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Application of Reliability-Centered Maintenance with a Computerized Maintenance Management System for the Wheelset in Rolling Stock

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ABSTRACT

Maintenance plays an important role in ensuring the reliability and safety of rolling stock in the railway sector. This study focuses on the application of an integrated Reliability-Centered Maintenance (RCM) and Computerized Maintenance Management System (CMMS) for wheelsets in a wheel profiling measurement system. The combined use of RCM and CMMS helps optimize key reliability indices, such as Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), and Availability. The results demonstrate that automation enhances performance, with MTBF increasing from 500 to 800 hours and MTTR decreasing from 8 to 4 hours. Additionally, CMMS improved inventory management efficiency from 60% to 90% and reduced emergency repairs, resulting in annual savings of ₹2,325,000. Despite the higher initial investment of ₹6,375,000, automation proved more cost-effective over a five-year period. Furthermore, system availability increased from 97.3% to 99.1%, minimizing downtime and improving operational efficiency. These findings have been shared with the maintenance manager of the system under study for further implementation and testing.

1. Introduction

In today's urban transportation scene, metro systems must be safe, reliable, and efficient. Metro systems, with their high frequency service and dense passenger loads, require rigorous maintenance techniques to assure smooth operation. The wheel profile measuring system is an essential component of metro maintenance that helps to keep the wheels in good condition. The condition of these wheels has a direct influence on the entire performance and safety of metro operations, making it critical to apply advanced maintenance procedures.

Reliability Centred Maintenance is a systematic strategy that focuses on identifying and implementing the most effective maintenance procedures to make sure that systems continue to function as intended. The fundamental goals of RCM are to improve equipment reliability, assure safety, and optimize maintenance costs. The RCM process consists of many essential processes, including identifying functions and potential failures, performing Failure Mode and Effects Analysis, developing maintenance plans, and executing and monitoring those strategies. RCM aids in the

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prioritization of maintenance tasks by identifying the system's essential functions as well as potential failure modes that might impair performance. FMEA also examines the consequences of each identified failure mode to identify its influence on system performance, safety, and cost, enabling for the formulation of focused maintenance programs that may include preventative, predictive, and corrective maintenance actions. These strategies are then executed, regularly reviewed for effectiveness, and adjusted as desired.

A Computerized Maintenance Management System is a sophisticated software solution that simplifies and automates maintenance management processes. Asset management, work order management, preventative maintenance scheduling, inventory management, and reporting and analysis are among the features provided by CMMS. Asset management entails maintaining complete records on all assets, including specifications, maintenance history, and performance data. Work order management facilitates the effective development, assignment, tracking, and execution of work orders. Preventive maintenance scheduling automates the scheduling of routine maintenance procedures to avoid equipment failure. Inventory management records and maintains spare and materials required for maintenance tasks, whereas reporting and analysis provide thorough reports and analytics for monitoring maintenance performance and making data-driven choices.

Integrating RCM with a CMMS may significantly enhance metro maintenance management. This integration enables a more systematic and data-driven approach to maintenance by integrating the strategic framework of RCM with the operational efficiency of a CMMS. The primary advantages of this integration are increased reliability and safety, optimized maintenance costs, and better decision-making. By concentrating on the most critical failure modes and adopting effective maintenance strategies, metro systems' reliability and safety are improved. Efficient scheduling and execution of maintenance chores reduces downtime and needless maintenance actions, resulting in cost savings. The CMMS provides detailed data and analytics to assist informed decision-making and continual improvement in maintenance processes. In the context of metro systems, the wheel profile measuring system is critical for keeping wheels in good condition. Metro wheels suffer severe wear and tear owing to their high frequency of use, which can have an influence on their profile and, as a result, the safety and efficiency of metro operations. There are numerous critical stages to using RCM with a CMMS in wheel profiling. First, the vital tasks of the wheel profiling system must be identified, as well as any potential failure modes that may impair wheel performance. Conducting FMEA involves analysing the impact of each failure mode on wheel performance and safety and determining the most critical failure modes to address. The next step is to create maintenance strategies tailored to the identified failure modes, which will include regular inspections, predictive maintenance based on sensor data, and corrective actions as needed. Finally, employing a CMMS to schedule and monitor maintenance jobs, manage inventories, and analyse maintenance data promotes continuous improvement.

By applying RCM with a CMMS to the wheel profiling measurement system, metro operators can ensure that wheels are maintained in optimal condition, thereby enhancing the overall reliability, safety, and efficiency of metro operations. This integrated method not only improves the life of the wheelsets, but also helps the metro network run smoothly and safely. The appropriate maintenance of wheelsets using innovative technology and methodical procedures is crucial in lowering the risk of accidents, reducing downtime, and maintaining the high standards anticipated of modern urban transportation systems. As metro systems continue to evolve and expand, the implementation of RCM combined with a robust CMMS will become increasingly vital in maintaining operational excellence and delivering reliable and safe transportation services to the public.

