

# **Reliability Management in a South African Railway Company**

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## **Abstract**

This paper investigates the reliability management of overhead track equipment in a South African railway company. The organization has been experiencing unsatisfactory operational efficiency due to infrastructure failures such as pantograph hook-ups, derailments, and washaways, which affect performance. The unsatisfactory operational efficiency affects the organization's revenue generation, economy, and customer confidence. Studies suggest that the overhead track equipment is the least reliable subsystem of the electric traction system, and its failures contribute significantly to train operations' poor performance. In the South African railway environment, studies have been conducted to evaluate the reliability of the overall railway infrastructure, traction substation and perway; however, there has been little research on the reliability of the overhead track equipment. This study addresses the shortcoming by assessing the reliability management of the overhead track equipment in South Africa. The convergent mixed-methods design was selected for the study, and a sample of the maintenance depots was selected to collect failure data, inspection and audit reports, and primary data were collected using a questionnaire. The analysis of the data sources showed that the maintenance strategies employed by some maintenance depots are ineffective, maintenance management tools such as RCM and FMECA can be adopted to improve the reliability of the equipment, and factors that affect the reliability of the overhead track equipment are operational, maintenance budget, and human factors.

## **Keywords**

Maintenance strategies, failures, reliability, overhead track equipment, theft and vandalism.

## **1. Introduction**

The Company has been experiencing poor operational efficiency and failing to achieve the set performance targets. The annual reports indicate that poor operational efficiency is caused by factors that include chronic infrastructure failures. These are derailments, pantograph hook-ups (retirement) and wash-aways. In 2012 the Company implemented a strategy to improve its performance; it included infrastructure upgrades, skills development, and procuring of rolling stock. Figure 1 shows the Company's performance between 2013/14 and 2018/19, and it shows that the performance has been unsatisfactory due to poor operational efficiency, and it has not been able to reach the set targets. The Company operates railway lines in electrified and non-electrified sections, and the operations in electrified sections affect the operational efficiency through overhead track equipment (OHTE)/overhead contact line failures, pantograph hook-ups and traction substation failures. The OHTE is regarded as the least reliable subsystem of the electric traction system (Zhang & Zhang, 2010; Cardasim, et al., 2018). OHTE failures affect the railway service significantly due to the lack of redundancy (Beagles, et al., 2016; Zhuwaki, 2017); this results in train delays and cancellations and reduced operational efficiency. Train cancellations refer to planned train slots cancelled due to the train's failure to depart or reach its destination, and train delays refer to delayed trains that reached their destination. The OHTE's operational performance is affected by its dynamic behaviour. Poor dynamic behaviour and equipment fatigue will result in failures (Beagles, et al., 2016). Failures on the OHTE can have different impacts to train operations, minor failures may be inconspicuous to train drivers, and significant failures can result in the closure of railway lines (Beagles, et al., 2016; Zhuwaki, 2017). South African studies have been conducted on improving the reliability of traction substations and the general railway infrastructure (Sprong, 2008; Zhuwaki, 2017; Shihlomule, 2019), but similar efforts have not been conducted to investigate the reliability of OHTE. The Company spends a

considerable amount on asset maintenance to deliver on set targets; however, operational efficiency is not satisfactory. Figure 1)

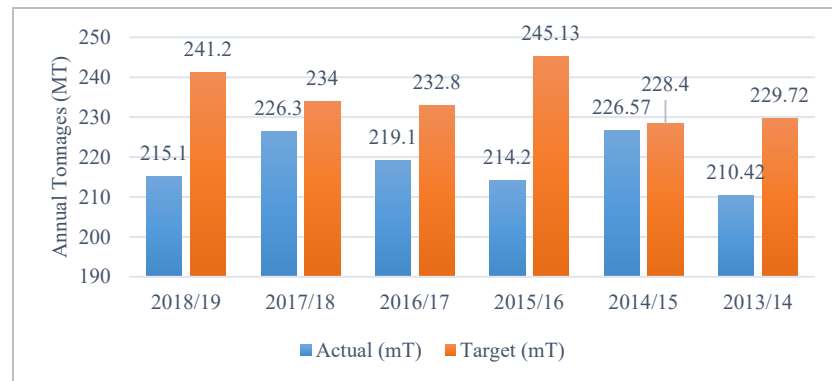


Figure 1: The Company's performance from 2014 to 2019.

## 1.1 Objectives

The Company experiences a high number of OHTE failures and pantograph hook-ups; thus, the research investigated the reliability management of the OHTE to improve operational efficiency. The main objective of the research was to evaluate the reliability management of the OHTE to establish how it affects the Company's operational efficiency. The research objectives were as follows:

- A. To determine the effectiveness of employed maintenance management strategies.
- B. To identify reliability management tools that can be adopted to improve reliability.
- C. To investigate factors affecting the reliability of overhead track equipment.

