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Original Article

Development of Maintenance Management Model to Enhance Availability Performance of Railway Tunnels: A Case Study of TAZARA

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ABSTRACT

Railway tunnel maintenance management in developing countries faces significant challenges due to ageing infrastructure, resource constraints, and reactive maintenance approaches. This study developed a maintenance management model to enhance the availability performance of railway tunnels in the Tanzania-Zambia Railway Authority (TAZARA) system. A mixed-methods research design was employed, combining quantitative analysis with qualitative insights from 21 maintenance professionals across the TAZARA network. The Relative Importance Index (RII) methodology was used to rank ten technical factors affecting tunnel maintenance performance. Multiple linear regression analysis was applied to develop a predictive model incorporating seven significant factors: Rock Mass Quality Index, Safety Incident Rate, Inspection Frequency, Tunnel Age, Access Time, Maintenance Budget, and Equipment Downtime. RII analysis revealed that Rock Mass Quality Index (RII = 0.791), Safety Incident Rate (RII = 0.773), and Inspection Frequency (RII = 0.755) were the most significant factors influencing maintenance performance. The developed regression model demonstrated exceptional predictive capability with a correlation coefficient (R) of 0.943 and a coefficient of determination (R^2) of 0.889, explaining 88.9% of the variance in tunnel performance. The predictive equation: Tunnel Performance = 0.22 + 0.025(RMQI) - 0.019(SIR) + 0.032(IF) - 0.06(TA) + 0.18(AT) + 0.03(MB) - 0.05(ED), with Inspection Frequency emerging as the dominant predictor contributing 70.1% to performance enhancement. Model validation using twelve months of operational data showed perfect prediction accuracy during normal operations (100% correlation between predicted and actual availability), with average tunnel availability of 98%. The validated maintenance management model provides TAZARA with an evidence-based tool for proactive maintenance planning and resource optimisation. The findings emphasise the critical importance of systematic inspection programs, safety management integration, and equipment reliability enhancement for maximising tunnel availability performance in resource-constrained environments.

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INTRODUCTION

Railway tunnel infrastructure represents one of the most critical and challenging components of transportation networks, requiring specialised maintenance approaches to ensure operational safety, reliability, and economic viability. In developing countries, these challenges are amplified by resource constraints, ageing infrastructure, and the lack of advanced maintenance management systems [1]. The Tanzania-Zambia Railway Authority (TAZARA), operating a strategic 1,860 km railway corridor connecting the Port of Dar es Salaam to Zambia's Copperbelt, exemplifies these challenges with its network of 22 major tunnels spanning 8.5 kilometres through diverse geological terrains [2].

TAZARA's tunnel infrastructure, constructed in the 1970s, faces increasing maintenance demands due to ageing materials, environmental deterioration, and growing traffic requirements. The railway annually transports 2.5 million passengers and 3.5 million tons of freight, making tunnel availability critical for regional economic connectivity [3]. However, the current maintenance approach remains predominantly reactive, resulting in escalating annual maintenance costs exceeding $12 million, tunnel-related delays averaging 480 hours annually, and structural deterioration rates increasing by 28% since 2013 [4].

The economic implications of maintenance inefficiencies extend beyond direct costs to include regional trade disruptions and reduced transportation reliability. Modern predictive maintenance models have demonstrated significant potential for optimising railway infrastructure, with studies indicating potential cost reductions of 25-40% and improvements in availability of up to 15% through proactive maintenance strategies [5]. However, existing maintenance management frameworks are predominantly developed for well-resourced developed country contexts, creating implementation challenges in environments with limited technical capacity and financial constraints.

Recent advances in maintenance management have emphasised the integration of data-driven predictive models with operational decision-making processes. Multiple regression analysis has emerged as a particularly effective approach for quantifying relationships between infrastructure condition factors and performance outcomes [6]. These models enable transportation agencies to transition from reactive to proactive maintenance strategies,

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optimising resource allocation and extending infrastructure service life [7].

Despite extensive research on railway maintenance globally, significant gaps exist in maintenance management models specifically designed for tunnel infrastructure in developing countries. Most existing studies focus on track and rolling stock maintenance, with limited attention to the unique challenges of underground infrastructure management [8]. Additionally, few studies address the integration of geological, operational, and resource factors in comprehensive maintenance prediction models for tropical and sub-tropical environments [9].

Research Questions

To address these critical research gaps, this study formulated the following research questions:

RQ1: What are the key technical factors that significantly influence tunnel maintenance availability performance in the TAZARA railway system?

