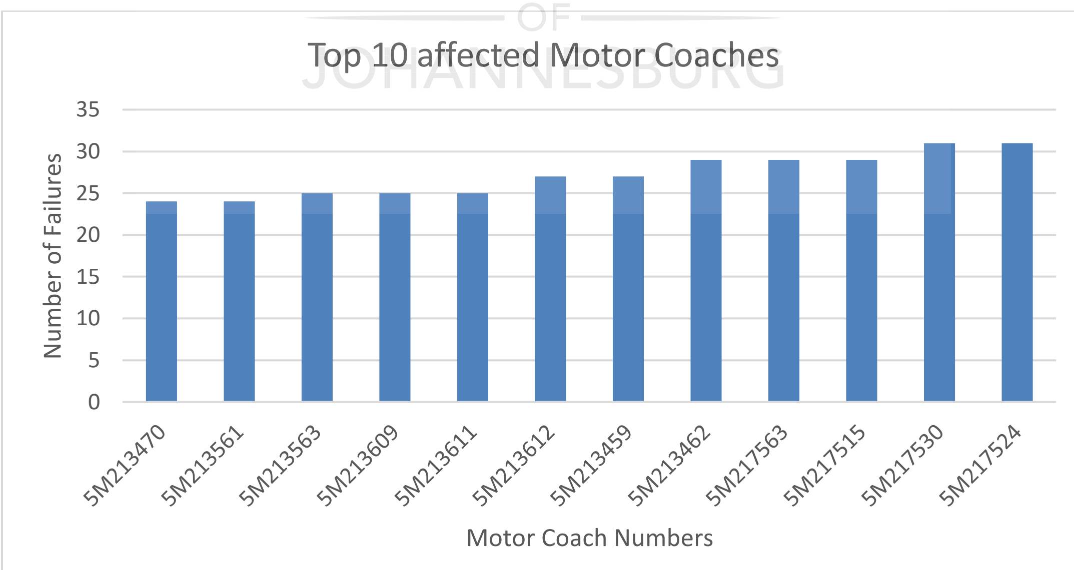

Figure 16: Top 10 affected motor coaches by compressor

The failure mode and effects of the cables are presented in the following section.

4.2.26 Failure mode and effects of cables

Damages (65%) were the highest failure mode for the cables as indicated in Table 20. The next highest failure mode was burnt cables (27%). Five per cent (5%) of the cables were broken.

Table 20: Failure mode and effects of cables

Failure mode and effects: cables			
Failure mode	**Total effects (No # of faults)**	**Contribution percentage**	**Cumulative percentage**
Burnt	81	27%	27%
Broken	16	5%	32%
Damaged	197	65%	97%
Others	10	3%	100%
	304		

4.2.27 Motor coach subsystem failures

Table 21 presents the reasons for the top 20% failure of cables. Most of the cables that burnt was due to incorrect crimping (63%) and loose connection (23%). The causes of cable breakage were due to wear and tear (69%), damage by foreign objects (31%). Cable damages were due to vandalism (82%) and operating conditions (10%).

Table 21: Failure mode and effects of cables

Failure mode and effect analysis: cables				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effect per cause (No. of faults)**	**Percentage**
Burnt	81	Incorrect crimping	51	63%
		Loose connection	19	23%
Broken	16	Wear and tear	11	69%
		Damage: foreign object	5	31%
Damaged	197	Vandalism	162	82%
		Operating conditions	19	10%

The top 10 motor coaches affected by cables are presented in the following section.

4.2.28 Top 10 motor coaches affected by cables

The motor coach with the highest number of failures (35) is 5M29012. The motor coach with the second highest number of failures (32) is 5M29015. Motor coaches 5M29016, 5M29018 and 5M213224 had 29 failures each. With 27 failures each, were motor coaches 5M213225 and 5M213227. Motor coaches 5M213229 and 5M213033 had 25 failures each. The last motor coaches on the top 10 list were 5M213025 and 5M213037 with 23 failures each.

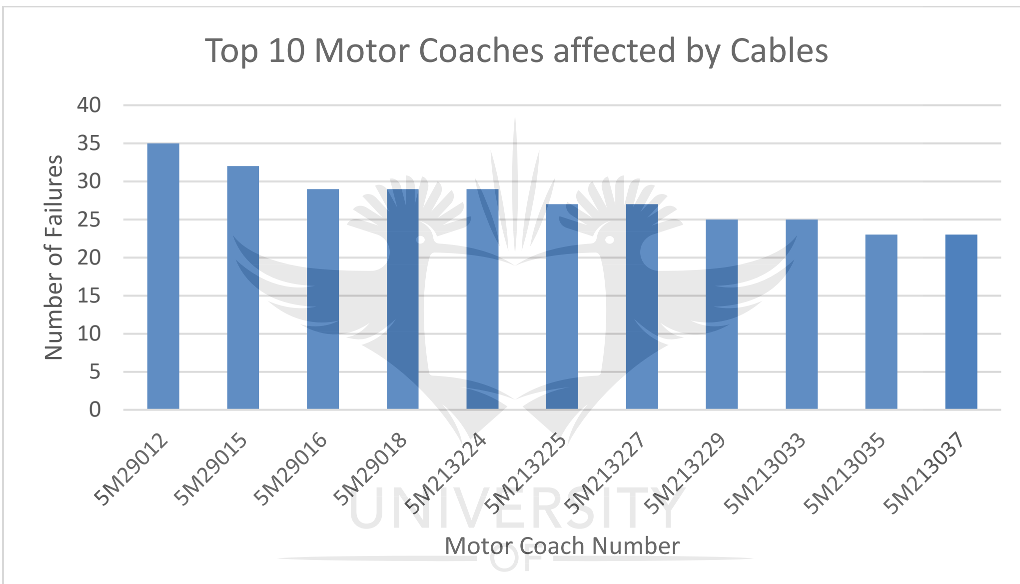

Figure 17: Top 10 motor coaches affected by cables

The next section presents the failure mode and effects of the Traction Controller.

4.2.29 Failure mode and effects of traction controller

Incorrect operation (53%) was the failure mode with the highest failures as presented in Table 22. Seventeen per cent (17%) of traction controllers were defective. Interference caused 15% of the traction controllers. Eleven per cent (11%) of traction controller failures were due to not operating.

Table 22: Failure mode and effects: traction controller

Failure mode and effects : traction controller			
Failure mode	**Total effects (No. of faults)**	**Contribution percentage**	**Cumulative percentage**
Defective	43	17%	17%
Interference	39	15%	32%
Incorrect operation	137	53%	85%
Not operating	27	11%	96%
Others	11	4%	100%
	257		

4.2.30 Failure mode and effects analysis of traction controller

Operating conditions caused 86% of the top 20% of the defective traction controller as presented in Table 23. Seventy-four per cent (74%) of interference was due to operating conditions. Operating conditions caused 88% of incorrect operation of the traction controller. Traction controllers not operating was caused by defects (41%) and operating conditions (26%).

Table 23: Failure mode and effects analysis: traction controller

Failure mode and effect analysis: traction controller				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effect per cause (No. of faults)**	**Percentage**
Defective	43	Operating conditions	37	86%
Interference	39	Operating conditions	29	74%
Incorrect operation	137	Operating conditions	121	88%
Not operating	27	Defective	11	41%
		Operating conditions	7	26%

The top 10 motor coaches affected by traction controller are presented in the next section.

4.2.31 Top 10 motor coaches affected by traction controller

The motor coaches with the highest traction controller failures (27) were 5M217621 and 5M13228. The motor coaches with the second highest traction controller failures (25) were 5M217602, 5M29501 and 5M213490. With 23 traction controller failures were motor coaches 5M217576, 5M19525 and 5M219528. Motor coaches 5M219535 and 5M219610 had 21 failures each. The last motor coach on the top 10 list was 5M219612 with 20 failures.

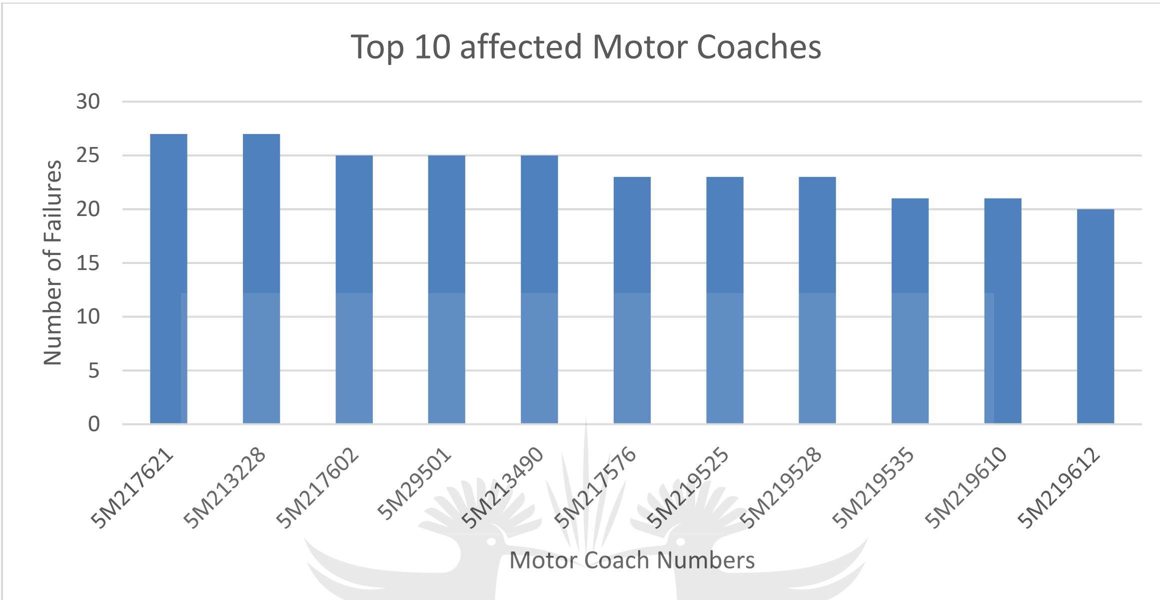

Figure 18: Top 10 motor coaches affected by traction controller

The next section presents the failure mode and effects of the accelerating/combination grids.