The railway operator will benefit from the research by identifying a reliability management strategy suitable to minimize OHTE failures and improve the Company's operational efficiency.

## 2. Literature Review

Technical and economic factors make it impractical to have redundancy of the OHTE (Beagles, et al., 2016; Zhuwaki, 2017). Two types of electrification technologies are employed in the organization: direct current (DC) and alternating current (AC); these electrification technologies are spread throughout the operational areas. The geographical expansion of the infrastructure results in the varied performance of the equipment due to different operational and environmental conditions. The organization intends to increase the tonnages railed, resulting in reduced maintenance slots. Thus, the organization's reliability management strategy must be prioritized for improvement.

### 2.1 Maintenance Management of OHTE

The OHTE comprises various components subject to mechanical, electrical, and environmental stresses from operational and weather conditions (Michael, et al., 2008; Seri, et al., 2013; Bojovschi, et al., 2019; Elovaara, 2019). The maintenance depots' responsibility is to ensure railways' reliability, availability, safety, and cost-effectiveness. They conduct maintenance in compliance with statutory obligations and standards to ensure that failures of components are minimized and afford safety to personnel and the public. The maintenance manager is responsible for developing and executing maintenance plans and rehabilitating the failed equipment. The depot employs various maintenance tools such as inspections by foot or motorized trolley fitted with a pantograph, condition assessment using infrastructure measuring vehicles which measures the dynamic interaction of the contact wire and the pantograph, and thermographic scanning. OHTE geometry parameters such as contact wire gradient, wear and stagger, and lateral and vertical forces are measured by the infrastructure measuring vehicle.

### 2.2 Equipment Failure and Reliability

The equipment's ability to function as specified over a period under defined conditions defines its reliability (Biolini, 2014). Railway maintainers implement reliability management programmes to ensure high-quality service is provided to their customers. The objectives of a reliability management programme include minimizing failures by applying

engineering knowledge, analysing reliability data, and evaluating the reliability of equipment designs (Lau, et al., 2004; O'Connor & Kleyner, 2012). Failures in the equipment can be generated during any phase of its lifecycle, from concept to maintenance (Jiang, 2015); these failures result in degraded performance or complete loss of function. Failures have different characteristics such as intermittent, extended, sudden and gradual (Jiang, 2015). Maintenance interventions impact the equipment's failure rate; a decreasing failure rate signifies effective maintenance interventions (O'Connor & Kleyner, 2012; Chan, 2016). The equipment may experience an increase in failure rate due to excessive degradation from poor maintenance (Jiang, 2015). Equipment's reliability is quantified by computing reliability metrics such as failure rate, mean-time-to-failure, mean-time-between failure, and mean-time-to-repair. The performance data of the equipment is used to perform a statistical analysis of its reliability.

### **2.3 Reliability Analysis Techniques**

Linear assets span across geographical locations and are subject to different operational and weather conditions, these assets are maintained by different teams distributed across the infrastructure network (Duque, et al., 2009), and thus, the deterioration and equipment performance is not the same across the assets; these factors contribute to the complexity of the management of railway infrastructure (Macchi, et al., 2012). The reliability management programme requires the maintenance managers/engineers to analyse infrastructure failures (Lau, et al., 2004; O'Connor & Kleyner, 2012). Several failure analysis techniques can be used to determine the root cause of failures and the impact of component failures on the performance of the rail infrastructure. Chan (2016) evaluated Taiwan Railway Administration's OHTE using the Fault-Tree-Analysis to determine the cause and effect between events and system failure using Boolean logic combinations of the events. Macchi et al. (2012) analysed the railway maintenance of the Italian public limited Company using the Reliability Block Diagram technique, which determines how a subsystem failure affects the system objectives. Other failure analysis techniques available to maintenance managers include FMECA (Duque, et al., 2009; Jiang, 2015) and Event-Tree-Analysis (Ku & Cha, 2011).

### **2.4 Maintenance Management**

Maintenance managers rely on maintenance interventions to achieve the objectives of the maintenance policy to deliver on the organization's objectives. Maintenance interventions can improve the equipment's reliability by reducing the equipment's failure rate. However, maintenance managers must balance maintenance activities and the available budget while considering the key objectives of the maintenance policy, such as availability, reliability, safety, and cost-effectiveness of the infrastructure. Maintenance managers can apply various maintenance philosophies; the broad categories of these philosophies are reactive; those that are conducted after a failure has occurred, such as corrective and emergency maintenance (Budai, et al., 2008; Lee & Wang, 2008), and proactive maintenance; those that are conducted before a failure based on age in service, frequency, or condition (Kothamasu, et al., 2006). Reactive maintenance can be costly due to the high production losses and high risk of safety and environmental impact (Budai, et al., 2008; Lee & Wang, 2008). Reliability Centred Maintenance (RCM) is a proactive strategy structured to determine suitable maintenance interventions that minimize failure risk whilst containing maintenance costs (Rausand & Vatn, 2008; Mehairjan, 2017). The RCM utilizes FMECA to establish the system's function, performance standards, failure causes, failure modes and consequences, and cost-effective maintenance tasks that minimize the risk of failures are selected for implementation (Rausand & Vatn, 2008; Mehairjan, 2017).

