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Maintenance Protocols for Improved Operational Efficiency: A Performance Review on Rail Operation's Systems

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Abstract

This study aimed to evaluate how digital transformation, including smart technology and predictive maintenance, impacts South African (SA) Rail operation's efficiency, asset dependability, and cost reduction. Correlation analysis revealed a stronger negative relationship between the independent and the dependent variables, suggesting that enabling technological and systematic interventions through failure prediction reduces downtime and unnecessary stops, decreases repair costs, and indicates that the more it is used, the lower the failure rate.

Keywords
Maintenance, Infrastructure, Safety adherence

1. Introduction

According to Mokobori et al. (2022) in South Africa, the market share of rail has been decreasing over the last ten years, while road transportation has seen an increase in usage. This could be attributed to several things, including inadequate resource allocation, deteriorating infrastructure, operational policy restrictions, and poor maintenance. For the train system to survive and function properly, its operations and maintenance are crucial. The railway sector, which depends on reliable and effective train infrastructure, is essential to both economic growth and international transit. When it comes to moving imported commodities to other parts of South Africa, railway transportation is essential. The rail system in South Africa links the port to the other towns and neighbouring nations, making up almost 80% of Africa's entire infrastructure (Olalere and Ramdass 2024).

The railway sector connects people and businesses, which significantly boosts a nation's economic development. The effectiveness and dependability of railways are essential to the functioning of transportation networks. Research on the operational effectiveness of the rail transport system is necessary to comprehend its current situation, considering the transition from rail to road transport (Olalere and Ramdass 2024). Train derailments, environmental harm, passenger safety risks, and revenue loss are all made more likely and severe by the increasing dynamic loading placed on decaying track infrastructure. The nation's rapidly deteriorating infrastructure, as a result of poor maintenance procedures and policies, poses a threat to economic growth. To better understand the reasons for infrastructure deterioration and draw conclusions that would help to improve infrastructure maintenance interventions in South Africa, it is important to examine the infrastructure maintenance ideologies (Holomisa et al. 2024).

Between 2019 and 2020, the number of mainline derailments increased from 65 to 88. Poor track conditions, including damaged rails, faulty crossings, and gauge widening, were the main cause of this increase. A decrease in capacity, increased maintenance expenses, and an inability to meet yearly goals were the outcomes of these failures (Transnet Freight Rail 2020). Olalere and Ramdass (2024) expressed that this field improves safety and reliability in a variety of technical systems by identifying and mitigating system failures. Thus, this study examines the condition of South Africa's railway infrastructure, assesses the system's effectiveness, and investigates the possibility of integrating technologies to enhance operations. According to Holomisa et al. (2024) late maintenance interventions that put train operations at risk and result in service delays, typical routine maintenance may lead to needless measures that do not ensure asset reliability. These maintenance management techniques have caused the infrastructure of the South African rail network to deteriorate.

For a transportation system to operate effectively, maintaining railway infrastructure is essential. When the infrastructure deteriorates due to neglect, the train network becomes unavailable, negatively impacting corporate operations and revenue. A maintenance strategy is a systematic approach to equipment upkeep that involves locating, investigating, repairing, replacing, and examining equipment, as well as creating the best possible lifespan plan for each facility in coordination with other departments (Boye et al. 2023). Railway operators and infrastructure managers must implement the latest fit-for-purpose technologies to address issues with South Africa's signalling and telecommunications systems. These technologies can assist with sourcing spare parts and help reduce theft and vandalism. Therefore, South Africa's signalling and telecommunications systems need to be upgraded or replaced, as this would significantly improve current systems (Gumede et al. 2025).

In order to create complete safety regulations, current rail safety rules must be updated, and rail safety directives must be followed. Establishing an independent organization to supervise railway safety is a crucial prerequisite. The deployment of real-time track condition, train operation, and environmental monitoring systems should be guaranteed by investments in infrastructure and technology. Potential issues must be found and fixed with predictive maintenance technology before they result in occurrences. The industry requires the creation of customized training programs that integrate the newest safety procedures and technology for railway workers (Bal et al. 2024).