4.2.32 Failure mode and effects of accelerating/combination grids

Table 24 presents the failure modes of accelerating/combination grids. Sixty-nine per cent (69%) of the grids were burnt. About 15% of grid failures were due to damages. Eleven per cent (11%) of the grids were broken.

Table 24: Failure mode and effects: grids

Failure mode and effects : Accelerating/braking grids			
Failure mode	**Total effects (No # of faults)**	**Contribution percentage**	**Cumulative percentage**
Burnt	257	69%	69%
Broken	40	11%	80%
Damaged	54	15%	95%
Others	19	5%	100%
	370		

4.2.33 Failure mode and effects analysis of accelerating/combination grids

Table 25 presents the top 20% failure of the grids. Over current (74%) caused the top 20% failures that led to grids burning. The following factor that led to grids burning was loose connection (21%). Grid breakage was caused by wear and tear (53%) and damage by foreign objects (28%). Operating conditions caused 89% of grids damages.

Table 25: Failure mode and effects analysis: grids

Failure mode and effect analysis: Accelerating/braking Grids				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effect per cause (No. of faults)**	**Percentage**
Burnt	257	Over current	184	72%
		Loose connection	53	21%
Broken	40	Wear and tear	21	53%
		Damage: foreign object	11	28%
Damaged	53	Operating conditions	47	89%

4.2.34 Top 10 motor coaches affected by accelerating/combination grids

Figure 15 presents the top 10 motor coaches affected by accelerating/combination grids. The motor coaches with the highest grids failures (31) were 5M29253 and 5M29255. The motor coaches with the second highest grid failure (29) were 5M29260, 5M29266 and 5M29266. With 27 grids failure were motor coaches 5M213272 and 5M213275. Motor coaches 5M213437, 5M213470 and 5M213542 had 25 failures each. The motor coach with the least failures (23) was 5M219534.

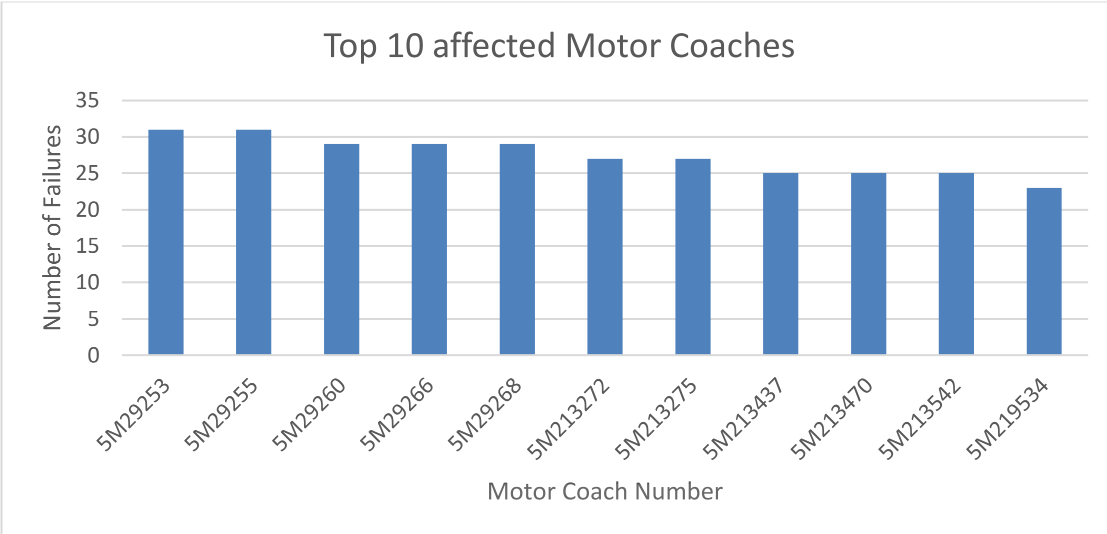

Figure 19: Top 10 motor coaches affected by grids

4.2.35 Failure mode and effects of valves

Thirty-one per cent of the valve failures were due to worn/damaged valves as presented in Table 26. Leaks contributed to 28% of valve failures. Not operating accounted for 15% of valve failures. Incorrect setting caused nine percent (9%) of the valves failures. Electrical failure of the control circuit contributed to 8% of valve failures.

Table 26: Failure mode and effects: valves

Failure mode and effects : valves			
Failure mode	**Total effects (No # of faults)**	**Contribution percentage**	**Cumulative percentage**
Worn/damaged	89	31%	31%
Leaking	79	28%	59%
Electrical failure: control circuit	24	8%	67%
Incorrect operation	24	8%	76%
Not operating	43	15%	91%
Incorrect setting	27	9%	100%
	286		

4.2.36 Failure mode and effect analysis of valves

Table 27 presents the top 20% of failures caused by valves. Worn/damaged valve failures were due to wear and tear (80%) and damage by foreign objects (11%). Most the valve leaks were due to operating conditions (78%). Electrical failure of the valve control circuit was due to the solenoid not energising (54%), short circuit (25%) and open circuit (17%). Incorrect operation of valves was due to out of calibration (79%). Valves not operating were due to defects (51%) and operating conditions (30%). Incorrect setting of the valves was due to out of calibration (52%) and operating conditions (41%).

Table 27: Failure mode and effect analysis: valves

Failure mode and effect analysis: valves				
Failure mode	**Total effects (No. of faults)**	**Cause description**	**Effect per cause (No. of faults)**	**Percentage**
Worn/damaged	89	Wear and tear	71	80%
		Damage: foreign object	10	11%
Leaking	79	Operating conditions	62	78%
Electrical failure: control circuit	24	Solenoid cannot energize	13	54%
		Short circuit	6	25%
		Open circuit	4	17%
Incorrect operation	24	Out of calibration	19	79%
Not operating	43	Defective	22	51%
		Operating conditions	13	30%
Incorrect setting	27	Out of calibration	14	52%
		Operating conditions	11	41%

4.2.37 Top 10 motor coaches affected by valves

The motor coaches with the highest valve failures (31) were 5M213153 and 5M213097. The following motor coaches had 29 failures each, 5M13095, 5M29093 and 5M213609. Both motor coaches 5M213615 and 5M213631 had 27 valve failures each. Motor coaches 5M213265 and 5M29938 had 25 failures. The motor coach with the least valves failures (23) was 5M29253.

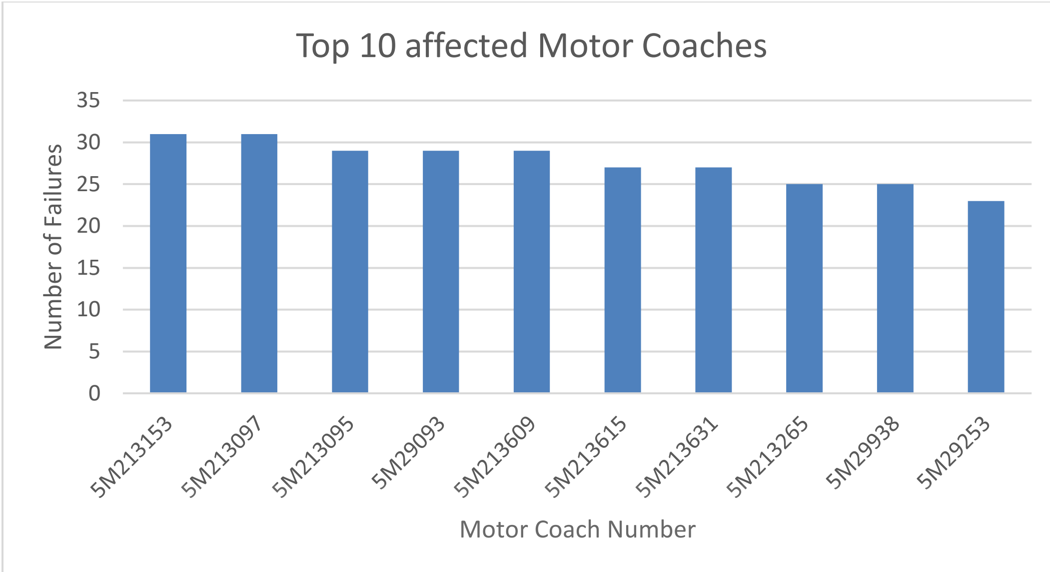

Figure 20: Top 10 motor coaches affected by valves

The following section will present an analysis of the survey questionnaires.