### **2.5 Factors affecting the reliability of equipment**

The reliability of equipment is affected by various factors such as human factors (Nkosi, et al., 2020), operational factors (Hu, et al., 2017), maintenance budget (Mc Dullin, et al., 2006), environmental factors (Elovaara, 2019), and maintenance policy (Endrenyi, et al., 2001; Lee & Scott, 2009). Humans interact with the equipment throughout its lifecycle stages and can affect how it performs (Dunn, 2007; Nkosi, et al., 2020). Failures on the equipment are likely to occur following an interaction with humans (Dunn, 2007). The maintenance policy defines strategy, standard, and resource allocation (Lee & Scott, 2009). The maintenance policy may call for longer or shorter maintenance intervals, and each has its disadvantages; more extended periods increase the likelihood of increasing failures and shorter periods increase maintenance costs (Endrenyi, et al., 2001). Organizations implement cost-saving initiatives for various reasons, including unfavourable economic conditions; these initiatives may also affect the budget allocated for maintenance. The drawback of reducing the maintenance budget is that maintenance is deferred, and there will be an increased risk of equipment failure leading to reduced safety performance and higher operational and maintenance costs. Operational factors are due to the interaction of various subsystems affecting the reliability of the equipment (Hu, et al., 2017). Environmental factors such as wind, pollution, rain, and ambient temperature affect the performance and reliability of electrical equipment (Bojovschi, et al., 2019; Elovaara, 2019), and these factors cause failures such as insulation degradation and corrosion to electrical equipment (Seri, et al., 2013; Bojovschi, et al., 2019).

## **2.6 Summary of Literature Review**

The reliability management of the equipment is important to ensure that the equipment can support the train operations. The effectiveness of the maintenance strategies can be evaluated by computing the reliability metrics, which can indicate whether the strategies can minimize failures or not; the failure rate can be used as a measure of the effectiveness of maintenance strategies. Failure analysis techniques are employed as part of the reliability management programme failures to ensure that the failure modes are understood, and failures are prevented. Maintainers should select maintenance strategies that support the organization's objectives, and planned strategies are favoured due to the ability to regulate failures, the impact and the cost of failures. The organization should set a maintenance policy regulating how resources should be allocated for maintenance. The maintenance budget impacts the maintenance frequency and reliability of equipment. The reliability of equipment is also affected by its interactions with humans, from concept to operations.

## **3. Methods**

The research design is a framework of the study that must provide answers to the research problem in a valid, objective, accurate, and economical manner and must address the following aspects (Leedy & Ormrod, 2016); data collection, sampling, data analysis and reporting of findings. Applied research was selected for the study because it aims to provide practical solutions to existing problems (Given, 2012). The pragmatism paradigm was selected because it uses every available approach to understand the research problem (Leedy & Ormrod, 2016; Creswell & Creswell, 2018). The mixed-methods research approach, which is underpinned by the pragmatic paradigm, was selected for the study. The mixed-methods approach utilizes qualitative and quantitative approaches to investigate the research problem (Creswell & Creswell, 2018). The benefits of using the mixed methods are that over-reliance on one approach is minimized, and multiple data sources allow for triangulation, resulting in a superior comprehension of the study (Jogulu & Pansiri, 2011; Malina, et al., 2011). The mixed-methods approach allowed for failure data and the perspective of the equipment maintainers to be used in the investigation. The convergent mixed methods design was selected for the study; in this method, qualitative and quantitative data are analysed independently and concurrently, and then the findings are compared for similarity (Leedy & Ormrod, 2016; Creswell & Creswell, 2018).

## **4. Data Collection**

The Company has 21 maintenance depots strategically located across the country. Nine maintenance depots were randomly selected to collect the quantitative and qualitative data, and these were stratified by traction technology DC (A – E) and AC (F – I). The quantitative and qualitative data were collected for the sample depots covering a period of four years (2017 – 2020). The quantitative data was collected from the computerized maintenance management system (CMMS). The CMMS records all infrastructure failure data, including causes of failures, location, and business impact. Qualitative data were collected from questionnaires, OHTE inspection reports, and electrical systems audit reports. The questionnaire was validated using face validity. The questionnaire was sent using email to the participants. Twenty-one participants were invited to complete the questionnaire, and ten completed questionnaire responses were received. There were no incomplete questionnaires received. The OHTE inspection and electrical systems audit reports were collected from the central maintenance standards department, which ensures quality assurance and compliance with standards by conducting inspections and audits of the infrastructure maintained by the maintenance depots. The department also develops the standards used in infrastructure maintenance. The OHTE inspection reports are derived from infrastructure inspections conducted using a motorized inspection trolley fitted with a non-measuring pantograph; the inspections are conducted to assess the infrastructure condition and compliance with maintenance and safety standards. The electrical systems audit reports are derived from audits conducted by the maintenance standards department on the maintenance depots; the audits focus on the management of infrastructure and resources.