1.1 Problem Statement

Rail operations experiences operational inefficiencies that result in reduced capacity, service delays, and asset downtime throughout its rail and port operations, due to old equipment, uneven maintenance performance, and costly maintenance expenses. Inadequate spare parts, challenges with data management, non-adherence to policies and procedures, and maintenance planning all contribute to the problem, which leads to reactive maintenance tactics that increase costs and fall short of operational requirements. During the 2025/26 annual performance report, Transnet reported that compared to the previous year, Transnet's revenue performance for the year ending March 31, 2025, increased by 7.8%. This was accomplished despite several obstacles that still affect the rail and port industries, including derailments, problems with the rail network, theft and vandalism, the legacy fleet's deteriorating dependability, unfavourable weather, malfunctions, and equipment reliability problems. Despite better revenue growth, the company recorded an R1.9 billion loss for the year, a 74.0% decrease from the previous year (Transnet SOC Limited 2025).

As a result, Transnet is committed to investments in people, technology, procedures, and infrastructure to guarantee the provision of a dependable, responsive, and top-notch service to its clients and the South African economy. The company is steadfastly dedicated to lowering traffic, speeding up turnaround times, adhering to policies and processes, and increasing the predictability of services for the pipeline, port, and rail industries. Positive outcomes are already being seen from investments in digital systems, new machinery, and operational excellence.

1.1 Objectives

The objective of this study are:

- To optimize maintenance strategies to minimise operational disruptions, unplanned failures, and service delays.

- To enhance system safety and reliability by adhering to safe operating procedures and improving equipment dependability.
- To increase the operational capacity and efficiency of the rail and port networks to handle more goods.
- To identify current deficiencies and improvement areas within the maintenance framework.
- To contribute to economic growth by improving the reliability and throughput of national logistics infrastructure.

2. Literature Review
The development of South Africa's rail sector has been heavily influenced by historical events that shaped the country's history. Combined with other external factors, this has resulted in a railway industry that currently faces numerous challenges (Boye et al. 2023). National and local infrastructure in South Africa is being destroyed by cable theft, which also results in financial losses when stolen cables need to be replaced. Transportation, electrical, and telecommunications services are being disrupted. One of the sectors most susceptible to wire theft is the railroad sector. Copper cables are used in railway infrastructure to run track circuits, signaling devices, and trains overhead. For opportunistic cable theft syndicates and scrap dealers who turn to criminal measures to get money, this seems like a gold mine (Mthombeni 2023).

Through a vast rail network that links important ports and economic hubs, Transnet oversees the movement of a variety of commodities, such as bulk cargo, containers, and general cargo. This infrastructure enables the effective and economical movement of goods, making a substantial contribution to the nation's economic growth. Transnet Telecommunications is committed to providing cutting-edge technology and customized telecommunications solutions tailored to meet the specific needs of the rail and logistics sectors (Tshehla 2024).

2.1 Rail Operational Efficiency
Railway efficiency has been a significant topic of interest for both academics and practitioners among railway managers worldwide. A highly efficient railway from a national perspective is crucial for maximizing revenue. It also plays an essential role in reducing expenses and helping to deliver the intended level of service. Due to their effects on mobility, capacity to improve land use and development within urban centers, and relatively low environmental impact compared to other transportation modes, railway systems are generally viewed favorably by citizens and policymakers around the world (Jwara and Sibanda 2021). When describing "railway efficiency" from a financial perspective, these realities are quite relevant. While output and public benefits matter, reducing costs and financing are of critical importance. In this context, investments in railway operations, maintenance, and renewal allow efficient railways to achieve meaningful results and outputs (Rodríguez-Hernández et al. 2025).

The government, users, regulators, and railway owners/operators all have different definitions of efficiency. This is due to the fact that operators always define it in terms of infrastructure cost and accessibility. However, customers frequently prioritize availability, speed, and dependability. Regulators are constantly interested in both technical and allocation efficiency. Additionally, they constantly want data that allows them to examine both. Deriving key performance indicators (KPIs) from available data is one of the most straightforward approaches that can be used for both conceptualization and assessing railway efficiency. For the creation of a straightforward yet balanced scorecard, this might be sufficient (Jwara and Sibanda 2021). When addressing issues related to traffic and carrying capacity, the railway is viewed as a comprehensive system made up of structures and equipment, to its unsatisfactory technical state may limit train speed on a particular stretch. Thus, it is essential to understand the permitted train speeds and device characteristics for each barrier site on the railway to reconstruct the railway in a way that achieves these speeds. Over the past 20 years, the British railway network has seen a significant increase in both freight and passenger traffic, raising questions about its capacity to handle further expansion. Numerous infrastructure projects were put into place with the goal of boosting traffic capacity and lowering conflict (Kurhan et al. 2022).