1.1. Literature Background

In the past, various researchers have implemented RCM for different industrial systems i.e Rezvanizaniani et al. [1] studied the implementation of RCM to make maintenance of rolling stock of the Raja Passenger Train Corporation for more cost effective. They implemented RCM for the wheel sets which is the most critical subsystem from the rolling stocks reliability point of view. Ciani et al. [2] concluded that RCM is a well-established method for preventive maintenance planning. Moreover, the authors focused on the optimization of a maintenance plan for an HVAC (Heating, Ventilation and Air conditioning) system located on high-speed trains. Cheng et al. [3] investigated the method for rolling stock's maintenance strategy selection that allows for the consideration of important interaction among the decision levels and criteria. Hidayat and Mahardiono et al. [4] analyzed to evaluate the equipment in Depot and Workshop in support of rolling stock equipment maintenance to fulfillment and achievement of maintenance goals. Panchal et al. [5] investigated the proposed framework employs intuitionistic fuzzy (IF) theory-based MCDM approaches, specifically IF-AHP and IF-TOPSIS, to handle uncertainty in maintenance decision-making. By incorporating expert hesitation, it enhances accuracy in selecting the optimal maintenance policy based on six criteria: safety, cost, maintenance, reliability, risk, and added values. Macedo et al. [6] focused on the scheduling of preventive railway maintenance activities. The objective was to keep the railway infrastructure in good operating conditions at low costs, also taking into account the limited available resources. Panchal et al. [7] presents a two-phase Intuitionistic Fuzzy (IF) framework for reliability analysis of Turbine Unit (TU) in a sugar mill.

Alkali et al. [8] analyzed the door system of the Class 158 Diesel Multiple Unit (DMU) train fleet using the RCM approach. With over 100 components following a Weibull distribution**,** failure analysis and maintenance optimization were conducted. A piecewise Deterministic Markov Process model was proposed to enhance preventive maintenance. RCM cost analysis highlighted potential savings and critical safety considerations, allowing maintenance intervals to be extended by 10,000-mile increments if safety-critical maintenance was improved. Kushwaha et al, [9] studied the reliability based performance of system related to sugar mill industry. Ling Wang et al. [10] investigated the Train wheels experience significant wear over time, necessitating re-profiling to restore their shape despite the resulting decrease in diameter, which impacts their lifespan. This paper proposes a data-driven model, based on wear and re-profiling analysis of metro wheels, to establish relationships between wheel diameters, flange thickness, wear rates, and re-profiling gain for Guangzhou Metro Line One. Singh et al. [11] studied Reliability-Centered Maintenance as a cost-effective strategy for railway systems, improving fault detection, reliability, and efficiency. Studies highlight predictive models, remote monitoring, and AI integration, proving RCM's superiority over traditional maintenance in reducing downtime and enhancing safety. Marten Jr et al. [12] explores RCM implementation challenges in a North American rail agency, highlighting seven key themes like communication, culture, and employee impact. While reliability and safety results were mixed, rolling stock availability improved**,** offering insights for future RCM adoption. Boye et al. [13] studied South Africa's railway maintenance challenges, identifying material shortages, skilled labor gaps, track availability, and poor scheduling as key issues. It also highlights infrastructure investment, regulations, and management training as critical gaps. Despite existing policies, lack of adherence remains a concern, impacting effective maintenance execution. Asplund et al. [14] highlights early wheel wear detection using wayside monitoring to prevent track damage and reduce failures on Sweden's Iron Ore Line, improving railway capacity and maintenance efficiency. Cioboata et al. [15] The study discusses an automated wheel profile measurement system integrated into Computer Numerical Conrol (CNC) re-profiling machines to ensure railway safety by detecting wear and maintaining geometric standards through precise contact-based measurements. Rantatalo et al. [16]

studied variations in wheel flange measurements, with wayside systems showing greater inconsistencies, questioning one-slice inspection reliability. Kushwaha et al. [17] investigated a two-phase Intuitionistic Fuzzy (IF) framework for reliability analysis of a cutting system of sugar industry, using IF Lambda Tau (IFLT) expressions. Gopal et al. [18] investigated hybrid fuzzy Jaya-Based Lambda-Tau (JBLT) framework for analyzing milk processing unit reliability, showing availability declines with increasing uncertainty. Comparisons with PSOBLT and FLT techniques aid in optimizing maintenance planning. Gopal et al. [19] studied fuzzy JLTO-based system to analyze Boiler Unit failures, integrating FMEA and decision-making approaches to enhance maintenance planning and reliability. Kushwaha et al. [20] studied IF-FMEA and IF-TOPSIS-based framework to analyze failure risks in a Turbine and Alternator Unit. It improves failure cause identification and aids in optimal maintenance planning, ensuring global applicability in chemical industries.

Based on the above reviewed literature, it has been found that the implementation of RCM based wheel profiling measurement system was not yet reported by any researcher. Considering this as a base for this work, the comparative analysis of manual and automated wheel profiling measurement system has been carried under this work.

2. Methodology

The methodology comprises several phases: baseline assessment, implementation of RCM and CMMS, data collection, and comparative analysis.

2.1 Baseline Assessment

Before implementing the new systems, a thorough baseline assessment of the existing manual wheel profiling system was conducted. This involved:

- Data Collection on Existing System
  1. Measurement accuracy of the manual tools.
  2. Frequency and duration of maintenance tasks.
  3. Incident and failure reports from maintenance logs.
  4. Records of downtime associated with wheel profiling.
- Reliability Metrics
  1. Mean Time Between Failures: The average operational time between failures.
  2. Mean Time to Repair: The average time required to repair a failure.
  3. Failure Rate: The number of failures per 1,000 operational hours.
- Cost Analysis
  1. Initial investment costs for the manual system.
  2. Annual operational costs, including labour and maintenance.