### **4.1 Descriptive Analysis of Collected Data**

The OHTE failure incidents may have various levels of impact, such as minor, major or no impact to train operations. The literature review indicated that a reliability management programme requires failure data analysis and that failures can be generated during any phase of the equipment's lifecycle. The unsatisfactory performance of the overhead track equipment requires evaluation of the failure data and the management of the assets; thus, the failure data must be analysed to determine the extent of the impact on the reliability of the OHTE. The failure data from the CMMS will describe the prevalent failures, failure modes, trend of failures and failure rates; this data can be used to determine the effectiveness of maintenance strategies. The inspection and audit report will provide insight into the factors affecting the reliability of OHTE and the employed maintenance strategies. The questionnaire will provide a perspective of the

maintainers on the trend of failures, factors affecting the reliability, failure analysis techniques and maintenance strategies. The data collected can be used to evaluate the reliability management of the OHTE by determining the effectiveness of maintenance strategies and failure analysis techniques and assessing maintenance management strategies employed and factors which must be addressed in the reliability management of OHTE. Other data available for collection which were not collected for this study include reports generated by condition measuring vehicles, the maintenance history of the OHTE and the tonnage loss because of failure incidents.

## 5. Results and Discussion

The primary objective of the research was to investigate the reliability management of OHTE in the Company and identify how the OHTE maintenance management can be improved.

### 5.1 Analysis of Computerized Maintenance Management System Failure Data

The goodness of fit test was conducted for the failure data of the depots using the Jarque-Bera test statistic to determine the normality of the data. The significance level alpha ( $\alpha$ ) value was set at 0.05; thus, a 95% confidence level that the distribution of the failure data is not normally distributed. The following hypothesis was tested:

$H_0$  : the data is normally distributed.

$H_1$  : the data is not normally distributed.

The goodness-of-fit test was used to determine the normality of the failure data from each depot in the sample, and the results are shown in Table 1. The depots had p-values less than 0.05; thus, the null hypotheses are rejected. The skewness and kurtosis of a normally distributed data set are 0 and 3, respectively (Thadewald & Büning, 2007). The skewness values for the failure data were greater than 0, and all depots except E-depot had a kurtosis value of less than 3. The sample failure distributions are not normally distributed.

Table 1: Goodness-of-fit test.

Depot	A	B	C	D	E	F	G	H	I
Observations	48	48	48	48	48	48	48	48	48
Skewness	1,350	0,789	0,516	1,150	1,359	0,791	1,061	0,795	1,007
Kurtosis	1,981	0,929	1,409	0,952	3,108	1,161	1,739	0,871	1,907
JB test statistic	22,424	6,704	6,100	12,385	34,089	7,699	15,048	6,572	15,385
p-value	1,35E-05	3,50E-02	4,74E-02	2,05E-03	3,96E-08	2,13E-02	5,40E-04	3,74E-02	4,56E-04

The Kruskal-Wallis H test, a non-parametric statistical test, was used to determine whether there is a statistically significant difference between the failure distributions of the depots. The significance level alpha ( $\alpha$ ) value was set at 0.05; thus, a 95% confidence level that the failure distribution of the depots is different. The following hypothesis was tested:

$H_0$  : the distribution of failures in the sample depots are the same.

$H_1$  : the distribution of failures in the sample depots is not the same.

The p-value was less than 0.0001; thus, it was less than the alpha value. The null hypothesis was rejected, and there is a statistically significant difference in the failure distributions of the depots.

$H(8) = 257.441$ ;  $P < 0.0001$  shows a statistically significant difference between the failures in the sample depots. The Kruskal-Wallis tests do not identify which tested samples were different or how many differences were present in the samples.

The post hoc test was conducted to determine which samples were different. The summarised post hoc results in Table 2 show that there are depots with similar failure distributions. These depots can be grouped and targeted together for

similar reliability management interventions. The post hoc test results also show that there are depots with unique failure distributions.

Table 2: Post hoc test results.

Factor	Discussion
<b>A-depot</b>	The failure distribution in this depot is different from all other depots
<b>C-depot</b>	The failure distribution in this depot is different from all other depots
<b>B- and H-depot</b>	The depots have similar failure distribution
<b>D-, F- and G-depot</b>	The depots have similar failure distribution
<b>E- and I-depot</b>	The depots have similar failure distribution

Figure 2 shows each depot's contribution to the train operation interruptions; A-depot is the most unreliable depot contributing to 1,404 train cancellations over the four years. This depot could have a combination of high failures and numerous single-track sections where there is no alternative route in case of OHTE failures. The figure shows that OHTE failures in A-depot result in severe disruptions as compared to other depots. A-depot could be a centrally located depot and interlinks with various other depots, thus having a high number of train operations within its boundaries.