4.3 Survey questionnaires presentation

The researcher issued survey questionnaires to a population of 100 participants involved in PRASA maintenance depots working on class 5M2A motor coaches in the Gauteng region. About 40 participants responded positively to the survey questionnaires. Firstly, the participants were requested to provide their age category, educational level and the number of year of experience in the maintenance industry. Subsequently, participants were also requested to rate the Likert scale questions/statements and at the end of the survey questionnaires, the participants were requested to provide general comments or opinions on the subject matter.

4.3.1 Section A: Demographics

4.3.1.1 Age distribution profile

Out of 100 survey questionnaires distributed, only 40 participants responded. The participants in the survey questionnaires had a well-distributed age profile ranging from 15 to above 50 years. Figure 21 shows that 80% of the participants were in the ages between 26 to above 50 years. The majority (35%) of the participants were between 36 to 40 years, followed by 25% between 41 to 50 years. Adults above 50 years also participated in the survey, accounting for 10% of the participants. About 31% of the participants were young, with ages ranging between 15 and 35 years.

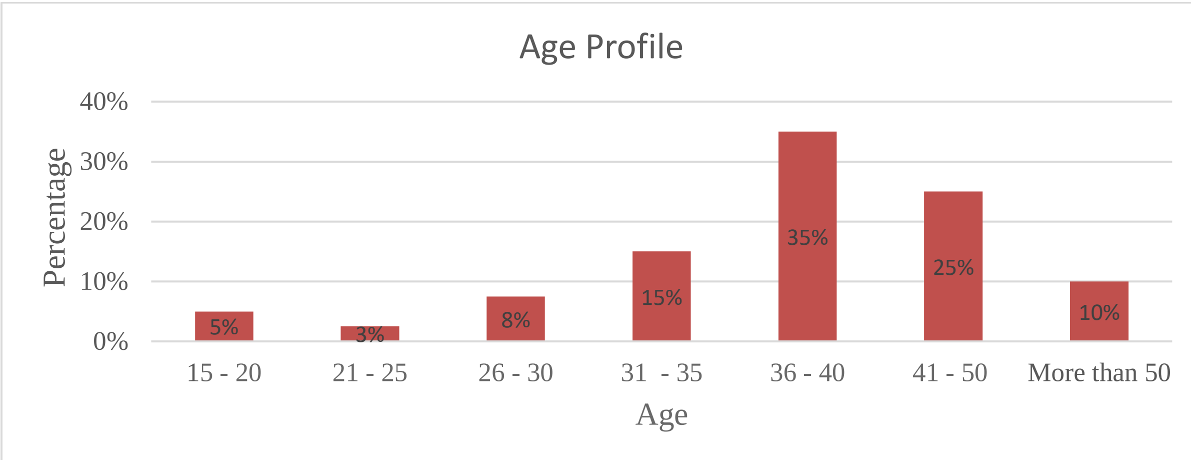

Figure 21: Age profile

4.3.1.2 Educational qualification

Figure 22 shows the educational qualifications of maintenance personnel who participated in the survey questionnaires. The majority (40%) of participants in the study hold a matric certificate plus a three-year degree (M3+). Another set of participants, accounting for 30% of the participants, had only a matric certificate. About 20% of participants for the study had a four-year degree. The last group of participants (10%) had a master's degree.

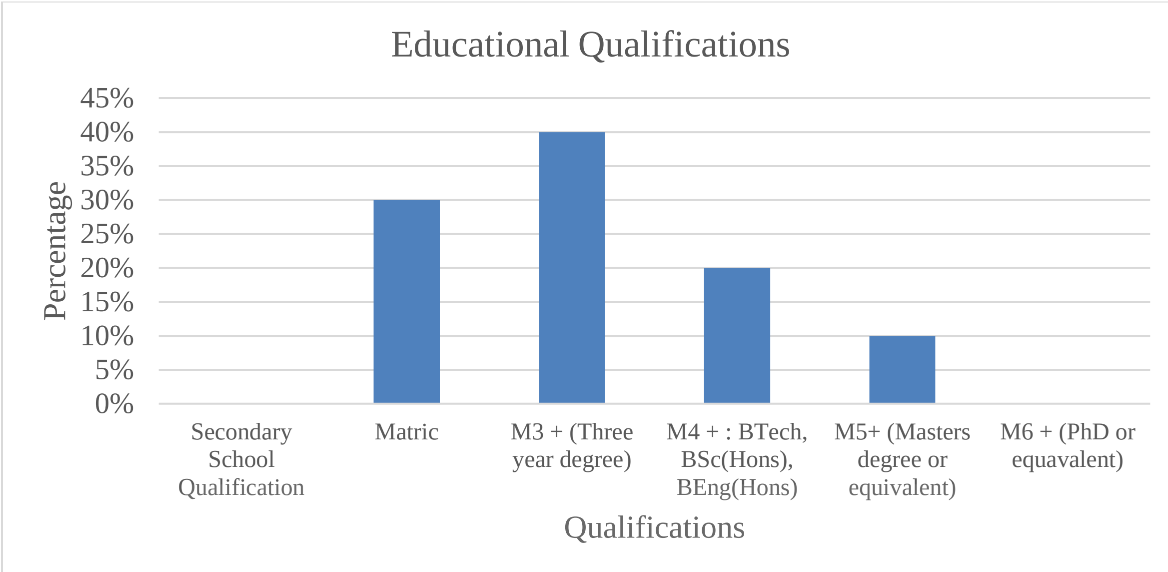

Figure 22: Educational qualifications

4.3.1.3 Experience in maintenance industry

About 40 participants responded to the question regarding their experience within the maintenance industry. Figure 23 shows that the majority of participants (20%) in the survey questionnaires had nine to ten years' maintenance experience. The next majority of participants (18%), consisting of two groups, had six to 8 years' maintenance experience and 15 to 17 years maintenance experience. Participants who had 12 to 15 years maintenance experience accounted for 13% of the participants who responded to the survey questionnaires. About 16% of the participants had 24 and more years' maintenance experience. The next batch of participants (10%) had 18 to 23 years' maintenance experience. About 8% of the participants to the survey questionnaires had zero to two years' maintenance experience. The results in Figure 23 show that the participants had enough knowledge and skills needed to respond to the survey questionnaires.

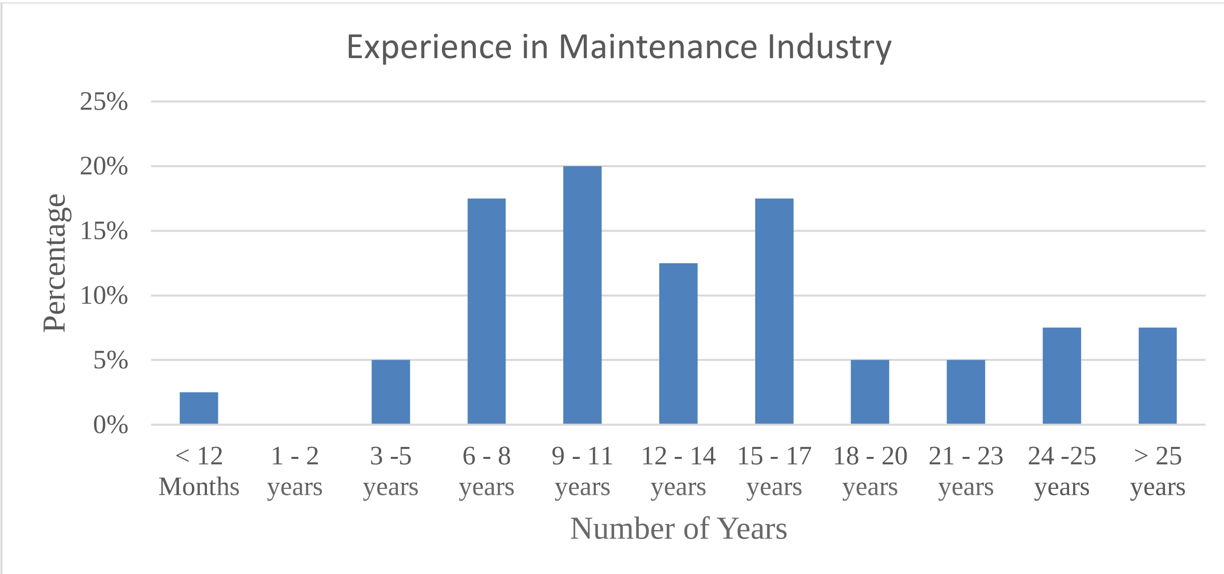

Figure 23: Experience in maintenance industry

4.3.2 Section B: Research questions

The researcher together with the supervisor developed questions that focused on getting opinions regarding the maintenance strategies adopted by PRASA for the maintenance of class 5M2A motor coaches. In addition, further questions were developed to seek opinions regarding the alignment between the PRASA maintenance strategies and the corporate strategy. Participants used the Likert scale of six levels to rate the alignment between the two strategies. Furthermore, the participants were requested to use the Likert scale to evaluate the ability of the asset management system and collect data regarding fleet performance.