2.2 Implementation of Reliability Centered Maintenance

RCM was applied to the wheel profiling process through the following steps:

- Functional Failure Analysis
  1. Identification of critical functions of the wheel sets.
  2. Determination of potential failure modes and their effects on the metro system.
- Maintenance Strategy Development
  1. Definition of preventive, predictive, and corrective maintenance tasks based on failure modes.
  2. Establishment of maintenance schedules driven by condition monitoring data.

- Integration with CMMS
  i. Configuration of the CMMS to manage and track maintenance activities.
  ii. Setting up CMMS alerts and notifications based on the RCM analysis to ensure timely maintenance actions.

2.3 Implementation of CMMS

The CMMS was deployed with the following procedures:

- System Setup and Configuration
  i. Installation of CMMS software on dedicated servers.
  ii. Configuration of user access levels and permissions to ensure data security and integrity.
- Data Integration
  i. Uploading historical maintenance data into the CMMS.
  ii. Integration of real-time data from the automated wheel profiling system to enable dynamic maintenance scheduling and tracking.
- Training
  i. Conducting training sessions for technicians and maintenance personnel to familiarize them with the CMMS interface and functionalities.
  ii. Providing user manuals and support resources for ongoing assistance.

2.4 Data Collection

Following the implementation, data was systematically collected over a specified period to evaluate the performance of both manual and automated systems under the RCM framework:

- Measurement Accuracy and Frequency
  i. Comparison of the accuracy of wheel profile measurements between manual and automated systems.
  ii. Frequency of maintenance tasks and inspections performed.
- Reliability Metrics
  i. Updating MTBF, MTTR, and failure rate data post-implementation.
  ii. Comparing the updated metrics with baseline data to assess improvements.
- Operational Costs
  i. Tracking annual labour and maintenance costs for both systems.
  ii. Calculating cost savings achieved through reduced downtime and increased maintenance efficiency.
- System Availability and Downtime
  i. Recording total annual downtime for both manual and automated systems.
  ii. Calculating system availability percentages to gauge improvements in operational uptime.

2.5 Comparative Analysis

The collected data was analysed to compare the manual and automated wheel profiling measurement systems across several key dimensions:

- Reliability Analysis
  i. Comparison of MTBF, MTTR, and failure rates to determine which system provides higher reliability.
- Maintenance Efficiency
  i. Evaluation of adherence to scheduled maintenance tasks.

ii. Assessment of the reduction in unscheduled maintenance events.

- Cost-Benefit Analysis
  i. Comparison of initial investments against long-term operational savings.
  ii. Calculation of return on investment over a 5-year period.
- Downtime and Availability
  i. Analysis of total annual downtime for each system.
  ii. Improvement in system availability and overall impact on metro operations.

3. Industrial Case and Results

For the implementation of RCM with the integration CMMS, an Industrial case-wheel profiling system of rolling stock (Metro Railways) has been considered under this work. As Metro is the lifeline of human transportation in National Capital Region (NCR) of India therefore, its availability is of supreme importance. The RCM and CMMS implementation based manual and automated wheel profiling measurement system results are as follows:

3.1 Manual wheel profiling measurement systems

Manual wheel profiling system involves the use of mechanical gauges and templates to measure the wheel profiles. Technicians manually align these tools with the wheel surface to take precise measurements.

- Advantages of Manual Systems:
  i. Cost-effective with minimal initial investment.
  ii. Simple to use without requiring complex technology.
  iii. Suitable for small-scale operations or infrequent measurements.
- Disadvantages of Manual Systems:
  i. Time-consuming and labour-intensive.
  ii. Prone to human error, affecting measurement accuracy.
  iii. Limited to spot-checking and less efficient for comprehensive monitoring.

3.2 Automated wheel profiling measurement

Automated wheel profiling measurement systems use advanced technology, such as laser or optical sensors, to measure the wheel profiles accurately and efficiently. These systems can be part of both fixed setups in maintenance depots or in-motion systems installed on tracks.

- Advantages of Automated Systems:
  i. Highly accurate and consistent measurements.
  ii. Efficient and quick, capable of measuring wheels in motion.
  iii. Reduces human error and labour costs.
  iv. Enables continuous monitoring and real-time data analysis.
  v. Provides comprehensive data for predictive maintenance and better decision-making.
- Disadvantages of Automated Systems:
  i. Higher initial investment and maintenance costs.
  ii. Requires technical expertise to operate and maintain.
  iii. It can be complex to integrate with existing infrastructure.