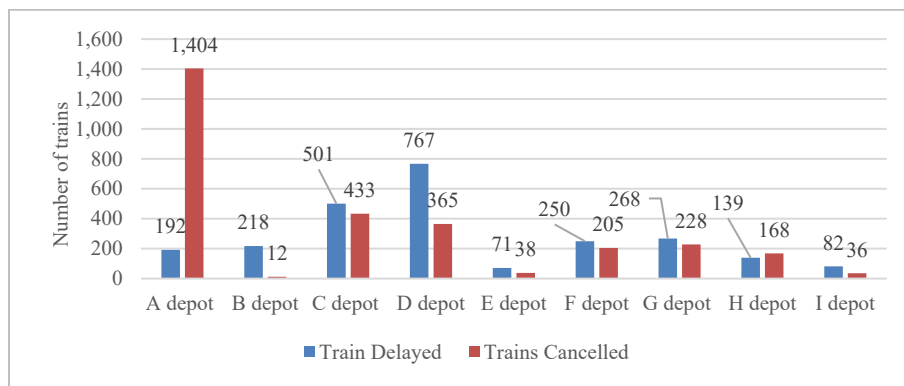


Figure 2: Comparison of train cancellations and delays per depot.

Figure 3 shows the failure comparison between AC and DC electrification, and the figure shows that the trend of DC electrification failures has been increasing over the four years; in contrast, the failures of AC electrification have been decreasing. The DC electrification depots are the highest contributors to the unreliability of the OHTE. The AC electrification failures were the highest in 2018 and declined in subsequent years.

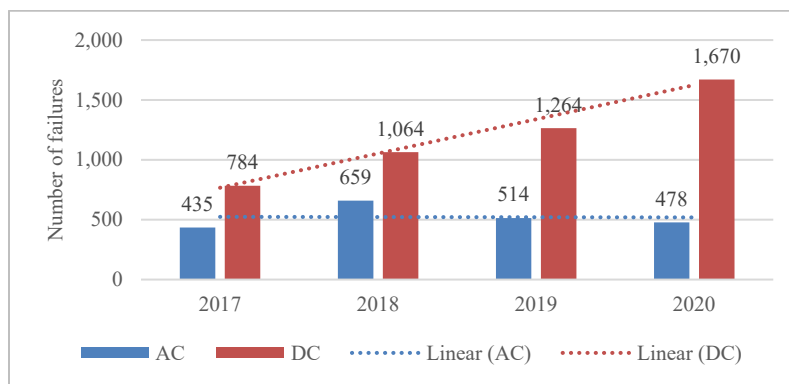


Figure 3: Annual failures per electrification technology.

Figure 4 shows a four-year comparison of the sample depots' failure rate; the failure rate increased at seven of the nine depots, and H- and I- depots recorded a decrease in the failure rate. All the DC depots recorded an increase in the failure rate over the study period; thus, the DC depots are the highest contributors to the unreliability of OHTE. However, it is noted that E-depot recorded a decrease in failure rate from 2019 to 2020. F- and G-depots also recorded a decrease in failure rate from 2018 to 2020.

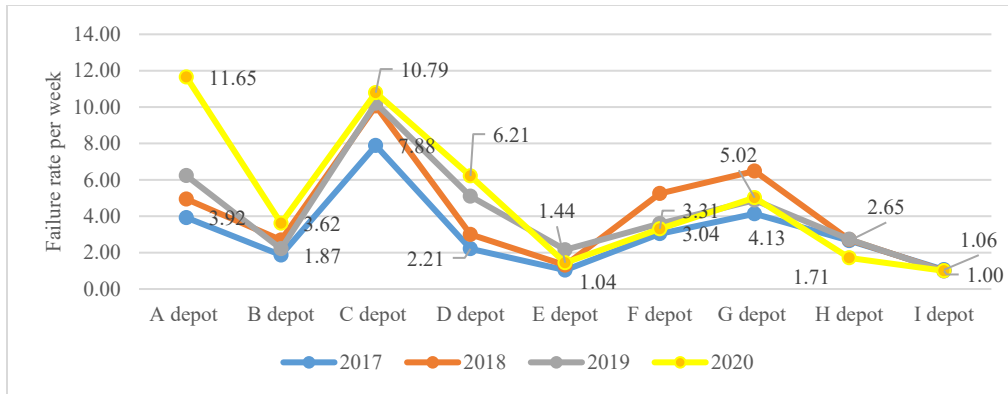


Figure 4: Depot's failure rate.