Current railway efficiency measurements primarily provide comprehensive efficiency, which considers statistical noise and the impact of the external environment. As a result, the findings are too general for railroad authorities to identify and control the causes of ineffective and weak policymaking. In contrast, the actual efficiency of railway transport primarily examines how the railway industry operates and indicates areas where efficiency can be improved (Niu et al. 2023). Maintaining a railway track is the production activity of businesses and divisions of the railway industry, one of the primary sectors of railway transportation, to ensure the track's technical condition and its installations; it guarantees the continuous and secure passage of trains at a specific speed. This is accomplished through daily and periodic railway maintenance and repairs that adhere to established standards and acceptable indicators of the technical condition of the main machinery, prompt breakdown and malfunction detection and prevention, the removal of the causes of these malfunctions based on systematic track monitoring and review, and modernization and reconstruction of the railway. In this instance, the railroad track's components must guarantee the train's safe and unhindered travel at the designated speed for this section of track (Patlasov 2021).

Rodríguez-Hernández et al. (2025) revealed that in order to increase the efficacy, dependability, and cost-effectiveness of maintenance operations in the railway industry, the Railway Maintenance Management and Optimization (RMMO) focuses on the creation and deployment of cutting-edge tools and procedures. By combining ideas from computer science, engineering, and statistics, the RRMO tackles issues with maintenance planning and management for railway systems, equipment, and infrastructure. The RRMO includes a broad range of subjects, from reliability analysis to optimization techniques, such as the following:

a) The creation of optimization models for scheduling preventive and corrective maintenance.
b) Putting decision support systems into place for effective cost and resource management.
c) The application of machine learning and data analysis methods to maintenance program optimization and failure prediction.
d) Using stochastic models and probabilistic techniques to evaluate the availability and dependability of railroad assets.
e) To increase availability and prolong the service life of components and equipment, condition-based maintenance techniques and service life predictions are being researched.
f) The creation of tools for sensitivity analysis and simulation to assess how various maintenance approaches affect operational and financial performance

2.2 Safe Operating Procedures, Awareness, and Training

A change in operating conditions puts more strain on railway operations and infrastructure, which raises the risk of mishaps and accidents. Automation and digitalization are two examples of technological advancements that increase railway safety while also posing new concerns (Bal et al. 2024). Each organizational unit is responsible for identifying hazards and evaluating risks in accordance with established protocols. The formulation of risk control plans is guided by the classification of risks as extreme, high, medium, or low based on identified hazards. The safety team is responsible for keeping abreast of the relevant legislation related to occupational health and railway safety and disseminating this knowledge throughout the company. Work guidelines, technical instructions, and processes all integrate adherence to these regulations. Improving crossing safety and reporting findings for inspection are the responsibilities of those with approval (Hendra et al. 2024).

The first step before adoption or execution is awareness. Information, knowledge, or observation regarding a specific phenomenon is referred to as awareness. The literature indicates that there is knowledge of new technical innovations and adoption in the industrialized economy (Awodele et al. 2024). More linked devices and increasingly sophisticated infrastructures are the result of the railway industry's digitization. To equip personnel to maintain railway infrastructure and effectively protect against anything, it is necessary to establish effective training and awareness programs. The implementation of policies intended to assist staff in applying the appropriate steps should come as education initiatives (López-Aguilar et al. 2022). To guarantee efficient skill development, a comprehensive education and training program for rail safety leaders should cover all pertinent topics and use cutting-edge teaching techniques. The curriculum can equip safety executives to manage and improve rail safety, creating a culture of safety inside the company, by emphasizing both technical and leadership abilities and implementing continuous improvement approaches (Bal et al. 2024).

