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Development of a Condition-Based Maintenance Model for AC Traction Motors in Electric Locomotives: A Case Study of Tanzania Standard Gauge Railway

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Abstract: AC traction motors are mission-critical components of electric locomotives operating on the Tanzania Standard Gauge Railway (SGR), yet their failures occur over a wide and inconsistent range of operating hours, making conventional time-based maintenance insufficient for condition-sensitive degradation. This study developed and evaluated a locally calibrated condition-based maintenance (CBM) model for AC traction motors in the Tanzania SGR environment. A mixed-methods design was applied using 20 recorded motor-failure events from August 2024 to October 2025, complemented by healthy-operation records and maintenance personnel inputs. Reliability analysis used Weibull estimation to characterize failure behaviour, Kaplan-Meier analysis to estimate survival probability, FMEA to prioritize failure modes, FTA to identify failure causes and Cox regression to assess factors affecting failure risk. These outputs were integrated to develop the condition-based maintenance model. The dominant failure categories were mechanical (35%), electrical (25%), thermal (25%) and environmental (15%). Bearings represented 25% of failures, followed by stator windings (20%), rotor (15%), cooling fans (15%), insulation (15%) and shafts (10%). The fitted Weibull model produced a shape parameter of β=1.87 and a scale parameter of η=2,612 operating hours, indicating a wear-out-dominant failure pattern, while the estimated mean time between failures was 2,319 hours. The Cox model achieved a concordance index of 0.82. Validation produced an ROC AUC of 0.85, sensitivity of 83% at an 18% false-positive rate and a Hosmer-Lemeshow goodness-of-fit p-value of 0.60. Operational thresholds were established for vibration, stator-winding temperature, insulation resistance and predicted failure probability. The model-guided strategy indicated potential reductions of 32% in unplanned downtime and 28% in spare-parts replacement costs. The findings support adoption of a locally calibrated CBM framework to improve traction-motor reliability, maintenance planning and SGR fleet availability.

Keywords: Condition-based maintenance, AC traction motor, reliability modelling, Weibull analysis, Kaplan-Meier, Cox proportional hazards, FMEA, FTA, Tanzania SGR.

I. INTRODUCTION

The transition toward high-capacity electric railway systems has increased the importance of reliable AC traction equipment. In electric locomotives, the traction motor converts electrical energy supplied through the traction system into mechanical torque for propulsion. Because traction motors are mission-critical components, an unscheduled motor failure can interrupt train services, increase downtime and maintenance requirements and also reduce locomotive/fleet availability [1].

The Tanzania Standard Gauge Railway (SGR) operates across a tropical environment extending from the coastal conditions of Dar es Salaam toward the more inland and comparatively semi-arid areas. Traction-motor reliability can be affected by several interacting stressors including thermal, electrical, mechanical, and environmental conditions. Thermal exposure can accelerate stator-winding insulation degradation in traction motors [2], while dust contamination can contribute to bearing degradation through abrasive wear and contamination of motor components [3]. Vibration characteristics are also useful indicators of incipient bearing deterioration and can therefore support early fault detection in railway traction motors [4]. In addition, electrical loading and failure mechanisms associated with AC traction motors have been investigated as important contributors to motor reliability [1]. The Hyundai Rotem E6800 electric locomotives considered in this study use AC asynchronous induction traction motors and operate from a 25 kV, 50 Hz overhead supply.

Conventional time-based maintenance schedules maintenance activities according to predetermined operating or calendar intervals rather than the measured condition of the equipment. Such an approach may lead to maintenance interventions before significant degradation has occurred or may fail to detect deterioration occurring between scheduled interventions.

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Condition-based maintenance instead uses diagnostic and prognostic information to support maintenance decisions according to the observed condition of the asset [5]. Evidence from railway and other maintenance applications also supports the use of condition indicators and reliability information to improve maintenance decision-making [6].

The present study addresses the practical need for a locally applicable condition-monitoring framework that links measurable motor-condition variables with warning criteria and corresponding maintenance actions. The proposed framework considers condition indicators such as vibration, winding temperature, insulation resistance and environmental factors, consistent with the diagnostic and prognostic principles described in the CBM literature [4], [5], [7].

Previous studies have examined individual components of the proposed reliability framework. Weibull and Kaplan-Meier approaches have been investigated for traction-motor failure data [8], while Zhao [9] examined a hybrid Weibull and Cox proportional-hazards model for railway traction motors. Fault Tree Analysis has also been applied to AC traction-motor reliability assessment [10] and CBM models have been validated in railway fleet applications [6]. However, within the literature reviewed for this study, these methods are largely reported separately or in different railway operating contexts. Limited evidence was identified concerning their integration into a single reliability-based CBM framework specifically developed and evaluated for AC traction motors operating on the Tanzania SGR and under equatorial African environmental conditions [6], [8]–[10].