A comparison of manual and automated wheel profiling systems is provided in Table 1. The measurement for the manual wheel profiling measurement with their Diameters, Flange, and Flange thickness has been provided in Tables 1 and 2 as:

3.3 Differentiation and Comparison

Table 1
Comparison of Manual and Automated wheel profiling system

Aspect	Manual Systems	Automated Systems
Accuracy	Moderate, dependent on operator skill	High, with minimal human error
Efficiency	Low, time-consuming, and labor-intensive	High, quick measurements
Cost	Low initial cost	High initial and maintenance costs
Data Processing	Manual recording and analysis	Automatic recording and real-time analysis
Measurement Frequency	Infrequent, periodic	Continuous, real-time monitoring
Integration	Simple setup	Complex integration with infrastructure

Table 2
Manual wheel profiling measurements

Measurement Point	Diameter (mm)	Flange Height (mm)	Flange Thickness (mm)
1	850	28	30
2	849	27.5	29.5
3	852	28.5	30.5
4	851	28	30
5	850	27	29
6	848	27.5	29.5
7	851	28	30
8	850	27.5	29.5
9	849	28	30
10	852	28.5	30.5

The graphical representation of manual diameter, manual flange height, manual flange thickness, and manual wheel profiling measurement is shown in Figures 1-4:

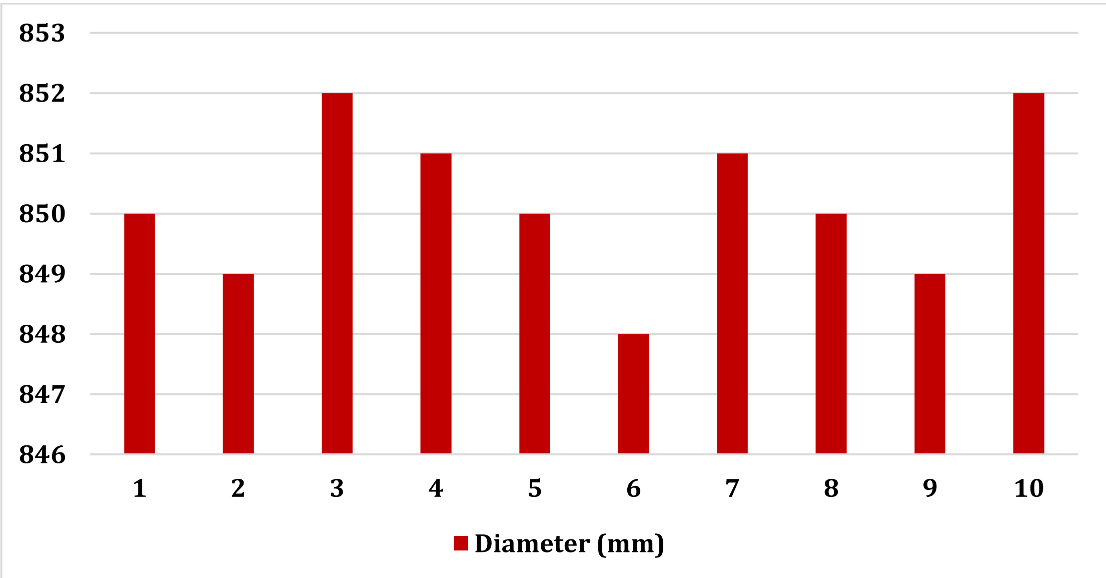

Fig. 1. Manual Diameter measurements
Min = 848 mm, Q1 = 849 mm, Median = 850 mm,
Q3 = 851 mm, Max = 852 mm

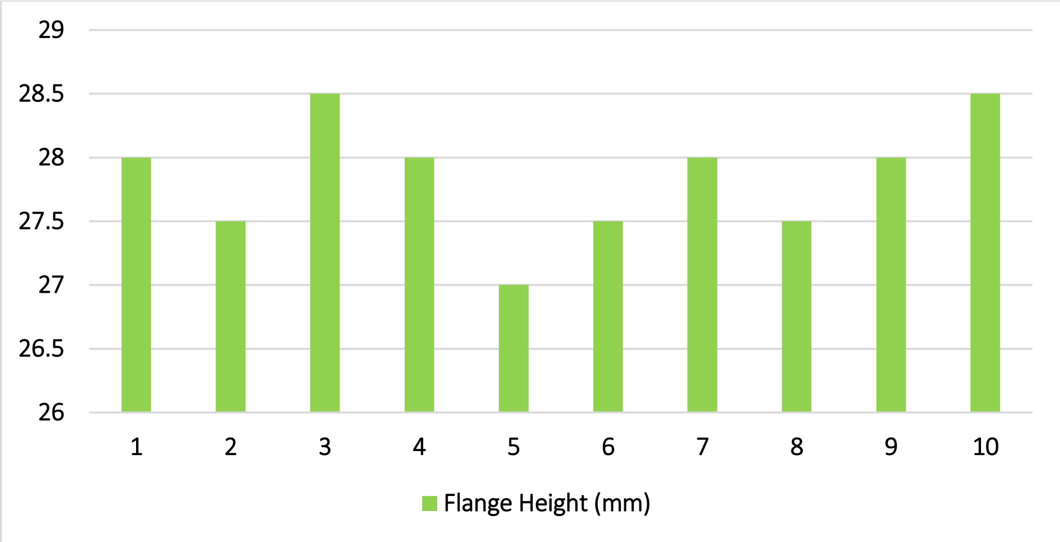

Fig. 2. Manual flange height measurements
Min = 27 mm, Q1 = 27.5 mm, Median = 28 mm,
Q3 = 28.5 mm, Max = 28.5 mm

