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Failure Mode and Effect Analysis for Intercity Train Wheel System

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Abstract

Beyond ensuring passenger safety, a key priority is maintaining the train's components in optimal condition to ensure smooth operations. This effort aims to deliver a seamless and worry-free experience for all, minimizing the risk of accidents or delays due to faulty parts. This study investigates the maintenance strategies for rolling stock bogie wheelsets, with a focus on optimizing practices to enhance reliability and safety. Various maintenance approaches including part-specific, mileage-based, preventive, and corrective programs were analyzed to understand their impact on maintenance decision-making for bogie wheelsets. The study specifically examines the Keretapi Tanah Melayu Berhad (KTMB) maintenance operational to address bogie wheel faults, utilizing data from KTMB’s Operation and Maintenance (O&M) manuals, monthly reports, and relevant literature. The primary goal is to develop a comprehensive framework for bogie system maintenance, particularly for wheelsets, while evaluating the safety protocols necessary for effective upkeep. A significant challenge addressed in this study is the sequencing of the bogie wheelset maintenance process, achieved through detailed analysis of maintenance documents. The findings from KTMB ETS O&M manuals and literature reviews were employed to conduct a wear and tear analysis, providing insights into the operational environment. This done mainly to improve the performance, reliability, and durability of KTMB ETS Class 91 rolling stock by proposing a robust maintenance policy. The suggested approach aligns maintenance practices with organizational objectives, enhancing operational efficiency and cost-effectiveness within the railway sector.

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1. Introduction

Since gaining independence in 1957, Malaysia has rapidly evolved into a prosperous developing nation, with the transportation industry serving as a critical driver of economic and infrastructural growth. The country’s railway sector, established in the late 1800s to expedite the transport of tin mining products to coastal ports, has since grown into a dynamic and diverse corporatized institution, playing a pivotal role in developing a sustainable transportation system.

Railway revolutionary in Malaysia starts with Keretapi Tanah Melayu Berhad (KTMB). Keretapi Tanah Melayu Berhad (KTMB) serves as Malaysia's national railway operator, with origins tracing back to the late 1800s. The railway system was initiated during the British colonial era, with the first line inaugurated in 1885, linking Taiping to Port Weld (now Kuala Sepetang) in Perak, mainly for transporting tin from mines to the port. The success of this initial route led to further development, and by the early 20th century, the railway network had extended throughout the Malay Peninsula, connecting important towns and cities. The Federated Malay States Railways (FMSR), created in 1901, oversaw the expanding network and significantly contributed to the region's economic growth. Following Malaysia's independence in 1957, the railway system was nationalized, and in 1962, it was renamed Keretapi Tanah Melayu (KTM) to align with the country's new identity. KTMB became the main provider of railway services in Peninsular Malaysia, catering to both passenger and freight transport. During this time, the railway network continued to grow, although it encountered increasing competition from road transport as Malaysia's road infrastructure developed.

In the 1990s, KTMB initiated a modernization initiative to improve its services and infrastructure. This included launching new train services like the Electric Train Service (ETS) for quicker intercity travel and efforts to upgrade and double-track major routes. Keretapi Tanah Melayu Berhad (KTMB) operates the Electric Train Service (ETS), Malaysia's fastest meter-gauge train, with speeds reaching up to 140 km/h. Since its introduction on August 12, 2010, the ETS has become Malaysia's most popular intercity rail system, with increasing demand driven by high ridership and extensive travel (Agensi Pengangkutan Awam Darat, 2021). However, KTMB faced challenges with financial sustainability and competition from other transportation options, prompting several restructuring attempts. In recent years, KTMB has continued to modernize, concentrating on enhancing the reliability and efficiency of its operations. The completion of double-tracking and electrification on key routes, such as the line from Padang Besar to Gemas, has enabled KTMB to provide faster and more frequent services, especially through the ETS. KTMB remains an essential component of Malaysia's transportation system, offering vital intercity rail services throughout the peninsula. Currently, KTMB is focused on further improving its operations, with ongoing projects aimed at expanding and upgrading the network to accommodate the needs of a growing population and economy.

Due to the increasing demand and variety of business model developed by KTMB to sustain the ridership, KTMB need to enhance their performance, increase their service quality with an optimal cost. The increasing need for a more intelligent and competitive railway system places additional pressure on existing networks to implement more effective performance-improvement measures. In the railway industry, performance evaluation and enhancement are integral to strategic management, involving methodologies such as efficiency assessments, customer satisfaction, and service quality evaluations.

While maintaining the performance and quality, the aim of railway transport system is to provide safe and seamless ride. One of the railway systems that is important to achieve the seamless and safety travel is underframe-wheel set. KTMB Maintenance Department pays particular attention to the bogie wheel, a critical component of train safety. Reports indicate that KTMB ETS wheels were re-profiled before reaching the design’s 200,000 km requirement (Jabatan Audit Negara, 2018).