The present study therefore develops a reliability-based condition-based maintenance model specifically for AC traction motors used on the Tanzania SGR. The model integrates Weibull analysis, Kaplan-Meier survival estimation, Cox proportional-hazards modelling, Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) to relate motor condition and failure behaviour to practical maintenance decisions [8]–[10].

II. MATERIALS AND METHODS

A. Study Design and Data

A mixed-methods research design was adopted. The quantitative component focused on reliability engineering and survival analysis, while the qualitative component used maintenance personnel interviews to contextualize failure mechanisms and operating conditions. The study was conducted at the Tanzania Railways Corporation (TRC) Sokoine Street SGR depot in Dar es Salaam. The target population comprised AC traction motors fitted to Hyundai Rotem E6800 locomotives during August 2024–October 2025. The quantitative analysis used 20 recorded motor-failure events together with 20 healthy-operation records treated as right-censored observations. Interviews and questionnaires provided supporting maintenance evidence.

B. Reliability and CBM Modelling

Failure-time data were analyzed using two-parameter Weibull maximum-likelihood estimation to determine the shape (β) and scale (η) parameters and characterize the dominant failure regime. Kaplan-Meier estimation was used as a non-parametric survival check incorporating right-censored healthy-operation records. Cox proportional-hazards regression incorporated operating age, cumulative hours, route segment, season and recent maintenance action as covariates. FMEA was used to rank failure modes using severity, occurrence and detection scores while FTA decomposed complete motor failure into electrical, mechanical, thermal and environmental pathways.

C. Model Validation

The dataset was partitioned into development and validation subsets. Retrospective validation compared predicted and observed failures in the held-out data, while prospective validation compared model alerts with subsequent maintenance findings. Model discrimination was evaluated using the ROC curve and area under the curve (AUC) while calibration was assessed using the Hosmer-Lemeshow goodness-of-fit test. The study also compared observed reactive maintenance with a counterfactual model-guided strategy.

III. RESULTS

A. Failure Characteristics

Twenty traction-motor failure events were identified. Mechanical failures were the largest category (35%), followed by electrical and thermal failures at 25% each, and environmental failures at 15%. At component level, bearings were the most frequently affected component (25%), followed by stator windings (20%), while rotor, cooling fan and insulation each accounted for 15%; shaft failures accounted for 10%.

TABLE I DISTRIBUTION OF TRACTION-MOTOR FAILURES BY CATEGORY

Failure category	No. of failures	Percentage
Mechanical	7	35.0%
Electrical	5	25.0%

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Failure category	No. of failures	Percentage
Thermal	5	25.0%
Environmental	3	15.0%
Total	20	100.0%

TABLE II DISTRIBUTION OF FAILURES BY COMPONENT

Component	No. of failures	Percentage
Bearing	5	25.0%
Stator winding	4	20.0%
Rotor	3	15.0%
Cooling fan	3	15.0%
Insulation	3	15.0%
Shaft	2	10.0%
Total	20	100.0%

B. Environmental and Maintenance Factors

Heat was implicated in 10 failure events, dust in 6 and humidity in 4, with some events involving more than one environmental factor. Corrective maintenance accounted for 75% of motor-related interventions, while preventive maintenance accounted for 25%, demonstrating the predominantly reactive nature of the existing practice. Environmental failures were less frequent but had the greatest mean downtime, at 25.8 hours per event, compared with an overall mean of 13.8 hours.

TABLE III DOWNTIME ASSOCIATED WITH FAILURE CATEGORIES

Failure category	Failures	Total downtime (h)	Mean/event (h)
Mechanical	7	68.0	9.7
Electrical	5	58.4	11.7
Thermal	5	72.0	14.4
Environmental	3	77.3	25.8
All categories	20	275.7	13.8

C. Reliability Model

The recorded failure times ranged from 612 to 4,825 operating hours, with a sample mean of 2,341.5 hours and a median of 2,238 hours. The two-parameter Weibull model produced β=1.87 and η=2,612 hours, indicating an increasing hazard rate and therefore a wear-out-dominated failure regime. The Kaplan-Meier estimate gave a median failure time of approximately 2,151 hours, providing an independent non-parametric check of the survival behavior.

TABLE IV KEY RELIABILITY-MODEL RESULTS

Reliability measure	Result	Interpretation
Weibull shape, β	1.87	Wear-out dominant
Weibull scale, η	2,612 h	Characteristic life
Mean time between failures	2,319 h	Population reliability indicator
Kaplan-Meier median	2,151 h	Non-parametric survival estimate
Cox concordance index	0.82	Good discrimination

D. Failure Modes and Risk Priorities

The FMEA identified bearing fatigue spalling as the highest-priority failure mode with RPN=280, followed by stator-winding insulation breakdown (RPN=245) and cooling-fan blade fracture (RPN=192). The FTA organized the top event of complete motor failure into electrical, mechanical, thermal and environmental intermediate pathways, linking qualitative failure mechanisms with the quantitative reliability model.