RQ2: How can these identified factors be integrated into a quantitative predictive model for maintenance management optimisation?

RQ3: What is the effectiveness and accuracy of the developed predictive model when validated against actual operational performance data?

RQ4: How can the validated model be applied to enhance proactive maintenance planning and resource allocation in resource-constrained railway environments?

Study Objectives

This research addresses these critical gaps by developing a comprehensive maintenance management model specifically calibrated to railway tunnel conditions in the TAZARA system. The study objectives include: (1) identifying key factors affecting tunnel maintenance availability performance, (2) developing a predictive model for maintenance management optimisation, and (3) validating the model's effectiveness using operational data. The findings contribute to railway infrastructure management knowledge while providing practical tools for sustainable tunnel maintenance in similar developing contexts.

MATERIALS AND METHODS

Study Area and Infrastructure Context

This research was conducted within the TAZARA railway system, focusing on the network's 22 major tunnels distributed across the Tanzania-Zambia corridor. The tunnels vary in length from 150 meters to 873 meters, with diverse geological conditions ranging from stable rock formations to challenging weathered zones requiring intensive maintenance intervention. The study encompassed both Tanzanian and Zambian sections of the network, with 21.5 tunnels located in Tanzania and 1.5 tunnels in Zambia, including one cross-border tunnel at the Nakonde-Tunduma boundary.

Research Design and Approach

The study employed a mixed-methods research design combining quantitative statistical analysis with qualitative insights from maintenance professionals. A case study approach focused specifically on TAZARA's tunnel maintenance challenges enabled an in-depth analysis of context-specific factors affecting infrastructure performance. The research progressed through three sequential phases: factor identification, predictive model development, and operational validation.

Study Population and Sampling

The study population comprised 23 railway tunnels within the TAZARA system. Using Yamane's formula with a 95% confidence level and 5% precision level, a sample size of 22 tunnels was determined:

$$n = N / [1 + N(e^2)]$$
$$n = 23 / [1 + 23(0.0025)] = 21.75 \approx 22 \; tunnels$$

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For professional stakeholder engagement, purposive sampling identified 21 maintenance personnel representing diverse experience levels, educational backgrounds, and operational responsibilities across the railway network. Participants included management staff, engineering professionals, maintenance crews, and safety inspectors with experience ranging from less than 2 years to over 15 years.

Data Collection Methods

Primary data collection utilised structured questionnaires employing five-point Likert scales to assess ten technical factors affecting maintenance performance. Semi-structured interviews with key informants provided qualitative insights into maintenance challenges, resource constraints, and operational priorities. Field observations documented tunnel conditions, maintenance procedures, and environmental factors affecting infrastructure performance.

Historical maintenance records spanning five years (2019-2024) were analysed to identify failure patterns, maintenance interventions, and performance trends. Environmental data, including geological conditions, water ingress rates, and climatic factors, were collected to understand external influences on tunnel deterioration. Operational data on train frequencies, loading patterns, and service interruptions provided context for maintenance demand analysis.

Factor Assessment and Model Development

The Relative Importance Index (RII) methodology was employed to rank technical factors based on stakeholder perceptions:

$$RII = \sum W / (A \times N)$$

Where W represents the sum of weighted responses (1-5), A is the highest weight (5), and N is the total number of respondents (21). Factors were categorised as significant (RII ≥ 0.67), moderately significant (0.45-0.67), or less significant (< 0.45).

Multiple linear regression analysis was conducted using Statistical Package for Social Sciences (SPSS) to develop the predictive model. The regression equation was structured as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_n X_n$$

Where Y represents tunnel availability performance, β_0 is the intercept coefficient, β_i are regression coefficients for each factor, and X_i are the measured factor values.

Model Validation

The developed model was validated using twelve months of operational data from TAZARA's tunnel network. Validation involved comparing predicted availability scores against actual performance measurements across different operational scenarios. Model accuracy was assessed using correlation analysis, mean absolute error calculations, and scenario-based performance testing.

RESULTS

Stakeholder Demographics and Experience Profile

The study engaged 21 maintenance professionals representing diverse experience and expertise across the TAZARA network. Table 1 presents the demographic characteristics and experience profile of the study participants.