4.3.2.1 Adopted maintenance strategy

This section presents the results regarding the maintenance strategy used by PRASA for maintenance of class 5M2A motor coaches. The analysis shown in Figure 24 is based on 40 participants who responded to the survey questionnaires. According to the participants to the survey, the most used maintenance strategy (95%) for class 5M2A was preventative maintenance. The next most (88%) used maintenance strategy for class 5M2A fleet was corrective maintenance, as stated by the participants.

About 55% of the participants believed RCM was also the preferred maintenance strategy used for 5M2A motor coaches. Twenty-five per cent (25%) of the participants believed that predictive maintenance was used for the maintenance of class 5M2A. At the bottom, 18% of the participants believed that corrective maintenance was the preferred maintenance strategy used for class 5M2A motor coaches.

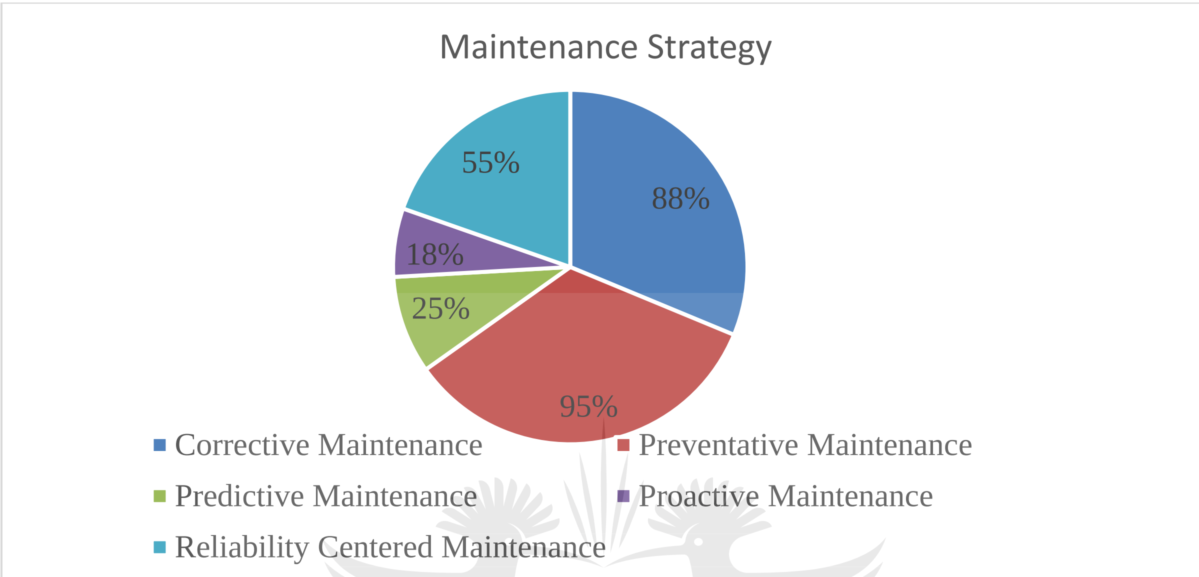

Figure 24: Maintenance strategies

4.3.2.2 Maintenance strategy formalisation

The analysis of the response in Table 28 shows that the majority (53%) of the participants agreed that PRASA used a formalised maintenance strategy. Twenty per cent (20%) of participants disagreed that PRASA utilised formalised maintenance strategy, while 28% of participants were neutral regarding PRASA using a formalised maintenance strategy.

Furthermore, the majority of the participants (41%) disagreed that PRASA was fully equipped and knowledgeable regarding their adopted maintenance strategy. Thirty-three per cent (33%) of participants agreed that PRASA was fully equipped and knowledgeable regarding the adopted maintenance strategy, while 10% of the participants were neutral.

For the next statement, the bulk of the participants (50%) felt that the PRASA maintenance strategy supported the mission and vision of the organisation. Twenty-five per cent (25%) of the participants disagreed that the PRASA maintenance strategy supported the mission and the vision of the organisation, while 25% of the participants were neutral regarding the statement.

Regarding PRASA having a well-defined maintenance policy and procedures relative to the adopted maintenance strategy, the majority (48%) of participants agreed with the statement. It also appeared that 23% of the participants disagreed with the statement, while 30% of the participants were neutral.

Table 28: Maintenance strategy formalisation

Statements	1 Strongly Disagree	2 Disagree	3 Neutral	4 Agree	5 Strongly Agree	Total
We utilize a formalized maintenance strategy	4	4	11	14	7	40
	10%	10%	28%	35%	18%	
Our organization is fully equipped and knowledgeable about the adopted maintenance strategy	5	11	11	9	4	40
	13%	28%	28%	23%	10%	
Our maintenance strategy supports the mission and vision of our organization	4	6	10	16	4	40
	10%	15%	25%	40%	10%	
We have well defined maintenance policy and procedures relative to the adopted maintenance strategy	4	5	12	14	5	40
	10%	13%	30%	35%	13%	
Necessary training was provided during adoption of this maintenance strategy	5	12	10	9	4	40
	13%	30%	25%	23%	10%	

4.3.2.3 Alignment of maintenance strategy to corporate plan

In this section, the participants were asked questions regarding the alignment of the maintenance strategy to corporate plan. From the first statement on Table 29, the majority (38%) of the participants agreed that the maintenance strategy adopted by PRASA was aligned to the corporate plan. Of the 40 participants, 33% disagreed that the maintenance strategy was aligned with corporate plan, while 30% of participants were neutral.

From the next statement, the majority of the participants (48%) agreed that recurring failures were eliminated by the adopted maintenance strategy. Although 13% of the participants did not agree that the adopted maintenance strategy had the ability to eliminate recurring failures, 30% of participants were neutral.

Regarding reviews in line with business performance, the majority (45%) of the participants were neutral, while 28% of the participants agreed. The remainder of the participants (28%) also disagreed that the maintenance strategy was reviewed in line with business performance.

For financial benefits, the majority of the participants (43%) disagreed that the adopted maintenance strategy reduced maintenance costs, while 40% of the participants were neutral. Eighteen per cent (18%) of the participants agreed that maintenance strategy reduced the maintenance costs.

Table 29: Alignment of maintenance strategy

Statements	1 Strongly disagree	2 Disagree	3 Neutral	4 Agree	5 Strongly agree	Total
It is aligned to the corporate plan	4	9	12	10	5	40
	10%	23%	30%	25%	13%	
It is designed to eliminate the recurring failures	3	6	12	13	6	40
	8%	15%	30%	33%	15%	
It is reviewed in line with the business performance	4	7	18	6	5	40
	10%	18%	45%	15%	13%	
It is providing visible financial benefits	4	13	16	3	4	40
	10%	33%	40%	8%	10%	
It is taking priority during financial constraints	7	13	10	5	5	40
	18%	33%	25%	13%	13%	

4.3.2.4 Ability of asset management

Table 30 presents an analysis of the participants regarding the ability of the asset management to detect failures before they occur. The majority of the participants (40%) said the system did not have the ability to detect failures before they occurred, while 35% of the participants' responses were neutral.

Out of 40 participants who responded to the statements, 25% of them believed the system had the ability to detect failures before they occurred.

The next question participants had to respond to related to be able to detect the failures in operations. The majority of the participants (58%) indeed agreed that the potential failures were detected in operation. Although 21% of the participants disagreed, 23% of the participants were neutral in their responses.

The majority (63%) of the participants agreed that potential failures were detected during maintenance execution. About 30% of the participants could not agree or disagree, and 8% of the participants disagreed that the potential failures could not be detected during maintenance.

Participants also responded to whether the asset management system could predict the life cycle of the subsystem based of failure rates. The majority of the participants (56%) agreed that the system had the ability to predict the life cycle of the subsystem, while 23% of the participants were neutral. Also out of 40 participants, 23% of them said the system did not have the ability to predict the life cycle of the subsystems.

Forty-one per cent (41%) of the participants believed that reliability data and subsystem failure analysis were for decision-making, while 35% of the participants were neutral. About 26% did not support that decision-making took into consideration reliability data and failure analysis of subsystems.

Table 30: The ability of asset management system

Statements	1 Strongly disagree	2 Disagree	3 Neutral	4 Agree	5 Strongly agree	Total
Potential failures are detected before they occur	2	14	14	8	2	40
	5%	35%	35%	20%	5%	
Potential failures are detected in operations	1	7	9	18	5	40
	3%	18%	23%	45%	13%	
Potential failures are detected during maintenance	0	3	12	21	4	40
	0%	8%	30%	53%	10%	
An asset management system can predict the life cycle of the subsystem based on failure rates	2	7	9	17	5	40
	5%	18%	23%	43%	13%	
Reliability data and failure analyses are used in decision making	3	7	14	11	5	40
	8%	18%	35%	28%	13%	

4.4 General comments

This section presents the responses of the participants who provided general comments from the survey questionnaires. Out of 100 questionnaires issued, only 12 participants provided general comments. A qualitative approach was used to analyse the comments. From the general comments, key words were taken out from the sentences to be used for analysis. Figure 25 was developed from the key words. All key words appeared once with the participants.