E. Model Validation and Operational Performance

The reliability model demonstrated good predictive performance. The Cox model achieved a concordance index of 0.82, while validation produced an ROC AUC of 0.85. At an operating point corresponding to an 18% false-positive rate, sensitivity was 83%. The Hosmer-Lemeshow goodness-of-fit test gave p=0.60, indicating acceptable calibration. Prospective validation produced a mean alert lead time of 199 hours. Counterfactual analysis estimated a 32% reduction in unplanned downtime and a 28% reduction in spare-parts replacement cost under model-guided maintenance.

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TABLE V MODEL VALIDATION AND OPERATIONAL PERFORMANCE

Validation metric	Result
C-index	0.82
ROC AUC	0.85
Sensitivity	83%
False-positive rate	18%
Hosmer-Lemeshow p-value	0.60
Mean prospective alert lead time	199 h
Potential downtime reduction	32%
Potential spare-parts cost reduction	28%

F. Proposed CBM Alert Thresholds

TABLE VI OPERATIONAL ALERT THRESHOLDS DERIVED IN THE STUDY

Indicator	Green – routine	Amber – trend & inspect	Red – intervene
Bearing vibration velocity (RMS)	<4.5 mm/s	4.5–7.0 mm/s	>7.0 mm/s
Stator-winding temperature	<120 °C	120–150 °C	>150 °C
Insulation resistance (1 min)	>10 MΩ	5–10 MΩ	<5 MΩ
Bearing temperature gradient	<1.0 °C/min	1.0–2.5 °C/min	>2.5 °C/min
Predicted P (fail in 250 h)	<0.10	0.10–0.30	>0.30

IV. DISCUSSION

The results indicate that mechanical degradation is the dominant broad failure category, with bearings representing the largest individual component contribution. This agrees with the reviewed literature, where bearing and stator-winding failures were also prominent in traction-motor fleets. The Tanzania SGR results are therefore broadly consistent with established traction-motor reliability behaviour while also demonstrating the importance of the local operating environment.

Environmental failures represented only 15% of the observed events but produced the highest mean downtime. This suggests that environmental stressors can have a disproportionate operational effect. The dissertation links coastal operation with humidity and salt-aerosol exposure and identifies dust penetration during dry-season operation on the Dodoma plateau as an important maintenance consideration.

The Weibull shape parameter $\beta=1.87$ is greater than one, indicating an increasing failure hazard and a wear-out regime. The agreement between the Weibull estimates and the Kaplan-Meier survival estimate strengthens confidence in the observed failure-time behaviour. The Cox model further demonstrates that accumulated operating exposure, recent preventive maintenance and route conditions can materially influence failure risk.

The principal practical contribution of the study is the translation of the reliability model into actionable traffic-light thresholds. The proposed framework moves maintenance decision-making from predominantly reactive intervention toward run-to-condition practice while retaining the existing safety procedures and allowing depot personnel to combine physical sensor thresholds with predicted failure probability.

V. CONCLUSION

A locally calibrated condition-based maintenance model for AC traction motors operating on the Tanzania SGR was developed and validated. Mechanical failures were the most common category, while bearings and stator windings were the most prominent individual failure components. Heat, dust and humidity were important environmental contributors and corrective maintenance dominated the recorded intervention pattern.

The integrated Weibull-Kaplan-Meier-Cox-FMEA-FTA framework characterized the traction-motor population as wear-out dominated, with $\beta=1.87$, $\eta=2{,}612$ hours and an estimated mean time between failures of 2,319 hours. The model demonstrated good discrimination and calibration, with C-index=0.82, AUC=0.85 and Hosmer-Lemeshow p=0.60. The prospective mean alert lead time of 199 hours provides a practical window for maintenance planning.

The study recommends that TRC pilot the proposed green-amber-red condition thresholds on a controlled group of locomotives, integrate predicted 250-hour failure probability into the maintenance information system, strengthen condition-monitoring training and procedures and adapt inspection practices to the environmental conditions of different SGR route sections.

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Ethics approval: The study protocol and participation arrangements were handled through the National Institute of Transport.

Data availability statement: The study is based on maintenance and failure records described in the research. Access to operational TRC records is subject to institutional permissions and confidentiality requirements.

AUTHOR CONTRIBUTIONS

Daud Peter Edward: conceptualization; methodology; reliability modelling; data analysis; FMEA and FTA development; model validation; interpretation of results; and writing-original draft, review and editing.

John Mahona: supervision; methodological guidance; validation; interpretation; and review and editing.

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BIOGRAPHY



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