Intercity trains require wheel reprofiling before reaching the design's 200,000 km requirement due to the inevitable wear and degradation of wheel profiles that adversely affect operational safety and performance. Some of the reasons discussed by past scholars due to nonuniform wear in wheel-rail contact alters the wheel profile, leading to compromised dynamic behavior and safety of the train (Xie *et al.,* 2024). Whilst Wang *et al.* (2023) highlighted the different wheel profiles exhibit varying wear characteristics, with some requiring reprofiling after significantly fewer kilometres, such as 112,000 km for certain profiles. This premature maintenance incurs significant costs, with each wheel replacement amounting to MYR 14,000 (Jabatan Audit Negara, 2018). Traditional maintenance strategies that lead to early re-profiling or replacement can escalate costs and cause unnecessary breakdowns. From economic consideration views, reprofiling strategies aim to balance maintenance costs and operational safety, allowing for less material removal while still meeting performance standards (Xie *et al.,* 2024). Hence, implementing a life cycle reprofiling strategy can minimize life cycle costs (LCC) while enhancing reliability and safety of the bogie wheelset. In addition to strategizing the reprofiling activities, this study highlighted one of the train wheelsets used by KTMB as the case study. The type of train set examined in the study is ETS Class 91 bogie.

The ETS Class 91 bogies are designed with a 1,000 mm track gauge, a maximum axle load of 15 tons, and a top speed of 160 km/h. Key components of motor and trailer bogies include wheelsets, primary and secondary suspensions, traction linkage devices, mechanical drive systems, and friction braking systems. The bogie features industry-standard components and a bolster less "H" frame construction with air springs, facilitating easier maintenance and efficient bogie switching (Warjito *et al.*, 2021). To enhance performance, stability, and ride comfort, secondary air suspension springs are positioned between the bogie frame and the car body, with traction forces transmitted through the central pivot linkage. The design emphasizes minimizing total life costs by allowing the train wheels to adjust their angle relative to the car body for smoother rail contact (Warjito *et al.*, 2021). Each vehicle consists of six cars, equipped with two bogies each with a total of 12 bogies per train set. The car body is primarily constructed from cold-rolled stainless steel and hot-rolled corrosion-resistant steel, excluding the bolster and center sill, which ensures structural integrity. Additionally, each driving car is equipped with a driver's cab, meeting strength requirements. The bogie frame design remains consistent, with selective additions like solid stick lubricators and lifeguards (Warjito *et al.*, 2021). Previous research has identified common issues with bogie wheelsets, such as scratches, fractures, rolling contact fatigue, and wear, all of which can affect structural safety and operational reliability (Zhang *et al.*, 2022).

Repairing damaged wheels or rails is more costly than purchasing new ones and raises safety concerns. The varying lifespans of certain wheels complicate the determination of accurate life limits. Therefore, this study focuses on improving wheel maintenance practices through optimized inspection intervals and mitigation strategies, particularly using Failure Mode Effect Analysis (FMEA). FMEA is a structured approach used to identify possible failure modes in a system and evaluate their consequences. FMEA entails examining components to pinpoint potential failure modes, their underlying causes, and their impacts, which facilitates the implementation of preventive strategies. It is commonly utilized across various sectors, including rail and automotive, to enhance the reliability of designs and processes (Kara-Zaitri *et al.,* 1991). When FMEA is applied to wheel set reprofiling, operators can detect critical failure points during the machining process, such as unexpected loads on cutting tools (Lung *et al.,* 1987). This forward-thinking method allows for the selection of suitable cutting materials and techniques, thereby minimizing the likelihood of tool damage and improving operational efficiency (Lung *et al.,* 1987). Evaluating current preventive and corrective measures is crucial to meeting wheel quality standards, supporting decision-making for better preventive maintenance, and extending the wheel life cycle (Jabatan Audit Negara, 2018).

2. Research Methodology

2.1 Research Design

The research design served as a procedural framework, effectively guiding the investigation towards addressing the research objectives by integrating relevant information. The study primarily utilized KTMB records and existing data, complemented by a targeted survey of industry experts, including engineers and workers from the KTMB Batu Gajah Depot. This method was chosen due to its efficiency in situations where gathering observable evidence is time-consuming. To gain descriptive insights into the maintainability of the bogie system's wheel equipment, data from published secondary sources were collected and utilized archival materials on failure analysis and wear and tear assessment.

This study starts by assessing the maintainability and failure issues related to the bogie wheel system of the KTMB ETS Class 91. Following a structural analysis of the bogie wheel system, the researcher conducted an extensive literature review and gathered data from the KTMB ETS archives. The data collection process involved searching the maintenance facility's database, utilizing a design instrument, and incorporating secondary data. Regular analysis of the data was performed to identify patterns in wheel wear, maintenance, and failure. Results and discussions were developed through an ongoing process of data collection and analysis, ensuring accurate data interpretation, with validation from industry experts.