Shortage of maintenance personnel was one of the main challenges for maintenance depots. The concern regarding shortage of personnel had an impact on the analysis of failure analysis and reliability data.

Lack of communication was flagged as one of the challenges for the organisation. The maintenance strategy was not well communicated from the engineering head office to the maintenance depots.

Even though the organisation had formalised maintenance and quality strategies, *financial policy was hampering maintenance execution*.

Still on maintenance strategy, *incompetence of some personnel* was identified as one of the factors that affected maintenance.

During execution of maintenance, most of the activities were *not well coordinated*. Maintenance strategy and its related *standard operating procedures (SOPs) were not reviewed* on a regular basis.

There was a *lack of understanding of different maintenance strategies* within the organisation and their implementation.

With the challenges faced by the organisation, there was a *lack of morale* from the personnel, resulting in poor execution of the responsibility, leading to poor business performance.

Full *implementation of asset management principles* within the organisation should take place and compliance with it should be made through policies by the leadership of the organisation.

Gaps were identified in the *quality management system* used by the organisation. These gaps should be mitigated at all level to ensure that the quality of service provided to commuters is of acceptable level.

There were gaps in *functional* and *compulsory training* due to *financial constraints*.

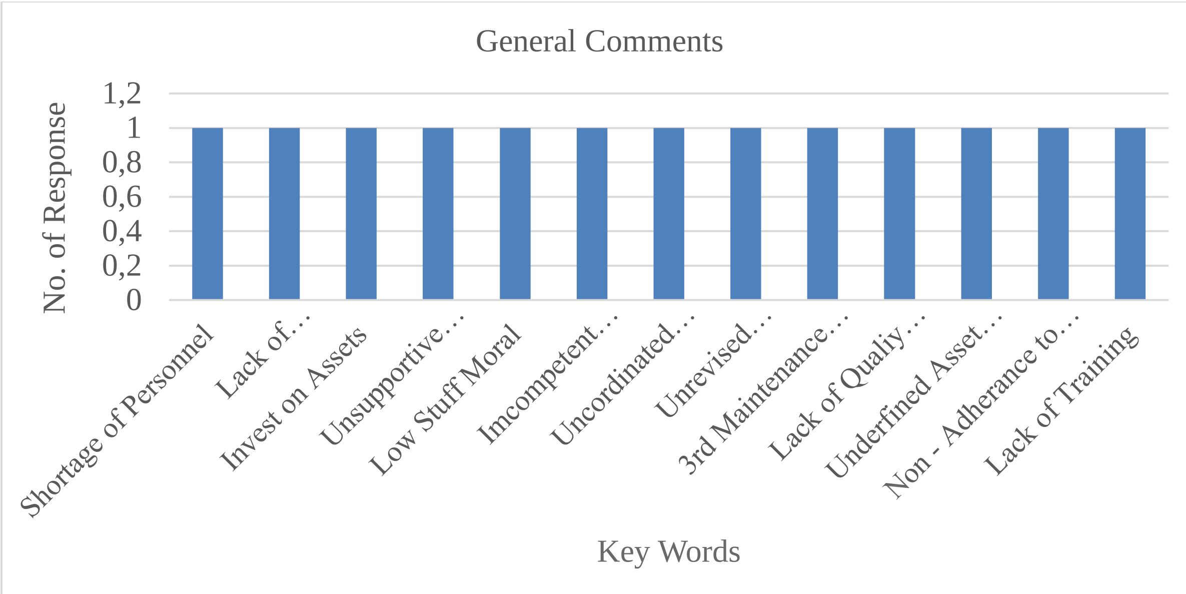

Figure 25: General comments

4.5 Summary

This chapter provided the findings from failure data and the survey questionnaires. For analysis of failure data, out of the 673 motor coaches, only 237 motor coaches met the set out criteria specified for sample selection. The failure data provided the subsystems that affected the performance of the fleet during the duration of the study.

By using the Pareto analysis, the top 20% failing subsystems that caused 90% of the failures were identified. These subsystems were windows, line switches, traction motors, exhausters, pantographs, brake system, wheels, compressors, cables, traction controllers, grids and valves, which caused 90% of the failures. In addition, failure modes and the effects of the top 20 failing subsystems were provided, including the top 10 motor coaches affected by these subsystems.

The results of the survey questionnaires were presented in this chapter. The researcher issued 100 questionnaires but only received response from 40 participants. The results showed that 85% of the participants were between 31 and 50 years old. The majority of the participants (70%) had matric plus a university qualification, and about 74% of the participants had 6 to 20 years' experience in maintenance. In addition, 95% of the participants said the organisation had adopted a preventative maintenance strategy and

88% of the participants believed that the organisation was utilising a corrective maintenance strategy. About 43% of the participants said the adopted maintenance strategy was formalised.

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1 Introduction

The study was conducted within the PRASA environment and the study was triggered by the low availability of passenger train sets and the poor performance of class 5M2A motor coaches. The primary objective of the study was to explore the factors that affect the reliability of the class 5M2A motor coaches operating in the Gauteng region.

Through the literature provided, the research questions and objectives were formulated. In addition, the literature assisted with which research approach to use. For data collection, the study employed the mixed method approach. Statistical failure data was collected using the set out criteria from the population of 673 motor coaches. Only 237 motor coaches met the set out criteria and they were included in a sample.

The researcher collected qualitative data through issuing survey questionnaires to 100 participants who were working in the maintenance of class 5M2A motor coaches operating in the Gauteng region. The participants had to provide their age profile, educational qualification and the number of maintenance experience they had in the railway environment. In addition, the participants had to rate Likert scale items using strongly disagree, disagree, neutral, agree; strongly agree to provide the general comments to the survey. The researcher received 40 responses from the participants and 12 of the participants provided general comments and suggestions.

This chapter seeks to find out if the research questions and objectives had been achieved. The next section will discuss the findings in conjunction with the set out research questions and objectives. The last section of this chapter will deliberate the conclusion, recommendations and will forecast future work to be done.

5.2 Discussion

The primary objective of this researcher was to explore the factors that affect the reliability of class 5M2A motor coaches operating in the Gauteng region. The study aimed to answer the following research questions:

a. Which factors affect the performance of class 5M2A motor coaches operating in the Gauteng region?
b. Which maintenance strategies are used to maintain class 5M2A motor coaches operating in the Gauteng region?
c. What can be done to improve reliability and availability of class 5M2A motor coaches operating in the Gauteng region?

Based on the above research questions, the following objectives were developed for the study:

- To examine the factors that affect the reliability and the availability of the class 5M2A motor coaches;
- To identify various maintenance strategies used to maintain class 5M2A motor coaches operating in the Gauteng region;
- To determine what can be done to improve the performance of the class 5M2A motor coaches in Gauteng.

5.2.1 Identification of factors that affect the performance of class 5M2A motor coach

The researcher used the failure statistical data of the class 5M2A motor coaches together with responses from maintenance personnel who participated in the survey questionnaires to identify the factors that affect the reliability of the fleet under study.

5.2.1.1 Failure data

In this study, the Pareto analysis and chart were used to identify the top 20% subsystems that caused 90% of the failures. The study also provided the failure modes for the major 20% subsystems with the top 20% causes. The top 10 motor coaches affected by each of the top 20% subsystems were identified.

The study found that the following top 20% subsystems caused 90% of the fleet failures: windows, line/combination switches, traction motors, exhausters, pantographs, brake system, wheels, compressors, cables, traction controllers, braking/accelerating grids and valves.

The line/combination switches were the most dominating subsystem (16.84%), with 95% of most reported failures caused by burn up, flashes, leaking air, defective and not operating failure modes. The main causes of the burn ups mode were mainly due to arch chutes, dirtiness in the system, overvoltage and sticky contact tips. The most failures that led to flashes were due to the dirtiness in the system. The main causes of leaking air failure mode were due to defective magnetic valves.

Windows were reported as the dominating subsystem with higher failure rates, accounting for 16.1% of fleet failures. Windows had three failure modes (worn/damaged, missing and not operating), accounting for 96.31% of the reported failures. Most worn/damaged windows were due to wear and tear and broken aperture. Most missing windows were due to theft and operational conditions. The not operating failure mode was due to broken windowpanes and operational conditions.

The other dominating subsystem with higher number of failures was the traction motors, accounting for 9.1% of the fleet failures. Ninety-eight per cent (98%) of the failure mode for the subsystem was due to flashes, burn ups, leaking oil, defective, not operating, broken, damaged and incorrect operation. Most failures that led flashes were due to dirtiness in the system and overvoltage. Burnt main poles coils, burnt inter-pole coils, burnt armature coils and burnt brush box caused most of the traction motor burn ups. Failures that led to traction motor oil leaks were due to broken gear cases and mechanical damage. The causes of defective traction motors were due to short brushes, low megger readings, seized bearings and burns. The not operating failure mode was due to broken armature. The broken failure mode was due to broken pinion and operating conditions. Traction motors damage failure mode was due to mechanical damage and operating conditions. The incorrect operation failure mode was caused by polarity swap, mechanical damage and operating conditions.