The training places a strong emphasis on the necessity of prioritizing safety in all daily actions and decisions. Each participant should have a thorough understanding of safety leadership and how to enhance it. The purpose of the Rail Safety Leadership training program is to educate railway managers and professionals on the value of safety leadership and how to enhance safety in their everyday operations and decision-making (Bal et al. 2024). People benefit greatly from training because it increases their confidence in their roles, which directly boosts their morale and operational effectiveness. When workers possess high levels of skill, their productivity always increases. An improvement in the various procedures used by the organization is implied by better training. Along with ensuring that workers are fully aware of what they are doing, it speeds up the completion of various activities, which improves the Caliber of the work they do. When workers are adequately prepared for their positions, mistakes that can cause systems to lag are also much less likely to occur (Jwara and Sibanda 2021).

3. Methods

The goal of this study is to keep the rail network operating safely and effectively, with communications that are secure and seamless. By optimizing and improving the current infrastructure, the system's operational efficiency should improve. A quantitative approach that determines the infrastructure's operational state based on the data from daily operations.

3.1 Research design

For this study, a questionnaire is used to collect data. The questionnaire's primary focus should align with the research objectives and purpose. Closed-ended and Likert scale questions are included in the questionnaire. The questions incorporate several inquiries to evaluate risk and compliance, including topics such as risk assessment, protocols, instruction, training, and tangible safety measures. It aims to identify potential risks, ensure adherence to standards, and collect data for ongoing improvement. Olalere and Ramdass (2024) examined the current condition of the railway system in South Africa as well as the possible effects of the digital revolution on system reliability engineering. While industry technologies have revolutionized new technologies, older and current infrastructures may need to be upgraded through replacement or modification. To maximize the current facilities and minimize the expense of complete replacement, the study explores the potential digital transformation of the current railway infrastructure

Safety adherence - Identifying hazards, evaluating, and controlling risks related to operational activities and human resources are all part of developing a thorough safety strategy for railway operations (Hendra et al. 2024). To contribute to the sustainable development of the railway industry, railway enterprises must pay greater attention to standardization work in a variety of ways, including strengthening procedures, improving the standard system, which helps them continuously improve their operational efficiency and service quality (Li et al. 2024).

4. Data collection and analysis

The study employed primary data collection methods; primary data was collected through the survey questionnaire method within a South African Rail Operations firm, whilst secondary sources included literature from various publications, including internal organisational reports. The questionnaire was administered to a SA Rail Operations firm employees who work in yards, depots, and the Centralised Traffic centres in Gauteng province, who oversee daily operations, train scheduling management, infrastructure repair, safety compliance, and maintenance. This includes creating an executable operations plan from the integrated train plan and overseeing any modifications to satisfy client demands. The researcher distributed an online questionnaire to 250 individuals through google form, email and WhatsApp and received 100 responses.

This Study used SPSS statistical tool to analyse the data collected. the data collected was analysed using the following statistical methods: descriptive statistics and frequencies, Exploratory Factor Analysis (EFA), empirical and theoretical reliabilities. These methods assists researchers to find answers and streamline procedures with the use of relevant data analysis instruments. They provide insights that help make well-informed decisions in a variety of domains, including academic research and industry, while improving the validity, accuracy, and reliability of research.

5. Results and Discussion

5.1 Descriptive statistics

Figure 1 provides the career occupation demographic representation of respondents who participated on this study.