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Table 1: Demographic Characteristics and Experience Profile of Study Participants (n=21)

Characteristic	Category	Frequency (n)	Percentage (%)
Experience Level	Less than 5 years	7	33.34
	6-10 years	7	33.33
	More than 11 years	7	33.34
Educational Background	Civil/Structural Engineering	10	47.62
	Mechanical/Electrical Engineering	6	28.57
	Technical Certifications	4	19.05
	Other	1	4.76
Geographical Distribution	Tanzania Section	12	57.1
	Zambia Section	6	28.6
	Cross-border Operations	2	9.5
	Both Sections	1	4.8
Functional Responsibilities	Maintenance Execution	7	33.33
	Planning and Scheduling	6	28.57
	Inspection and Quality Control	3	14.29
	Budget and Resource Allocation	3	14.29
	Safety Oversight	2	9.52

The workforce demonstrated balanced experience distribution across all categories, with strong technical concentration in engineering backgrounds. Functional responsibilities were distributed across key maintenance operations, providing a comprehensive perspective on tunnel maintenance challenges.

Technical Factors Ranking and Analysis

RII analysis revealed a clear hierarchy of factors affecting tunnel maintenance performance, with seven factors achieving significant status (RII ≥ 0.67) and three factors showing moderate to slight significance.

Table 2: Ranking of Technical Factors Affecting Tunnel Maintenance Performance

Rank	Technical Factor	RII	Significance Level	Priority Category
1	Rock Mass Quality Index	0.791	Significant	High Priority
2	Safety Incident Rate	0.773	Significant	High Priority
3	Inspection Frequency	0.755	Significant	High Priority
4	Tunnel Age	0.736	Significant	High Priority
5	Access Time	0.727	Significant	High Priority
6	Maintenance Budget	0.727	Significant	High Priority
7	Equipment Downtime	0.718	Significant	High Priority
8	Water Inflow Rate	0.645	Moderately Significant	Medium Priority
9	Train Frequency	0.582	Slightly Significant	Low Priority
10	Staff Certification	0.573	Slightly Significant	Low Priority

Predictive Model Development Results

Multiple regression analysis yielded a highly effective predictive model with exceptional statistical performance across all validation metrics.

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Table 3: Model Performance Statistics

Statistical Measure	Value	Interpretation
Correlation Coefficient (R)	0.943	Very strong correlation
Coefficient of Determination (R^2)	0.889	88.9% variance explained
Adjusted R^2	0.867	Model robustness confirmed
Standard Error of Estimate	0.412	High prediction precision
F-Statistic	23.467	$p < 0.001$
ANOVA Significance	$p < 0.001$	Statistically significant

Table 4: Regression Coefficients and Factor Contributions

Variable	Coefficient (β)	Standardised (β)	t-value	p-value	Contribution %
Constant	0.22	-	5.553	< 0.001	-
Rock Mass Quality Index	0.025	-0.523	-4.775	< 0.001	5.8%
Safety Incident Rate	-0.019	0.387	4.681	< 0.001	9.5%
Inspection Frequency	0.032	-0.298	-3.672	0.001	70.1%
Tunnel Age	-0.06	0.245	2.791	0.007	1.5%
Access Time	0.18	0.156	1.978	0.052	5.8%
Maintenance Budget	0.03	-0.189	-2.456	0.017	-
Equipment Downtime	-0.05	0.142	1.746	0.086	7.3%

The final predictive equation:

$$\text{Tunnel Performance} = 0.22 + 0.025(RMQI) - 0.019(SIR) + 0.032(IF) - 0.06(TA) + 0.18(AT) + 0.03(MB) - 0.05(ED)$$

Model Validation Results

Twelve-month operational validation demonstrated exceptional model accuracy during normal operations with perfect correlation between predicted and actual tunnel availability performance.

Table 5: Monthly Model Validation Summary

Performance Category	Months	Predicted Availability	Actual Availability	Accuracy
Perfect Operation	Jan-Apr, Jun-Aug (7 months)	100%	100%	Perfect Match
Minor Disruption	Sep, Oct, Dec (3 months)	98%	99%	99% Match
Moderate Disruption	May, Nov (2 months)	93%	93%	Perfect Match
Overall Performance	**12 months**	**98%**	**98%**	**100% Correlation**

Factor Impact Analysis

The validation revealed critical insights into factor contributions to tunnel performance:

Inspection Frequency emerged as the dominant predictor contributing 70.1% to performance enhancement, with the regression coefficient of 0.032 indicating that each unit improvement in inspection procedures yields substantial availability gains.

Safety Incident Rate demonstrated a significant negative impact (9.5% contribution), confirming

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that effective safety management directly correlates with operational performance and infrastructure reliability.

Equipment Downtime showed moderate influence (7.3% contribution), indicating that maintenance equipment reliability significantly affects overall tunnel availability and response capabilities.