Exhausters (7.93%) also formed part of the subsystems accounting for subsystems that caused 90% of the fleet failures. The most reported failure modes affecting the exhausters included electrical failure, mechanical failure, damaged, leaking air, defective incorrect operation and incorrect setting. Most of the electrical failure was due to burnt inter-poles, motor overload, burnt main pole and armature coils. Most of the exhauster mechanical failures were due to broken gasket, wear and tear, bearing seized and operating conditions. Most reported damaged exhausters were due to wear and tear and operating conditions. The exhausters reported for leaking air failure mode were due to operating conditions. Defective failure mode of exhausters was due to damage by foreign object and operating conditions. The incorrect setting failure mode was due to out of calibration and operating conditions.

The pantograph (5.64%) was also the subsystem that accounted for 90% of the class 5M2A motor coaches. The majority (97%) of the failure mode for the pantograph was due to damaged copper strip, worn copper strip, and bent, broken, not rising, leaking cylinder, sticky, missing and insufficient contact. Most reported failures with worn and damaged copper strip failure mode were due to wear and tear. Bent failure mode for pantographs was due to Panto hook-up and damage by foreign object. The pantographs reported for broken failure were due to Panto hook-up. The not rising failure mode reported failures were due to no upper pressure. Defective cylinders caused the pantographs reported for the leaking cylinder failure mode. Missing and sticky failure mode was due to insufficient lubrication. The pantographs reported for insufficient contact failure mode were due to defective suspension springs and wear and tear.

The brake system (5.87%) also formed part of the top 20% of subsystems that caused 90% of fleet failures. Ninety-seven per cent (97%) of the subsystem failures were due to incorrect operation, leaking, damaged, and broken off, incorrect setting and dirt. The incorrect operation failure mode was due to out of calibration. The main cause of the leaking and damaged brake failure mode was due to operating conditions. Most reported broken off failure mode for brake system was due to damage by foreign object and operating conditions.

Wheels also formed part of the subsystem that caused 90% of the fleet failures accounting for 6.97% of the fleet failures. Defective and out of limit were the only failure modes for wheels. The defective failure mode (98%) for wheels were due to sharp and high flange, skidded wheels, faulty wheel gear and hollow wear. The out of limit failure modes were due to sharp and high flange, skidded wheel, hollow wear and worn out wheels.

At the bottom of the list for the top 20% subsystems that caused 90% of the fleet failures were compressors, cables, traction controllers, accelerating/braking grids and valves. Compressors accounted for 4.79% of the fleet failures. Most of the compressor failures were due to electrical failure, mechanical failure, damaged, leaking air, incorrect setting, incorrect operation and defective failure modes. The electrical failure was the most reported failure for the compressor due to burnt armature coils, motor overload, burnt main and inter-pole coils. The mechanical failure mode was caused by supply of wrong vanes, broken gasket, seized bearing and operating conditions. Both damaged and leaking air failure mode failures were due to operating conditions. The incorrect setting failure mode was due to out of calibration and operating conditions. Out of calibration was the main cause of incorrect operation failure mode. The defective failure mode was caused by damage by foreign object and operating conditions.

The cables (4.11%) also formed part of the top 20% of subsystems that caused 90% of fleet failures. Cables had three failure modes (burnt, broken and damaged), which accounted for 97% of the subsystem failures. The most reported burnt cable failures were due to incorrect crimping and loose connection. The broken cables failure mode was due to damage by foreign object and wear and tear. Vandalism and operating conditions were the most reported failure modes for cables.

Another subsystem on the bottom of the list for causing 90% of the fleet failures was traction controller, accounting for (3.47%) of the fleet failures. Traction controller had four failure modes (defective, interference, incorrect operation and not operating) that accounted for 96% of the subsystem failures. The cause of the defective, interference and incorrect operation failure modes was operating conditions. The not operating failure mode was due to defects and operating conditions.

Accelerating/braking grids (5%) also dominated the bottom of the list for the subsystem that caused 90% of the fleet failures. Grids had three failure modes (burnt, broken and damaged) that accounted for 95% of the subsystem failures. Overcurrent and loose connection were the cause of the burnt grids failure mode. The broken grids failure mode was due to damage by foreign object and wear and tear. Operating conditions caused the damaged grids failure mode.

The last subsystem of the top 20% subsystem that caused 90% of the fleet failures was the valves (3.87%). The following failure modes were responsible for most of the valve failures, worn/damaged, leaking, electrical failure for control circuit, incorrect operation, not operating and incorrect setting. Leaking failure mode was due to operating conditions. The worn/damaged failure mode was caused by damage by foreign object and wear and tear. The electrical failure for the control circuit was due to solenoid not energising and open and short circuit. Out of calibration was responsible for the incorrect operation failure mode. The not operating failure mode was due to defective valves and operating conditions. Out of calibration and operating conditions were responsible for the failure mode incorrect setting.

5.2.1.2 Survey questionnaires results

The researcher issued 100 survey questionnaires to PRASA personnel who were involved in the maintenance of the class 5M2A motor coaches. Out of 100 issued questionnaires, the researcher received 40 responses from the participants. The participants had a well-distributed age profile ranging from 15 years to above 50 years. The study showed that 90% of the participants were in the ages between 26 years and above 50 years old. The study also revealed that most of the participants (70%) had formal university qualifications. About 85% of the participants had experience ranging from six to 25 years in the maintenance environment.

Even though the objective of the study was not to analyse the demographics of the participants working in the Gauteng region, the demographics showed how well rounded and knowledgeable the participants were on the topic of the research, both regarding their educational qualification and their maintenance experience.

According to the survey results, the most used maintenance strategies by PRASA were preventative maintenance (95%), followed by corrective maintenance (88%) and reliability centred maintenance (55%). The least used maintenance strategies were predictive maintenance (25%) and proactive maintenance (18%).

The Likert scale was used to measure the link between the adopted maintenance strategies and the corporate plan. From the survey questionnaires, 41% of the participants agreed that the organisation had a formalised maintenance strategy, while 20% of the participants did not support that the organisation had a formalised maintenance strategy. However, 28% of the participants were neither agreeing nor disagreeing.

Forty-one per cent (41%) of the participants did not believe that PRASA was fully equipped and knowledgeable about the adopted maintenance strategies, while about 33% of the participants supported the statement and 28% of participants were neutral.

Regarding the maintenance strategy supporting the vision and mission of the organisation, 50% of the participants supported the statement and 25% did not believe that the maintenance strategy supported the vision and mission of the organisation. Twenty-five per cent (25%) of the participants were neutral regarding the statement.

Forty-eight per cent (48%) of the participants agreed that PRASA had a maintenance policy and procedures that support the adopted maintenance strategy. Twenty-three per cent (23%) of participants disagreed that PRASA had a maintenance policy and procedures that support the adopted maintenance strategy, while 30% of the participant is neither agreed nor disagreed.

About 33% of the participants believed that necessary training was provided to maintenance personnel during the implementation of the adopted maintenance strategy, and the same percentage disagreed, while 25% of the participants were neutral.

Thirty-eight per cent (38%) of the participants agreed that the adopted PRASA maintenance strategy was aligned to the corporate plan, while 33% of the participants disagreed and 30% of the participants neither agreed nor disagreed.

About 48% of the participants agreed that the adopted maintenance strategy was designed to eliminate recurring failures, while 23% of the participants did not agree and 30% of the participants were neutral.

Twenty-eight per cent (28%) of the participants agreed that the maintenance strategy adopted by PRASA was reviewed in line with business performance, and the same percentage disagreed, while 45% of the participants neither agreed nor disagreed.

About forty-three per cent (43%) of the participants did not agree that the adopted PRASA maintenance strategy provided visible financial benefits, and 18% of the participants believed that the adopted maintenance strategy provided financial benefits, while 40% of the participants were neutral.

Regarding the maintenance strategy taking priority during financial constraints, 41% of the participants believed that the maintenance budget was forever cut down during financial constraints and 26% of the participants believed maintenance took priority during financial constraints, while 25% of participants neither agreed nor disagreed.

The participants to respond to statements that aimed at evaluating the ability of the asset management to detect failures before they occur used the second Likert scale. Forty per cent (40%) of the participants believed that the asset management system did not have the ability to detect the potential failures before they occurred, while 25% of the participants agreed that the asset management system had the ability to detect potential failures before they occurred, and 35% of the participants neither agreed nor disagreed.

Fifty-eight per cent (58%) of participants believed that the system had the ability to detect failures during operations, while 21% did not agree, and 23% of the participants were neutral.

Sixty-three per cent (63%) of the participants agreed that the system had the ability to detect potential failures during maintenance execution, while 8% participants disagreed and 30% neither agreed nor agreed.

About 56% of the participants agreed that the asset management system could predict the life cycle of the subsystem based on failure rates, while 21% disagreed and 23% were neutral.

Forty-one per cent (41%) of the participants agreed that reliability data and failure analysis was used in decision making, while 26% disagreed and 35% neither disagreed nor agreed.

The above summary provided the factors that affected the reliability of the class 5M2A motor coaches operating in the Gauteng region for the duration of the study.