Figure 5 shows the top failing components during the period under study; the contact wire, which is meant to provide a quality current collection for the locomotive's pantograph, had the highest number of failures and was the least reliable component; contact wire failures are likely to impact the train service severely. The top failure mode over the four years was missing components resulting from theft and vandalism. The second, third and fourth highest failure modes were broken, loose and burnt equipment, indicating poor and substandard maintenance practices. The highest individual cause of unreliability of the OHTE is theft and vandalism incidents.

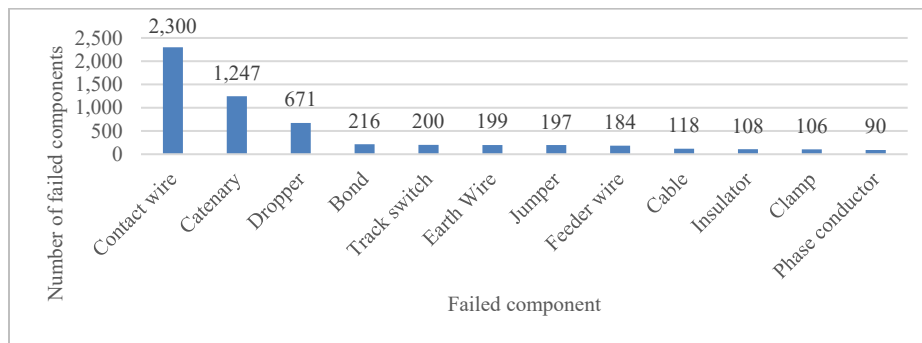


Figure 5: Top failing components.

Figure 6 shows the Pareto chart of the OHTE failure causes; eighty percent of the failures are due to (1) theft and vandalism, (2) small component failure, (3) No fault found, (4) worn beyond the standard and (5) environmental. The failure causes are either external or internal, theft and vandalism are external to the maintenance strategies, and the depots have little to no control except replacing copper material with less attractive alternatives when technically feasible. Small component failures are due to poor maintenance strategies and the quality of maintenance material. No-fault found causes are related to various factors such as personnel training to identify and diagnose faults, lack of tools and equipment and pressure to open the railway line for service from the operator (Qi, et al., 2008; Khan, et al., 2014). Equipment worn beyond the standard is due to poor maintenance strategies; thus, lack of inspections and opportunities to conduct maintenance. Environmental factors cause equipment failures, such as degradation of insulation due to pollution, corrosion due to rain and insulation failure due to lightning strikes (Elovaara, 2019).

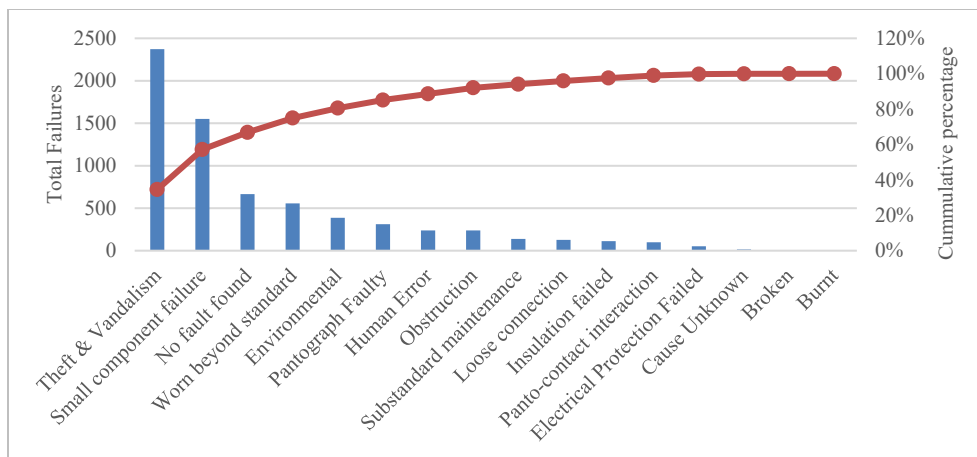


Figure 6: Pareto chart of OHTE failure causes.

### 5.2 Inspection reports findings and analysis

Inspections were conducted using a motorized trolley with high seating for close-up observation of the OHTE and fitted with a pantograph to evaluate the dynamic interaction between the contact wire and the pantograph. A summary of the top common findings is provided in Table 3.

Table 3: Summary of A-depot's OHTE inspection findings.

Findings	A depot	B depot	C depot	D depot	E depot	F depot	G depot	H depot	I depot	Total
<b>Obstruction on OHTE</b>	✓		✓	✓	✓		✓	✓	✓	7
<b>Frayed and Missing conductors</b>	✓	✓	✓	✓	✓	✓				6
<b>Poor mast &amp; foundations condition</b>				✓	✓	✓	✓	✓		5
<b>Broken and polluted insulators</b>		✓			✓			✓	✓	4
<b>Loose and broken droppers</b>		✓	✓		✓			✓		4

The highest common finding was the obstruction of OHTE by vegetation encroaching onto the "live" wires and foreign material deposited on the wires. The second most common finding was missing and frayed conductors due to theft and poor maintenance practices where frayed jumpers are not identified and replaced to prevent hotspots from forming on the OHTE.