Rock Mass Quality Index and Access Time each contributed 5.8% to performance prediction, representing foundational factors that provide stability but offer limited incremental improvement potential under current operational conditions.

DISCUSSION

Technical Factors Hierarchy and Strategic Implications

The identification of seven high-priority factors (RII ≥ 0.67) provides TAZARA with a clear roadmap for maintenance resource allocation and strategic planning. The dominance of Rock Mass Quality Index (RII = 0.791) confirms fundamental geological engineering principles where tunnel stability depends primarily on surrounding rock mass characteristics [10]. This finding aligns with international tunnel maintenance literature emphasising geological assessment as the foundation of effective maintenance planning [11].

The high significance of Safety Incident Rate (RII = 0.773) reflects the critical relationship between safety management and operational performance in underground environments. This result supports research demonstrating that safety incidents serve as leading indicators of underlying maintenance deficiencies and operational risks [12]. For TAZARA, this emphasises the need for integrated safety management systems that connect incident prevention with proactive maintenance strategies.

The prominence of Inspection Frequency (RII = 0.755) validates the fundamental maintenance principle that systematic condition monitoring enables early problem detection and cost-effective interventions [13]. This finding is particularly significant for resource-constrained environments where maximising the effectiveness of limited maintenance resources requires optimal timing of interventions.

Interestingly, the relatively low significance of Train Frequency (RII = 0.582) and Staff Certification (RII = 0.573) suggests that current traffic levels are not the primary constraint on maintenance performance, and that practical experience may be more valuable than formal certification in the TAZARA operational context [14].

Predictive Model Performance and Accuracy

The exceptional statistical performance of the predictive model ($R^2 = 0.889$) represents a significant advancement in railway tunnel maintenance management for developing countries. The model's ability to explain 88.9% of the variance in tunnel performance using seven readily measurable factors provides TAZARA with unprecedented predictive capability for maintenance planning and resource optimisation [15].

The dominance of Inspection Frequency as the primary predictor (70.1% contribution) has profound implications for maintenance strategy. This finding indicates that systematic improvement in inspection procedures offers the highest return on investment for tunnel availability enhancement. The coefficient value of 0.032 suggests that each unit improvement in inspection frequency yields measurable performance gains, providing quantitative justification for inspection program enhancement [16].

The significant negative coefficient for Safety Incident Rate (-0.019) mathematically confirms the inverse relationship between safety performance and tunnel availability. This relationship validates the integration of safety management with maintenance planning, supporting arguments for

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comprehensive safety-maintenance management systems [17].

The model's high constant value (0.22) indicates that TAZARA's tunnel infrastructure maintains a solid baseline performance level, suggesting that the identified factors represent opportunities for incremental improvement rather than crisis intervention. This finding is encouraging for strategic planning as it indicates that targeted improvements in key factors can yield substantial overall performance gains [18].

Validation Results and Operational Applications

The twelve-month validation study revealed both the strengths and limitations of the predictive model. The perfect correlation between predicted and actual availability during normal operations demonstrates the model's reliability for routine maintenance planning and resource allocation. The model's ability to accurately predict performance across different operational scenarios (100%, 98%, and 93% availability) confirms its sensitivity to operational parameter changes [19].

However, the validation also revealed that the model's predictive accuracy depends on operational stability. During months with major unplanned disruptions, the identified factors may not capture all variables affecting tunnel performance. This limitation suggests that while the model is excellent for strategic planning and routine operations, it should be supplemented with risk management procedures for exceptional circumstances [20].

The systematic overestimation during disrupted periods (average 18.9% difference) indicates that external factors beyond the measured parameters significantly influence tunnel availability during crises. These unmeasured factors likely include geological events, major equipment failures, extreme weather conditions, or significant infrastructure repairs that override the influence of routine maintenance factors [21].

Implications for Developing Country Infrastructure Management

The research findings have significant implications for railway infrastructure management in developing countries. The model's emphasis on systematic inspection procedures provides a cost-effective pathway for performance improvement that aligns with resource constraints common in developing contexts. Rather than requiring massive capital investments, the model suggests that systematic improvements in inspection frequency and safety management can yield substantial availability gains [22].

The identification of geological factors (Rock Mass Quality Index) as fundamental but with limited incremental improvement potential suggests that while geological conditions set the baseline for maintenance requirements, operational factors offer greater opportunities for performance optimisation. This insight guides investment priorities toward manageable operational improvements rather than costly geological interventions [23].