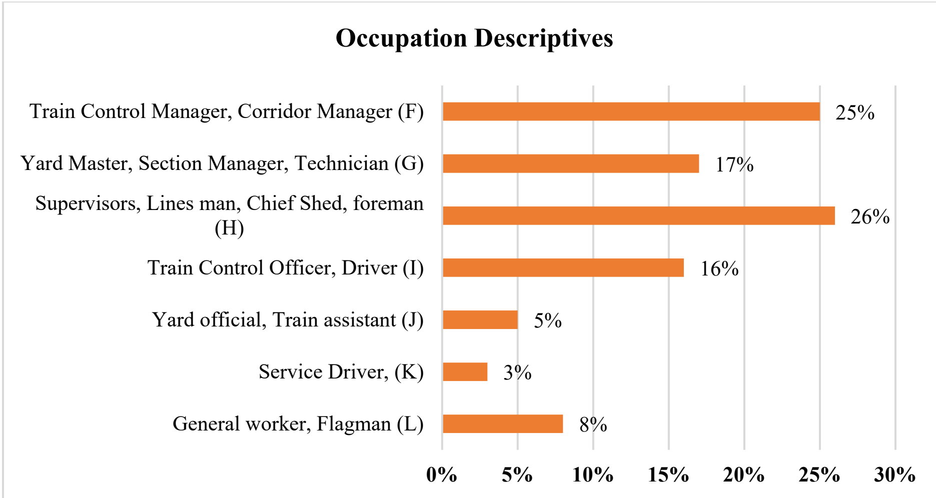

Figure 1. Occupation Descriptives

In terms of responses based on career types and levels, supervisors, line men, chief shed, and foreman (H), had a participation rate of 26%. Train Control Managers and Corridor Managers (F) generated a participation rate of 25%. Following by Yard Master, Section Manager, Technician (G) with a 17% participation rate. Train Control Officer, Driver (I) with a 16% participation rate. General Workers and Flagmen (L) have a participation rate of 8,0%. Yard official, Train assistant (J) generated 5% participation rate, and Service driver (K) has the lowest participation rate at 3,0% (Figure 2).

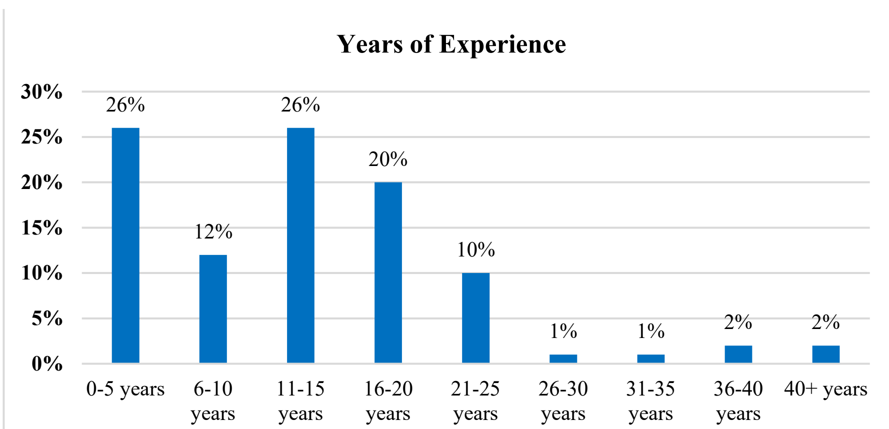

Figure 2. Years of Experience Descriptives

In terms of respondents' experience in the the SA rail operations firm, 26% of employees who participated have between 0-5 years and 11-15 years of experience, 20% have between 16-20 years, 12% have 6-10 years, and 10% have 21-25 years. 2% have 36-40 years of experience, and 1% have between 26-30 years and 31-35 years of experience (Table 1).

Table 1. Performance Maintenance Protocols

Sec B: Performance of the maintenance protocols.	Mean	Std. Deviation
B4. Adherence to Safety Operating Procedures.	4,09	0,944
B2. Safety regulations and standards are updated.	4,08	0,950
B6. Conduct track inspection.	3,82	1,038

With regards to selected performance of maintenance protocols reflected on Table I, Adherence to Safety Operating Procedures has the highest average of 4.09 and a standard deviation of 0.944, indicating that the scores are closely grouped around the mean. The organization continuously adheres to policies and procedures to reduce risks and prevent incidents. A strong safety culture and legal compliance are supported by following SOPs. B6. Conduct track inspection with the lowest mean of 3,82 and a standard deviation of 1.038, which suggests that the data is more dispersed. There is a moderate amount of track inspection activity.

5.2 Exploratory Factor Analysis

Factor analysis was also undertaken to identify components with commonalities, the strength of intercorrelation and to assess sampling adequacy amongst key variables identified for this study. The extraction method used in this study is Principal Axis Factoring The majority of the items on the matrix revealed intercorrelations greater than 0.3, indicating that the factor model is generally suitable (Table 2).