### 5.3 Electrical Systems Audits findings and analysis

The electrical systems audits are conducted to assess the compliance of depots to the set maintenance standards. The audit reports of the sample depots were evaluated. Three depots had complete equipment and material database, which details the equipment type and its location; the database is helpful for maintenance planning to ensure that all assets are maintained per prescribed standards. All the depots conducted failure analysis. However, they only conducted failure analysis for failures that impacted the train operations. Six of the nine depots provided evidence of adherence to the maintenance plans, such as work permits, job cards and occupation notices. Only three of the nine depots conducted complete condition assessments; six of the nine depots had incomplete condition assessments. Five of the nine depots did not have sufficiently skilled personnel appointed and had vacancies in safety-critical positions. These affected the maintenance because it could not be executed according to the set standards.

### 5.4 Analysis of Questionnaire Responses

The questionnaire consisted of various sections which aimed to establish the following (A) the demographics of the participants, (B) the maintenance management tools used by respondents, (C) the perceived effectiveness of maintenance strategies, and (D) the factors affecting the reliability of OHTE. The summarised analysis of the



responses is presented in this section. The demographics of the ten respondents were maintenance managers (4), engineers (3), trainee engineers (2), and engineering technicians (1).

Figure 7 shows the failure analysis techniques used by the respondents; all respondents used the five whys technique to analyze failures. This technique is simple compared to other techniques; however, it has limitations, such as multiple investigators reaching different conclusions and the investigation being concluded based on symptoms rather than the root cause (Card, 2017). The fishbone technique was the second most used failure analysis technique. The maintenance philosophy used by the respondents was corrective maintenance used by all and preventative maintenance used by nine respondents.

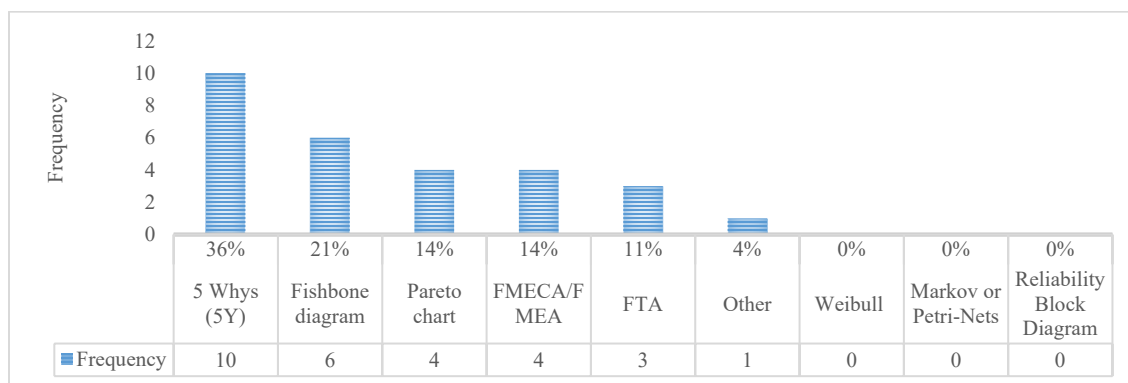


Figure 7: Failure analysis techniques used by the respondents.

The respondents indicated the factors that affect the reliability of OHTE; all respondents indicated that the human factors affect the reliability of OHTE; the other factors included maintenance budget and operational factors. The respondents were asked to indicate the causes of the factors they selected that affect the reliability of the OHTE. One respondent stated that the maintenance team are "Fatigue[d] due to always attending breakdowns", and another stated that "As theft of OHTE has risen nationally, teams responding to theft callouts at night at a given main or sub depot are then on rest the next day, the staff shortage thus leaves much of the routine preventive maintenance incomplete...". Theft and vandalism (operational factors) affected the reliability of OHTE, and it caused human factors and reduced adherence to maintenance plans. The maintenance depots had their maintenance budget reduced, which affected the adherence to maintenance plans; one respondent stated that "Budget cuts affect planned maintenance and resources."

The excessive theft and vandalism put the rail operator in a predicament because it must choose between allocating slots for train operations and maintenance of the OHTE; one respondent stated, "The challenge is striking a balance between giving maintenance slots and running trains.". The respondents reported that the leading human factor affecting the reliability of the OHTE was time pressures, stress, and fatigue (nine respondents), followed by poor organizational culture and communication, which five respondents selected. One respondent stated that the time pressures, stress, and fatigue factor was caused by "Not having enough team strength to attend to callouts and maintenance execution due to high theft callouts.", and another agreed that there are "Few people to service the whole line and increasing theft and vandalism".