5.2.2 Identification of maintenance strategies used to maintain class 5M2A

The researcher used the survey questionnaires to identify the maintenance strategies used for the maintenance of the class 5M2A motor coaches.

According to the survey results, the most used maintenance strategies by PRASA were preventative maintenance (95%), followed by corrective maintenance (88%) and reliability centred maintenance (55%). The least used maintenance strategies were predictive maintenance (25%) and proactive maintenance (18%).

5.2.3 To determine what can be done to improve the reliability and availability of class 5M2A motor coaches operating in the Gauteng region.

The researcher used failure data and survey questionnaires to identify the areas of improvement for the reliability and the availability of the class 5M2A motor coaches.

From failure data, the following subsystems were in the top 20% of subsystems that caused 90% of the motor coach failures (windows, line/combination switches, traction motors, exhausters, pantographs, brake system, wheels, compressors, cables, traction controllers, accelerating/braking grids and valves). To support this, the results of the survey with the use of the Likert scale showed the asset management system used was unable to detect the failures before they occurred. In addition, it was evident that reliability data and failure data analysis were not used in decision-making.

The survey results also showed that, even though the asset management had the ability to eliminate recurring failures, there was stillroom for improvement for detecting the failures during operations. The survey results also showed that even though PRASA had a formalised maintenance strategy in place, the organisation was not fully equipped and knowledgeable about the adopted maintenance strategy. It was also evident that during the implementation of the adopted maintenance strategy, adequate training was not provided to the maintenance personnel.

With the summary provided above, the researcher can conclude that the research questions have been answered, and the research objectives have been achieved.

5.3 Recommendations

The results of the study showed that many factors affected the reliability of the class 5M2A motor coaches operating in the Gauteng region for the duration of the study. Through the results of the statistical failure data, it was evident the 90% of the fleet failures were due to line/combination switches, windows, traction motors, exhausters, pantographs, brake system, wheels, compressors, cables, traction controllers, accelerating/braking grids and valves. For fleet improvement in the Gauteng region, PRASA should use these systems as the first point of contact.

PRASA should further perform investigation into the condition of the rails, which might have contributed more to wheel failures. Regarding theft of windows, the organisation, through its engineering department, must develop new windows, which must have less material that can be prone to theft and could not be easily removed without special tools.

To address overvoltage related failures relating to the switches, pantographs and traction motors, the quality of power supply must be investigated together with the infrastructure colleagues. In addition, PRASA should spend more time on cleaning the whole system, in particular the high voltage compartment that houses most of the switches, and the rotating machines, such as compressors and exhausters.

From the survey questionnaire results, it was clear that the organisation could not proactively detect the failures before they occurred. The organisation should implement a process the can assist with monitoring the conditions and that would be able to detect the failures before they occur. In addition, from the survey, it was clear that in even though the organisation has a formalised maintenance strategy in place, there were gaps regarding the training of personnel, while the organisation was also not fully equipped with the tools and knowledge to support the adopted maintenance strategy. PRASA should provide training regarding the adopted maintenance strategy and buy the necessary tools to support the maintenance strategy.

The organisation should also learn from its peers in the industry and benchmark with the best practices and companies within the passenger rail industry.

5.4 Study challenges and limitations

During the duration of the study, the researcher had the following constraints and challenges:

- The researcher was limited to twelve months of statistical failure data for the class 5M2A motor coaches operating in the Gauteng region, hence the results of this study cannot be generalised for all the class 5M2A motor coaches operating within the entire Republic of South Africa.
- The study highlighted the top 20% subsystems that caused 90% of the fleet failures. In addition, the study did not analyse the financial implications of these subsystems.
- The subsystems with the lowest failures were not analysed together in terms of the financial implications. These systems could have the highest financial implications.
- Regarding the subject matter, there is less literature published in South Africa and African at large, while most publications are from America, Asia and Europe. Owing to different climate and operational conditions, the suggestions and recommendations of these publications could change in South Africa.

5.5 Conclusions

The purpose of the study was to explore the factors that affect the reliability of the class 5M2A motor coaches operating in Gauteng. The results of the study indicated that PRASA was experiencing many subsystem failures during its operation. The literature reviewed showed that there were fewer publications regarding the subject matter, in particular across South Africa and Africa.

The study used statistical failure data and questionnaires to collect data for answering research questions and objectives. The study used statistical failure data for the class 5M2A motor coaches and the survey questionnaires. Gauteng region was used as the area of study.

The results of the study showed that subsystem failures were the main factors causing poor performance of the fleet. Furthermore, the study suggested that the PRASA asset management system did not have the ability to detect failures before they occurred.

PRASA should focus on providing training to its maintenance personnel and invest in tools and equipment to assist the organisation to monitor the performance of the fleet subsystem in operations.

5.5.1 Future work

There is a need for further research on improving the performance of passenger rolling stock within South Africa, particularly PRASA, and the following is recommended:

- Conduct a study on which maintenance strategy to be used for an aging rolling stock fleet;
- Explore which asset management system could be suitable for usage in passenger rolling stock maintenance;
- Conduct a study to explore the infrastructure factors that impact the performance of rolling stock fleet;
- Conduct a study on what is the perception of engineering personnel regarding the engineering management qualification in the South African railway industry and
- Conduct a study that will apply the theories of reliability and maintenance to inform the timing of maintenance activities for each sub-system.

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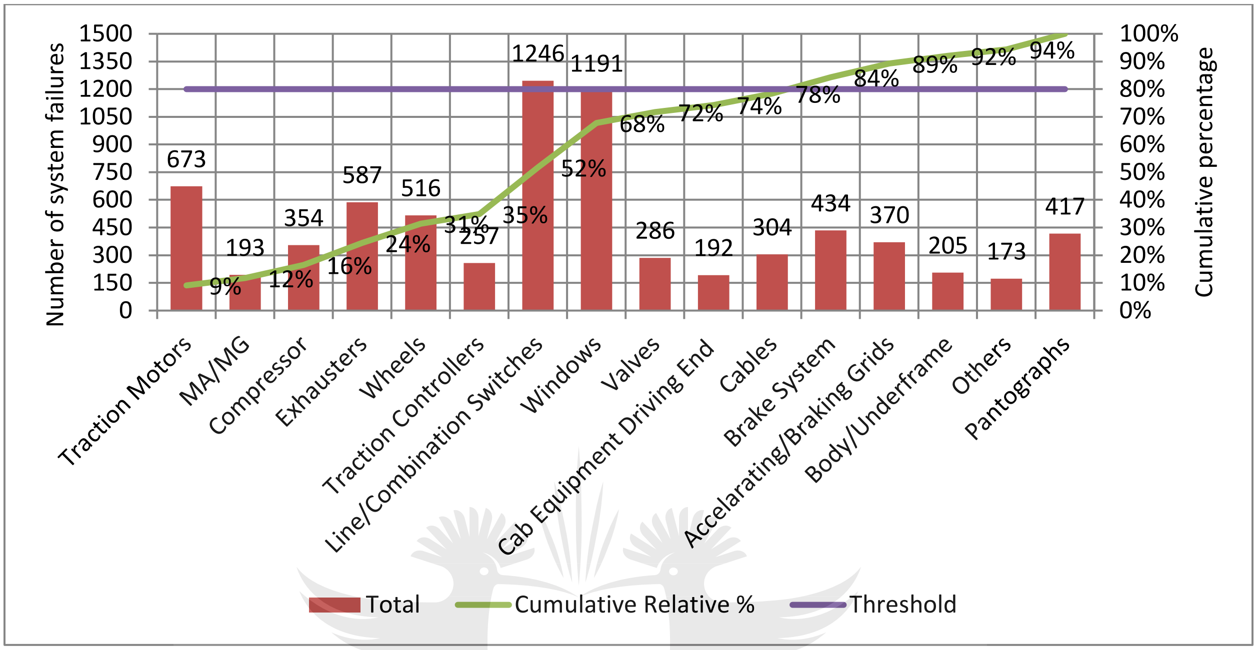
APPENDICES

A.1 Classification of Faults

Motor Coach Sub-System Failure : June 2018 - May 2019				
Sub-Systems	**Total**	**Percentage Relative**	**Cumulative Relative %**	**80% Mark**
Traction Motors	673	9.10%	9.10%	80%
MA/MG	193	2.61%	11.71%	80%
Compressor	354	4.79%	16.49%	80%
Exhausters	587	7.93%	24.43%	80%
Wheels	516	6.97%	31.40%	80%
Traction Controllers	257	3.47%	34.87%	80%
Line/Combination Switches	1246	16.84%	51.72%	80%
Windows	1191	16.10%	67.82%	80%
Valves	286	3.87%	71.68%	80%
Cab Equipment Driving End	192	2.60%	74.28%	80%
Cables	304	4.11%	78.39%	80%
Brake System	434	5.87%	84.25%	80%
Accelerating/Braking Grids	370	5.00%	89.25%	80%
Body/Underframe	205	2.77%	92.02%	80%
Others	173	2.34%	94.36%	80%
Pantographs	417	5.64%	100.00%	80%
Total Number of Failures	7398	100.00%		

Table above shows the classification of the faults, and the subsystems highlighted in blue accounted for 90% of the class 5M2A motor coach failures.