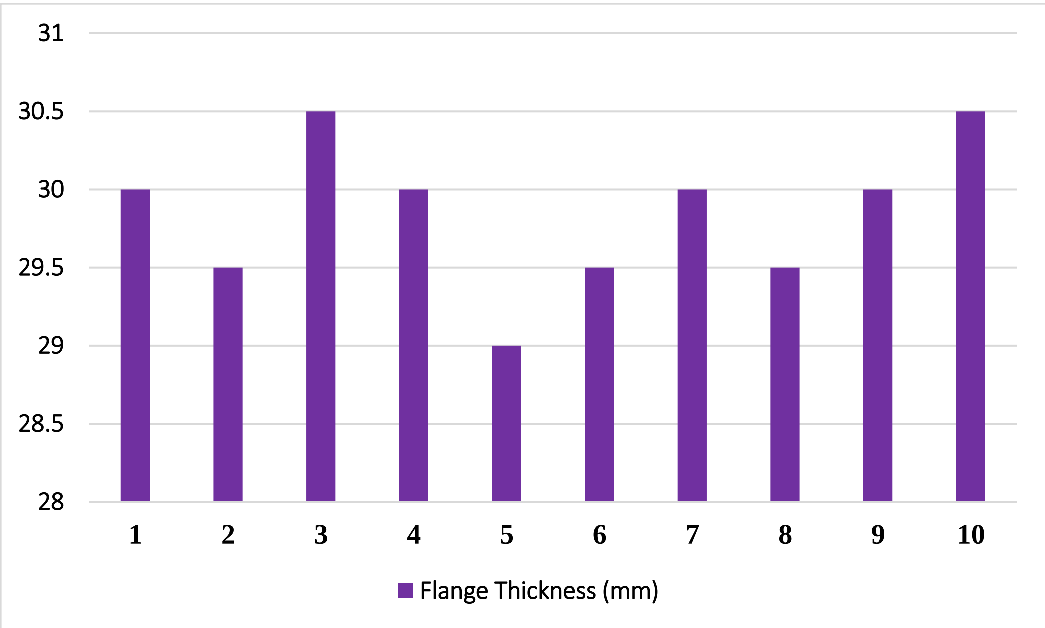

Fig. 3. Manual flange thickness measurements
Min = 29 mm, Q1 = 29.5 mm, Median = 30 mm,
Q3 = 30.5 mm, Max = 30.5 mm

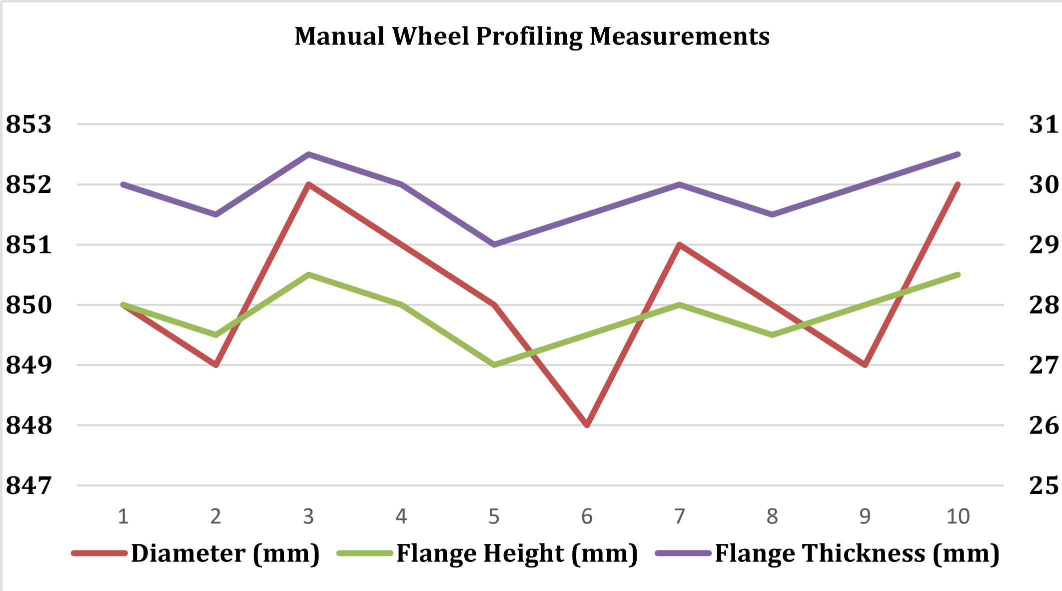

Fig. 4. Manual wheel profiling measurements

The automated wheel profiling measurement values are shown in Table 3, and the graphical values are represented in Figures 5-8:

Table 3
Automated wheel profiling measurements

Measurement Point	Diameter (mm)	Flange Height (mm)	Flange Thickness (mm)
1	850.1	27.9	29.8
2	849.8	27.7	29.6
3	850.2	28.0	29.9
4	850.3	28.1	30.0
5	850.0	27.8	29.7
6	850.1	27.9	29.8
7	850.3	28.0	30.0
8	850.2	27.9	29.8
9	850.0	27.8	29.7
10	850.1	28.0	29.9