### 5.3 Proposed Improvements

The depots with ineffective maintenance management strategies were identified, as observed in the increase in failures during the period under study. The Company should consider implementing similar maintenance strategies for the depots with identical failure distributions. The Company should investigate why the depots with AC OHTE were more reliable than the ones with DC. The depots use simplistic failure analysis techniques, and analysis is not conducted for all failures but only for those impacting the train operations. The Company should analyse all failures and implement comprehensive techniques such as the FMECA. The Company should implement reliability-centred maintenance due to the increased failures, reduced budget and opportunities to conduct maintenance. The Company should develop strategies to reduce the theft and vandalism of equipment; this includes technological surveillance of assets and replacing copper-based material with less attractive alternatives, provided it is technically feasible. The

maintenance budget and slots should be allocated by conducting a cost-benefit analysis over a short- and long-term period.

#### **5.4 Validation**

The research was validated using triangulation of data findings.

Objective A: to determine the effectiveness of employed maintenance management strategies. The CMMS data showed that the failure rate increased for seven of the nine depots and that five of the seven depots were DC depots. There are depots which recorded a decrease in failure rate inter-period (E-depot (2019-2020), F- and G-depots (2018-2020)). The inspection reports showed that poor and ineffective maintenance practices caused the unreliability of OHTE. According to the analysis of the audit reports, six depots did not conduct complete condition assessments, and seven of the ten questionnaire respondents stated that the failure rate in their depots was increasing. The Pareto chart shows that 33% of all failures resulted from maintenance-related causes such as sub-standard maintenance, equipment worn beyond the standard and small component failure. Maintenance-related failures are second to the highest cause of unreliability, theft, and vandalism of infrastructure, contributing to 35% of failures. Other factors can affect the maintenance effectiveness, such as traffic volumes, opportunity to conduct maintenance, and quantity of assets to be maintained.

Objective B: to identify reliability management tools that can be adopted to improve reliability. The CMMS data showed significant failures due to poor and substandard maintenance practices; the audit reports showed that the depots mainly conducted reactive maintenance and poorly implemented condition assessments. All depots used the five whys analysis technique, and it was predominantly used. The findings suggest that the Company should adopt the RCM because of the increase in failure rates across most of the sample depots, the inability of some depots to comply with the prescribed maintenance, and the reduction in maintenance budget and slots. The railway operator should also adopt comprehensive failure analysis techniques such as the FMECA.

Objective C; to investigate factors affecting the reliability of overhead track equipment. The CMMS showed that the causes of the failures were theft, vandalism, and poor maintenance practices. The inspection showed that the faults were caused by theft and poor maintenance practices; the audit reports showed that the unreliability of OHTE was due to incomplete condition assessments, inadequate team strength, and poor adherence to maintenance practices. The respondents to the questionnaire indicated that the unreliability was due to time pressures, stress, fatigue, inadequate team strength, theft and vandalism, reduction of maintenance budget, and reduced time for maintenance. The findings suggest that the factors affecting the reliability of OHTE are theft and vandalism, human factors, poor maintenance strategies, reduced maintenance budget and maintenance opportunities.

#### **6. Conclusion**

The evaluated failure data from the sample depots suggests that overall, the OHTE maintenance strategies employed were poor due to the trend of failures increasing during the period under study. However, there are depots that decreased the failure rate over the study period, and these were less than half of the sample. There are also depots that decreased the failure rate inter-period, suggesting improving maintenance strategies at those depots. All DC depots contributed significantly to the unreliability of the Company. AC depots appear to have better maintenance strategies than DC depots. The maintenance depots conduct failure analysis on incidents that impacted the train service, and they can improve by conducting failure analysis for all failures to identify failure modes and maintenance interventions that can minimize the risk of failures. The failures that are not analyzed are likely to lead to failures that impact the train operations. The organization should employ comprehensive failure analysis techniques such as FMECA to identify the correct root causes, failure modes and impact of failures. It is proposed that the organization implement the RCM due to the declining maintenance budget and the risk failures pose to the train operations. Maintenance depots with similar failure distributions should be evaluated to implement common maintenance interventions. Various factors affect the reliability of OHTE, including theft and vandalism, reduced maintenance budget, human factors, and operational factors. Theft and vandalism are the key drivers of failures and operational and human factors. The excessive theft and vandalism incident results in the maintenance teams being unable to conduct the planned maintenance, and the teams are fatigued and work under pressure to repair the affected equipment; this results in unintentional faults being generated during the repairs. The Company should strive to curb the prevalence of theft and vandalism incidents; this is the first step to improving its operational efficiency. The analysis showed that depots with

AC electrification had fewer failures than those with DC electrification; the DC depots should be the first to be targeted for the proposed reliability improvement interventions.

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