A.2 Pareto Analysis of Subsystem Failures



The figure above shows the Pareto Analysis of the subsystems that caused the failures of the 5M2A motor coaches for the duration of the study.

B.1 Approval Letter from PRASA

prasa

PASSENGER RAIL AGENCY OF SOUTH AFRICA

PRASA HOUSE
1040 Burnett Street
Hatfield
Pretoria

Private Bag X101
Braamfontein 2017
T: +27 12 748 5000

www.prasa.com

04 June 2020

TO WHOM IT MAY CONCERN

I, Tholo Dikobe as delegated authority of PASSENGER RAIL AGENCY OF SOUTH AFRICA (PRASA) here by give permission to the primary researcher SEKHUTHE MAKOLE of the FEBE, University of Johannesburg the followings:

To engage (survey/interview) with the employees of the above mentioned company. I have reviewed questionnaire / interview questions given to me by the researcher. I hereby give my approval for using the questionnaire / interview questions by the researcher.

For the research project titled: ***Factors affecting the reliability of the motor coaches within Metrorail in the Gauteng region.***

The information provided by the employees or any other means (such as company's archived documents or reports) of the above mentioned company is purely for academic purposes and cannot be used for any other purpose.

Regards,

Tholo Dikobe
Acting Executive Manager: ARS and Rolling Stock Maintenance
PRASA TECHNICAL

Cell: 083 706 8843
Email: tdikobe@prasa.com

Administrator
D. Mpondo

Acting Group Company Secretary
N. Tsebethe

B.2 Survey Questionnaires

Section A: Biography

Please answer the following question by selecting a category relevant to you.

2.1 How old are you (values given in years)?

- ☐ 15 – 20
- ☐ 21 – 25
- ☐ 26 – 30
- ☐ 31 – 35
- ☐ 36 – 40
- ☐ 41 – 50
- ☐ More than 50 years

2.2 How will you describe your highest qualification?

- ☐ Secondary school qualification
- ☐ Matric
- ☐ M + 3 (Three year degree)
- ☐ M + four (Four year degree e.g. Tech, BSc Hons, BEng Hons etc.)
- ☐ M + 5 (Master’s degree or equivalent)
- ☐ M + 6 (PhD or equivalent)

2.3 How long have you been in the maintenance industry?

- ☐ Less than 12 months
- ☐ 1-2 years

- [ ] 3-5 years
- [ ] 6-8 years
- [ ] 9-11 years
- [ ] 12-14 years
- [ ] 15-17 years
- [ ] 18-20 years
- [ ] 21-23 years
- [ ] 24-25 years
- [ ] More than 25 years

Section B: Research Questions

This section of the questionnaire focuses on maintenance practices that can be applied to improve the reliability of the class 5M2A motor coaches operating in the Gauteng region.

2.4 Our organisation has adopted this type of maintenance strategy (Please tick all options that are relevant.)

2.4.1 Corrective Maintenance	
2.4.2 Preventative Maintenance	
2.4.3 Predictive Maintenance	
2.4.4 Proactive Maintenance	
2.4.5 Reliability Centred Maintenance	

Please indicate to what extent you agree with the following statements regarding the maintenance strategy your organisation has adopted. (Please tick the appropriate box.)

	Statements	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
2.4.6	We utilise a formalised maintenance strategy.					
2.4.7	Our organisation is fully equipped and knowledgeable about the adopted maintenance strategy.					
2.4.8	Our maintenance strategy supports the mission and vision of our organisation.					
2.4.9	We have well defined maintenance policy and procedures relative to the adopted maintenance strategy.					
2.4.10	Necessary training was provided during adoption of this maintenance strategy.					

2.5 How would you describe the quality of the PRASA Maintenance Strategy?

Please indicate how you would describe the quality of the PRASA Maintenance Strategy. (Please tick the appropriate box.)

	Items	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
2.5.1	It is aligned to the corporate plan.					
2.5.2	It is designed to eliminate recurring failures.					
2.5.3	It is reviewed in line with business performance.					
2.5.4	It is providing visible financial benefits.					
2.5.5	It is taking priority during financial constraints.					

2.6 How would you rate the ability of an asset management system to improve rolling stock performance?

Please indicate how you would rate the ability of an asset management system to improve rolling stock performance. (Please tick the appropriate box.)

	Items	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
2.6.1	Potential failures are detected before they occur.					
2.6.2	Potential failures are detected in operations.					
2.6.3	Potential failures are detected during maintenance.					
2.6.4	An asset management system can predict the life cycle of the subsystem based on failure rates.					
2.6.5	Reliability data and failure analyses are used in decision-making.					

2.7 Do you have any comments, questions and/or concerns?

Key Words	No. of Response
Shortage of Personnel	1
Lack of Communication	1
Invest on Assets	1
Unsupportive Financial Policy	1
Low Stuff Moral	1
Incompetent Personnel	1
Uncoordinated Maintenance Execution	1
Unrevised Maintenance Strategy	1
3rd Maintenance Revolution	1
Lack of Quality Control	1
Under-defined Asset Management	1
Non - Adherence to SOP's	1
Lack of Training	1

Table above shows keys words from general comments of the survey questionnaires.

B.3 Survey Questionnaires Raw Data

a. Age profile

Age	No. of Responses	Related Percentage (%)
15 - 20	2	5%
21 - 25	1	3%
26 - 30	3	8%
31 - 35	6	15%
36 - 40	14	35%
41 - 50	10	25%
More than 50	4	10%

b. Qualification Profile

Highest Qualification	No. of Responses	Related Percentage (%)
Secondary School Qualification	0	0%
Matric	12	30%
M3 + (Three year degree)	16	40%
M4 + : BTech, BSc(Hons), BEng(Hons)	8	20%
M5+ (Master's degree or equivalent)	4	10%
M6 + (PhD or equivalent)	0	0%

d. Experience in Maintenance

No. of years	No. of Responses	Related Percentage (%)
< 12 Months	1	3%
1 - 2 years	0	0%
3 -5 years	2	5%
6 - 8 years	7	18%
9 - 11 years	8	20%
12 - 14 years	5	13%
15 - 17 years	7	18%
18 - 20 years	2	5%
21 - 23 years	2	5%
24 -25 years	3	8%
> 25 years	3	8%

e. Maintenance Strategy

Maintenance Strategy	Frequency	Related Percentage
Corrective Maintenance	35	88%
Preventative Maintenance	38	95%
Predictive Maintenance	10	25%
Proactive Maintenance	7	18%
Reliability Centered Maintenance	22	55%
	40	

f. Formalized Maintenance Strategy

Statements	1 Strongly Disagree	2 Disagree	3 Neutral	4 Agree	5 Strongly Agree	Total
We utilize a formalized maintenance strategy	4	4	11	14	7	40
	10%	10%	28%	35%	18%	
Our organization is fully equipped and knowledgeable about the adopted maintenance strategy	5	11	11	9	4	40
	13%	28%	28%	23%	10%	
Our maintenance strategy supports the mission and vision of our ourganization	4	6	10	16	4	40
	10%	15%	25%	40%	10%	
We have well defined maintenance policy and procedures relative to the adopted maintenance strategy	4	5	12	14	5	40
	10%	13%	30%	35%	13%	
Necessary training was provided during adoption of this maintenance strategy	5	12	10	9	4	40
	13%	30%	25%	23%	10%	

g. Alignment of Maintenance Strategy to Corporate Plan

Statements	1 Strongly Disagree	2 Disagree	3 Neutral	4 Agree	5 Strongly Agree	Total
It is aligned to the Corporate Plan	4	9	12	10	5	40
	10%	23%	30%	25%	13%	
It is designed to eliminate the recurring failures	3	6	12	13	6	40
	8%	15%	30%	33%	15%	
It is reviewed in line with the business performance	4	7	18	6	5	40
	10%	18%	45%	15%	13%	
It is providng visible financial benefits	4	13	16	3	4	40
	10%	33%	40%	8%	10%	
It is taking priority during financial constraints	7	13	10	5	5	40
	18%	33%	25%	13%	13%	

h. Asset Management System

Statements	1 Strongly Disagree	2 Disagree	3 Neutral	4 Agree	5 Strongly Agree	Total
Potential failures are detected before they occur	2	14	14	8	2	40
	5%	35%	35%	20%	5%	
Potential failures are detected in operations	1	7	9	18	5	40
	3%	18%	23%	45%	13%	
Potential failures are detected during maintenance	0	3	12	21	4	40
	0%	8%	30%	53%	10%	
An asset management system can predict the life cycle of the subsystem based on failure rates	2	7	9	17	5	40
	5%	18%	23%	43%	13%	
Reliability data and failure analyzes are uded in decision making	3	7	14	11	5	40
	8%	18%	35%	28%	13%	

i. General Comments

Key Words	No. of Response
Shortage of Personnel	1
Lack of Communication	1
Invest on Assets	1
Unsupportive Financial Policy	1
Low Stuff Moral	1
Incompetent Personnel	1
Uncoordinated Maintenance Execution	1
Unrevised Maintenance Strategy	1
3rd Maintenance Revolution	1
Lack of Quality Control	1
Under defined Asset Management	1
Non - Adherence to SOP's	1
Lack of Training	1