Table 2. KMO and Bartlett's test

KMO and Bartlett's test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		*0,862*
Bartlett's Test of Sphericity	Approx. Chi-Square	483,000
	df	45
	Sig	0,00

Table II indicates a KMO value of 0.862, which is greater than 0,6. This suggests that factor analysis is appropriate for this data. Bartlett's test of sphericity was used to verify if the correlation matrix is adequate. Bartlett's test is very significant when the p-value is less than 0.001, indicating that there is a significant correlation between some of the variables in the correlation matrix. The test statistic result in this instance is 483,000, the degrees of freedom are 45, and the significance level is less than 0.001. The significant value < 0.001 indicates that the data set is suitable for factor analysis.

The measure of Sampling Adequacy (MSA) values across all factor results are above 0.8, which is higher than the suggested threshold of 0.5. Following extraction, the communalities show the percentage of each variable's variance that can be accounted for by the factor that was kept. The dataset's common variance is reflected in communalities. All communalities are more than 0.3, indicating that the items share at least 30% of their variance. All things considered, this demonstrates the validity of the items by showing that they accurately measure the use of maintenance procedures**.**

In terms of Total Variances Explained as per table III below, the data set contained ten linear components before extraction, two of which have eigenvalues greater than 1. Before rotation, these two factors account for 62,58% of the total variance. It is advised that at least 50% of the variation should be explained by the components that are kept. The findings indicate that two factors account for 54,16% of the ten variables' shared variance following rotation. In the final solution, no more than two components were recovered based on this preliminary study. With an eigenvalue of 5,230, the first component accounts for 30,08% of the variance. 54,16% of the variance is explained by the second component, which has an eigenvalue of 1,029 (Table 3).

Table 3. Total Variances Explained

Total Variance Explained

Factor	Initial Eigenvalues			Extraction Sums of Squared Loadings			Rotation Sums of Squared Loadings		
	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %	Total	% of Variance	Cumulative %
1	5,230	52,295	52,295	4,782	47,818	47,818	3,008	30,077	30,077
2	1,029	10,288	62,583	0,634	6,342	54,160	2,408	24,082	54,160
3	0,772	7,717	70,300						
4	0,622	6,222	76,522						
5	0,612	6,121	82,643						
6	0,532	5,321	87,964						
7	0,418	4,184	92,148						
8	0,309	3,087	95,235						
9	0,255	2,549	97,784						
10	0,222	2,216	100,000						

The scree plot is also used to guide the decision of how many components should be kept. In this instance, the Figure 3 below indicates that two factors, each with an eigenvalue larger than one, account for most of the data variability. The remaining elements only make up a small portion of the variability and are regarded as less important. Although there is only one element theoretically. Empirically, there are two factors.

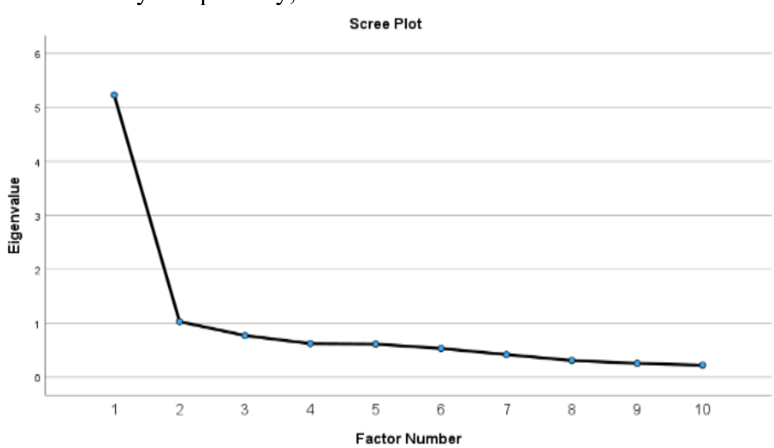

Figure 3. Scree Plot of Factors

Two factors are extracted. The first factor has five items and is named the performance of maintenance protocols in terms of compliance. The second factor consists also of five items and is the performance of maintenance protocols regarding safety adherence.