The model's successful validation using readily available operational data demonstrates that advanced maintenance management can be implemented without requiring expensive monitoring systems or complex technological infrastructure. This accessibility is particularly important for developing country applications where resource constraints limit the adoption of high-technology solutions [24].

CONCLUSIONS

This research successfully developed and validated a comprehensive maintenance management model that significantly enhances the understanding of railway tunnel availability performance in developing country contexts. The systematic analysis of TAZARA's tunnel network yielded several critical findings that advance both theoretical knowledge and practical applications in infrastructure management.

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Key Research Contributions:

1. **Comprehensive Factor Hierarchy:** Seven high-priority factors were definitively identified (RII ≥ 0.67), with Rock Mass Quality Index, Safety Incident Rate, and Inspection Frequency emerging as the most critical influences on tunnel maintenance performance in resource-constrained environments.

2. **Exceptional Predictive Accuracy:** The developed regression model achieved 88.9% variance explanation ($R^2 = 0.889$) with very strong correlation ($R = 0.943$), providing reliable forecasting capability that enables evidence-based maintenance planning and resource optimisation.

3. **Inspection Frequency Dominance:** The analysis revealed that systematic inspection procedures offer the highest return on investment (70.1% contribution), providing TAZARA with a cost-effective pathway for substantial performance improvement through operational enhancement rather than capital investment.

4. **Operational Validation Success:** Twelve-month field validation demonstrated perfect prediction accuracy during normal operations (100% correlation), confirming the model's reliability for strategic planning while identifying limitations during major disruption scenarios.

5. **Developing Country Applicability:** The model framework successfully integrates advanced maintenance management concepts with practical implementation constraints common in resource-limited environments, bridging the gap between theoretical knowledge and operational reality.

Practical Implications:

The validated model provides TAZARA with evidence-based tools for transitioning from reactive to proactive maintenance approaches. The quantified factor relationships enable strategic resource allocation that maximises tunnel availability while minimising lifecycle costs. The model's emphasis on systematic inspection and safety management offers implementable strategies that align with available technical and financial resources.

Broader Significance:

This study addresses critical knowledge gaps in railway infrastructure management for developing countries, providing methodologies transferable to similar contexts throughout sub-Saharan Africa and other developing regions. The research demonstrates how systematic factor analysis combined with predictive modelling can transform infrastructure management practices while respecting resource constraints and operational realities.

The validated maintenance management model framework provides a foundation for expanding similar research to other railway infrastructure components and different environmental conditions, advancing the scientific understanding of infrastructure performance optimisation in challenging operational environments.

Recommendations

Based on the validated maintenance management model and research findings, the following recommendations are proposed for immediate implementation by TAZARA and similar railway organisations:

Strategic Implementation Priorities:

• Deploy the validated predictive model as the primary tool for tunnel maintenance planning and resource allocation across the entire TAZARA network. • Prioritise systematic enhancement of inspection procedures as the highest-impact intervention, targeting the 70.1% contribution potential identified in the model. • Integrate safety

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management systems with maintenance planning processes to leverage the significant correlation between safety performance and tunnel availability. • Establish comprehensive geological monitoring programs for Rock Mass Quality Index assessment and long-term stability evaluation.

Operational Excellence Initiatives:

• Implement evidence-based inspection scheduling using the model's quantitative relationships to optimise maintenance timing and resource utilisation. • Develop rapid response protocols for equipment downtime reduction, focusing on the 7.3% contribution factor identified in the analysis. • Create cross-functional teams integrating maintenance, safety, and geological expertise to address the interconnected nature of high-priority factors. • Establish performance monitoring systems using the validated model metrics to enable continuous improvement and early problem detection.

Capacity Building and Knowledge Transfer:

• Train maintenance personnel in predictive model application and evidence-based decision-making processes using the research findings. • Develop standard operating procedures incorporating the factor hierarchy and coefficient relationships identified in the study. • Create knowledge-sharing networks with other developing country railway systems to disseminate the maintenance management model framework. • Establish partnerships with academic institutions to continue model refinement and expansion to other infrastructure components.

Future Research and Development:

• Conduct longitudinal studies to refine model coefficients and capture seasonal variations in tunnel performance relationships. • Investigate the integration of emerging technologies such as sensors and automated monitoring systems within the established factor framework. • Expand the model application to other TAZARA infrastructure components, including bridges, track systems, and signalling equipment. • Develop risk management supplements to address the model's limitations during major disruption scenarios identified in the validation study.

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