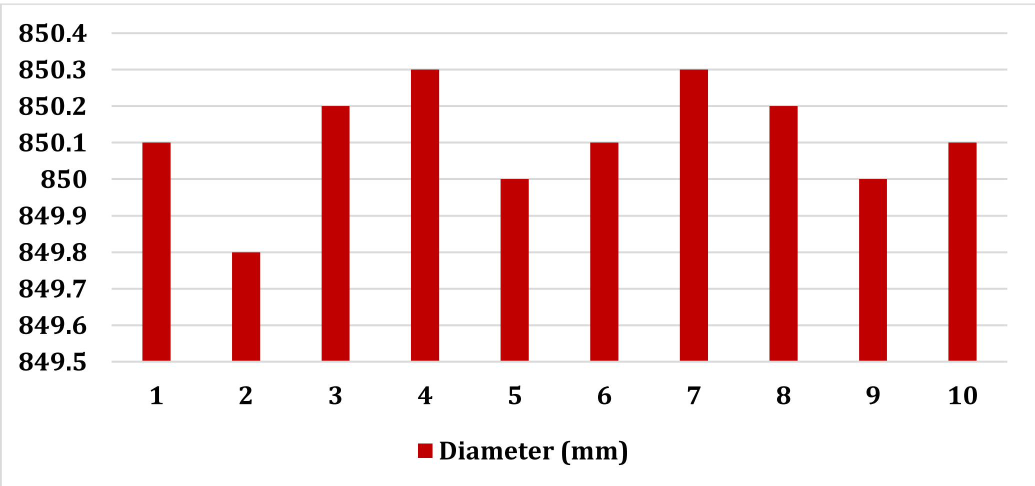

Fig. 5. Automated diameter measurements
Min = 849.8 mm, Q1 = 850.0 mm, Median = 850.1 mm,
Q3 = 850.2 mm, Max = 850.3 mm

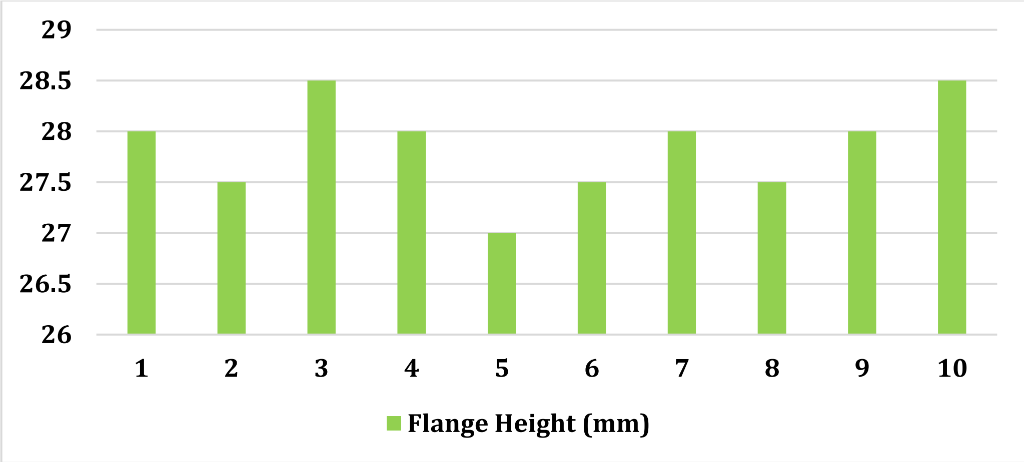

Fig. 6. Automated Flange height measurements
Min = 27.7 mm, Q1 = 27.8 mm, Median = 28.0 mm,
Q3 = 28.0 mm, Max = 28.1 mm

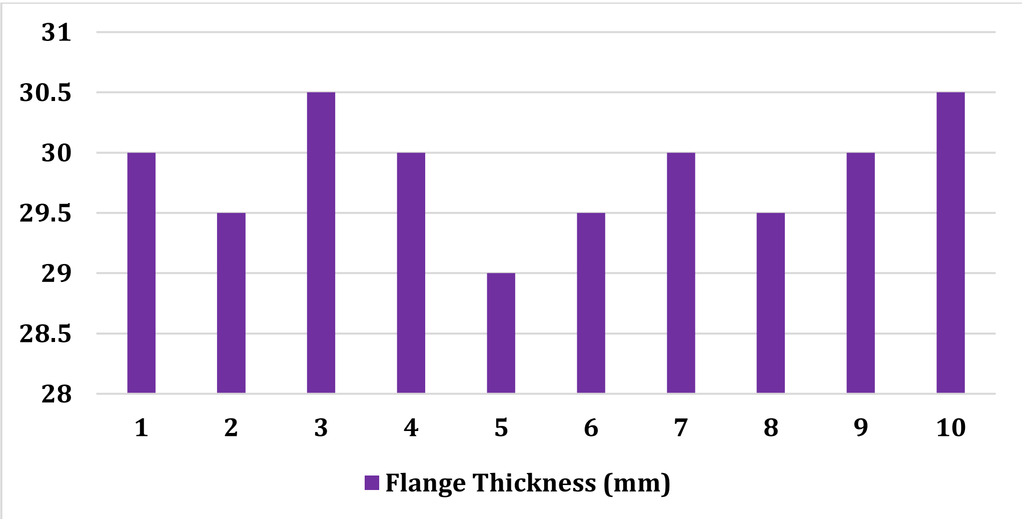

Fig. 7. Automated Flange thickness measurements
Min = 29.6 mm, Q1 = 29.7 mm, Median = 29.8 mm,
Q3 = 29.9 mm, Max = 30.0 mm