Theoretically, there is only one factor: the Performance of the maintenance protocols. Following Exploratory factor analysis (EFA), two factors are extracted. Factor 1: Performance of the maintenance protocols related to Compliance. Factor 2: Performance of the maintenance protocols in terms of safety adherence. For the overall factor scores, Factor 2: The maintenance protocols' performance in terms of safety adherence has a mean score of 4.03, which suggests that it was measured to a greater extent. Equipment is kept up to date to facilitate more efficient workflows and enable employees to perform their jobs efficiently. According to Davari et al. (2021) predictive maintenance minimizes downtime by detecting unplanned malfunctions, which lowers expenses and boosts operational effectiveness. Additionally, it improves safety by making it possible to identify possible flaws early, prolongs component life by scheduling maintenance according to actual wear rather than predetermined timetables, and maximizes resource utilization.

Factor 1: The performance of the maintenance protocols in terms of compliance has a mean score of 3,90, which is slightly below a large extent. The railways fulfil their legal and regulatory responsibilities by adhering to industry standards and certifications. Employee safety is ensured, and the danger of accidents during maintenance tasks is decreased by standard operating procedures and adherence to industry-specific standards (Davari et al. 2021).

5.3 Correlation Analysis

Correlation analysis were also undertaken to determine the strength and direction of constructs related to maintenance practices and their relationship with improved operational efficiency for rail operations. The Spearman's rho correlation was adopted due to adequacy to measure linear continuous relationships for normally distribute constructs (Figure 4).

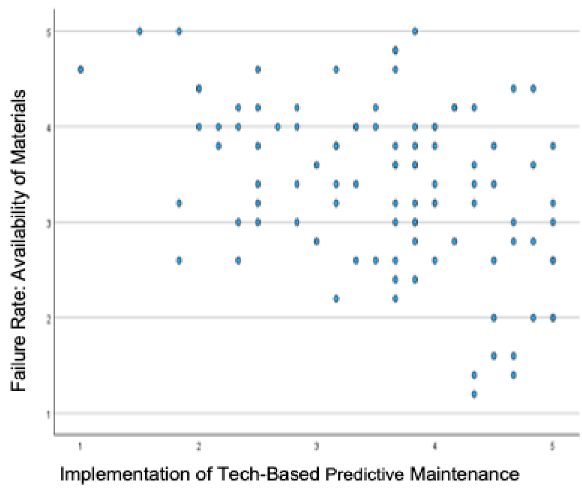

Figure 4. Implementation of Technological-Based Predictive Maintenance vs Failure Rate: Availability of Materials

Figure 4 above shows the relationship between the implementation of technological-based predictive maintenance and failure rate: availability of materials. The results demonstrate a negative correlation, indicating that higher implementation of technological-based predictive maintenance corresponds to a lower failure rate. This imply that enabling technological and systematic interventions through failure prediction, this approach reduces downtime and unnecessary stops, decreases repair costs, and indicates that the more it is used, the lower the failure rate.

6. Conclusion

The research findings provide valuable perspectives that help improve the reliability of the railway. The reliability techniques are essential to guaranteeing the longevity, functionality, efficiency, and safety of the railway. An essential component of railway signaling and control systems is the monitoring and control of the railway points plus and minus locations. For safe and effective rail operations, it is crucial to make sure that organizations establish plans to guarantee adherence to the established protocols and policies for carrying out maintenance. The objective of the study was to reduce operational disruption. By following safe operating methods, maintenance optimization seeks to increase overall operational capacity, reduce risk, and shorten service delays by preventing unscheduled equipment breakdowns and deterioration. Both methods indicated that the organisation continues to adhere to rules and protocols to avoid mishaps and injury. Maintaining a clean work environment, reporting dangers, and being. Adhering to these guidelines is essential for safeguarding workers, meeting legal obligations, and reducing hazards. These protocols aim to stabilize SA Rail Operations firm's working performance and improve dependability.

To fully realize the potential of continental trade corridors, Rail Operations should strengthen its alliances with regional and industry partners, establishing South Africa as a competitive and integrated trade gateway. Increase the private sector's involvement in rail and port operations; improve governance and financial stability; spur innovation and digital transformation; and instil a culture of excellence in performance, safety, and service.

7. Recommendation

Future studies could examine how to apply artificial intelligence innovations to railway maintenance management and how to match existing rail network maintenance procedures with these developments. To ensure that reform benefits workers, communities, and the economy, the railway should acknowledge the significance of skill development, job preservation, and transformation.

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