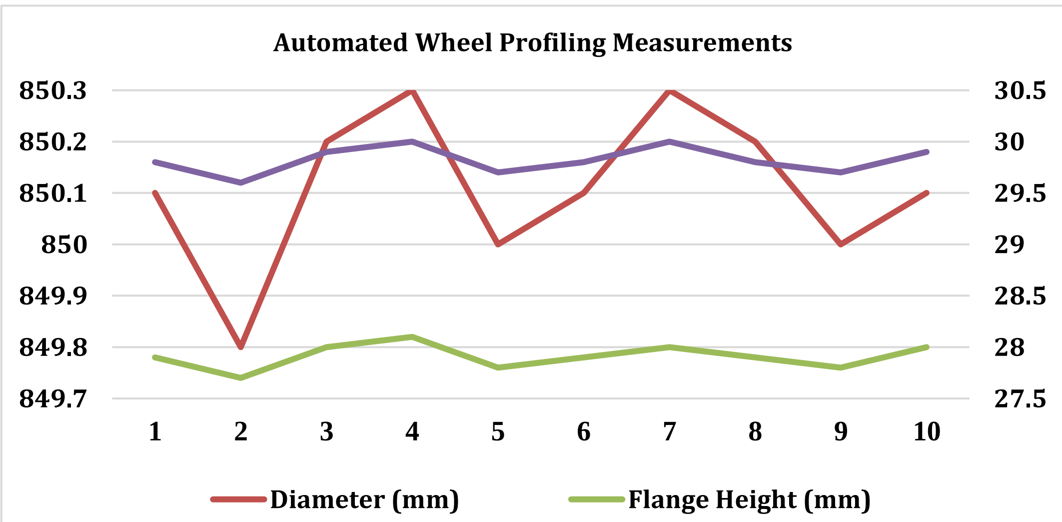

Fig. 8. Automated wheel profiling measurements

The automated system provides significantly higher precision and consistency in measurements compared to the manual system. This precision is critical for ensuring the safety and efficiency of rolling stock operations, as even small deviations can impact the train's performance and track wear.

3.4 Cost analysis and comparison

The manual and automated system costs are represented corresponding to cost aspects shown in Table 4:

Table 4
Cost aspects of manual and automated

Cost Aspect	Manual System (₹)	Automated System (₹)
Initial investment	525,000	6,375,000
Annual operation cost	3,075,000	1,275,000
5- year operational cost	15,375,000	6,375,000
Total cost over 5 years	15,900,000	12,750,000

The cost comparison for manual and automated are shown in Figure 9 as:

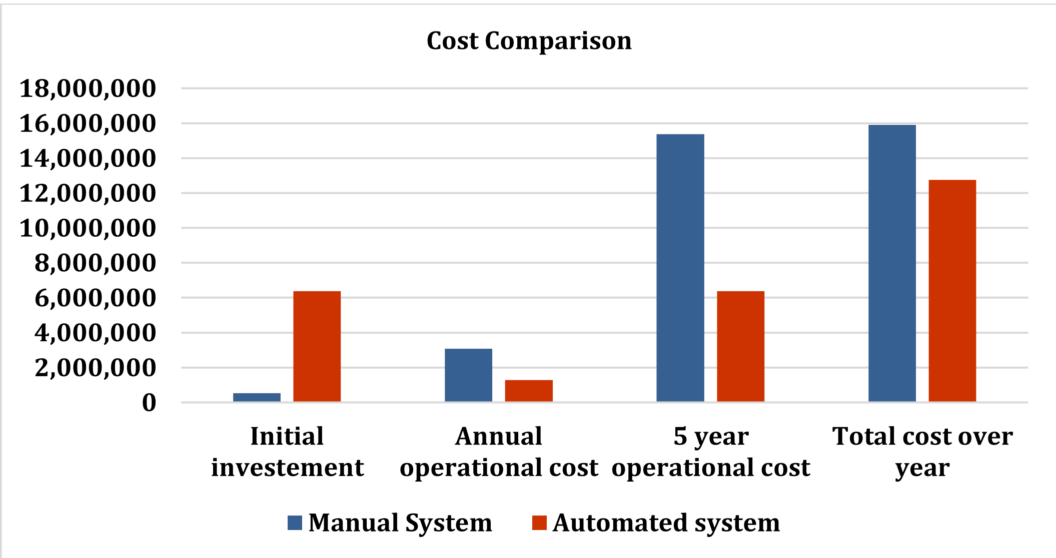

Fig. 9. Cost comparison of manual and automated system

Despite having a significantly higher initial investment, the automated system proves to be more cost-effective over a 5-year period due to lower annual operational costs. While cheaper to set up, the manual system incurs higher ongoing labor and maintenance costs, making it more expensive in the long run.

3.5 Reliability Metrics, Maintenance Efficiency, Downtime and Availability, Cost Savings and Benefits & CMMS Tool Effectiveness

Table 5-9 represents the reliability metrics, maintenance efficiency of manual and automated systems, downtime and availability, manual automated cost saving, and CMMS tool effectiveness values as:

Table 5
Reliability Metrics

Metric	Manual System	Automated System
MTBF (hours)	500	800
MTTR (hours)	8	4
Failure Rate (per 1,000)	2	1.24

Table 6
Maintenance Efficiency of manual and automated system

Metric	Manual System	Automated System
Scheduled Maintenance Adherence	85%	95%
Unscheduled Maintenance Adherence	30	15

Table 7
Downtime and Availability

Metric	Manual System	Automated System
Annual Downtime (hours)	240	80
System Availability	97.3%	99.1%

Table 8
Manual and Automated cost savings

Cost Aspect	Manual System	Automated System
Annual Labor Cost(₹)	3,000,000	750,000
Annual Maintenance(₹)	75,000	375,000
Total Annual Saving(₹)	-	2,325,000

Table 9
CMMS tool effectiveness

Metric	Before CMMS	After CMMS
Preventive Maintenance Compliance	70%	95%
Inventory Management Efficiency	60%	90%
Reduction in Emergency Repairs (per year)	20	8

4. Conclusions and Future Scope

The research focused on implementing Reliability Centered Maintenance and a Computerized Maintenance Management System into a wheel profile measuring system for rolling stock, comparing manual and automated systems. This comprehensive analysis revealed significant insights into the benefits and challenges associated with these approaches.

i. *Reliability Improvements:* The automated wheel profiling system demonstrated higher reliability metrics compared to the manual system. The Mean Time Between Failures increased from 500 to 800 hours, while the Mean Time to Repair dropped from 8 to 4 hours. This resulted in a decreased failure rate, improving overall system reliability and performance.
ii. *Maintenance Efficiency:* Implementing RCM in conjunction with CMMS significantly improved maintenance efficiency. Scheduled maintenance adherence increased from 85% to 95%, while the number of unscheduled maintenance events decreased from 30 to 15 annually. This proactive approach minimized downtime and maximized asset availability.
iii. *Cost Savings:* Despite a higher initial investment (₹6,375,000 compared to ₹525,000 for the manual system), the automated system proved more cost-effective over a 5-year period. The total cost over 5 years for the manual system was ₹15,900,000, whereas the

automated system incurred ₹12,750,000. Annual operational costs for the automated system were significantly lower due to reduced labor and maintenance expenses, resulting in annual savings of ₹2,325,000.

iv. *Downtime Reduction:* The annual downtime for the automated system was 80 hours, compared to 240 hours for the manual system. This reduction in downtime increased system availability from 97.3% to 99.1%, contributing to more efficient metro operations and improved passenger satisfaction.

v. *CMMS Effectiveness:* The CMMS implementation streamlined maintenance operations, improved inventory management accuracy from 60% to 90%, and reduced emergency repairs from 20 to 8 annually. The integration of CMMS with automated measurement systems facilitated real-time data acquisition and analysis, enhancing decision-making capabilities.

While this study has provided valuable insights and demonstrated the benefits of RCM and CMMS in wheel profiling measurement systems, several areas warrant further exploration to maximize the potential of these technologies in metro systems:

i. *Advanced Predictive Analytics:* Future research could focus on integrating advanced predictive analytics and machine learning algorithms with CMMS to predict failures more accurately and optimize maintenance schedules. This would further reduce downtime and maintenance costs.

ii. *Enhanced Data Integration:* Improving data integration across various subsystems within the metro network could provide a more holistic view of system health and performance. Enhancing the interoperability of CMMS with other operational systems can lead to more efficient maintenance and operations management.

iii. *Lifecycle Cost Analysis:* Conducting a comprehensive lifecycle cost analysis, including depreciation, energy consumption, and environmental impact, would provide a deeper understanding of the long-term benefits and trade-offs between manual and automated systems.

iv. *Scalability and Adaptability:* Investigating the scalability and adaptability of automated wheel profiling systems and CMMS in different metro environments and configurations could help tailor these technologies to specific operational needs and constraints.

v. *User Training and Change Management:* Future studies could explore the impact of user training and change management strategies on the successful implementation of CMMS and automated systems. Understanding human factors and addressing resistance to change is critical for maximizing the benefits of new technologies.

vi. *Integration with Smart Infrastructure:* Exploring wheel profiling systems and CMMS integration with emerging smart infrastructure technologies, such as the Internet of Things (IoT) and digital twins, could further enhance maintenance efficiency and operational reliability.

vii. *Regulatory and Safety Standards:* Investigating the alignment of RCM and CMMS practices with evolving regulatory and safety standards will ensure compliance and enhance the safety and reliability of metro operations.

To summarize, using Reliability Centered Maintenance and a Computerized Maintenance Management System in the wheel profile measuring system for rolling stock resulted in significant improvements in reliability, maintenance efficiency, and cost savings. The automated system outperforms the manual system in various aspects, including reduced downtime, increased system availability, and long-term cost-effectiveness. These findings highlight the necessity of implementing advanced maintenance procedures and technology to improve metro operations and the passenger experience. Future research and development in this sector will focus on refining current systems, addressing upcoming challenges, and utilizing new technologies to increase metro network efficiency and reliability.

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Conflicts of Interest

The authors declare no conflicts of interest.

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