2.2 Data Collection

In this study, the data was collected by using secondary data. The secondary data sources for this research were the monthly reports from KTMB related to their ETS operations, and the Operations & Maintenance (O&M) manual. These documents provided detailed records of maintenance activities, performance metrics, and any incidents related to the bogie wheel system. The monthly reports typically contain summaries of operational efficiency, maintenance schedules, and any issues encountered during the train service, while the O&M manual includes technical guidelines, preventive maintenance schedules, and corrective maintenance procedures.

Specific reports were collected focused on the preventive and corrective maintenance of the bogie wheel system. Preventive maintenance reports typically outline routine inspections and maintenance activities carried out to prevent failures, while corrective maintenance reports document the repair activities performed after a failure has occurred. These reports were crucial in understanding the types of failures that occurred, the frequency of these failures, and the effectiveness of the maintenance strategies employed.

Once the reports were collected, the data was sorted and filtered to extract relevant information specifically related to bogie wheel system failures. This involved identifying key information such as the type of failure, the frequency of occurrences, the components involved, and the outcomes of the maintenance actions taken. The data was then converted into a computer-readable format (Microsoft Excel), which allowed for easier analysis and interpretation. This step ensured that the data was organized in a way that facilitated trend analysis and identification of recurring issues.

The Computational Maintenance Management System (CMMS) data was also utilized. CMMS is a digital tool used by KTMB for tracking and managing maintenance activities. The CMMS provided historical data on maintenance activities, including logs of all repairs, inspections, and maintenance tasks performed on the bogie wheel system. By analyzing this data, the researcher could identify whether certain repairs were one-time events or if they represented recurring issues. This system also allowed the researcher to track maintenance trends over time, providing insights into the long-term reliability of the bogie wheel system.

In this study, the data sources were limited to records from 2017 to 2020. This three-year timeframe was chosen to provide a comprehensive view of the maintenance history of the bogie wheel system while ensuring that the data was recent enough to reflect current maintenance practices. The chosen period also helped in identifying any recent trends or changes in the maintenance approach that could be relevant to the study.

In summary, the research leveraged secondary data from KTMB's monthly reports, O&M manuals, and the CMMS to carry out a detailed analysis of the bogie wheel system's maintenance history. By focusing on data from 2017 to 2020, the researcher could identify trends and recurring issues, providing a foundation for evaluating and improving the maintenance strategies employed by KTMB.

2.3 Data Analysis

After collecting and organizing the data, the researcher conducted a thorough analysis to identify patterns of wheel wear, failure, and maintenance. This involved examining the frequency of specific types of failures, the effectiveness of different maintenance strategies, and any changes in the maintenance approach over time. The insights gained from this analysis were then used to evaluate the current maintenance practices and suggest potential improvements to enhance the reliability and performance of the bogie wheel system.

2.3.1 Wear and Tear Analysis

To conduct the wear and tear analysis, the maintenance database for the relevant bogie wheel system was first searched to retrieve the necessary data. This data was then categorized into two main types: preventive maintenance and corrective maintenance. After filtering the information, the maintenance activities were ranked in descending order based on their frequency of occurrence.

2.3.2 FMEA Analysis

FMEA was conducted to assess the safety and reliability of the wheelset components by investigating potential causes of failure and their severity. The analysis was guided by the Risk Priority Number (RPN), a key metric in FMEA that helps prioritize failure modes based on their risk. The following steps outline the FMEA process used to rank failure scenarios and propose preventive maintenance strategies aimed at reducing wheel wear in the bogie system.

The first step involved identifying all potential failure modes for the wheel, such as cracks, wear, or deformation. This step is crucial as it sets the foundation for analyzing what could go wrong with the wheelset components.

Once the possible failure modes were identified, the next step was to define the specific conditions under which these failures could occur. This includes understanding the operational environment, load conditions, and maintenance history that might influence the likelihood of failure.

With the failure modes and conditions established, the analysis proceeded to calculate the RPN for each failure scenario. The RPN is determined by evaluating the severity of the failure, the likelihood of occurrence, and the ability to detect the failure before it happens. The higher the RPN, the more critical the failure mode, indicating a need for urgent attention.

Finally, based on the identified failure modes and their RPNs, preventive maintenance actions were proposed. These measures aim to mitigate the risks by addressing the most critical failure modes, thereby enhancing the durability and safety of the bogie wheel system.

The FMEA process, as depicted in Fig. 1, provides a systematic approach to identifying, analyzing, and addressing potential failures in the wheelset components, contributing to improved maintenance strategies and overall system reliability.

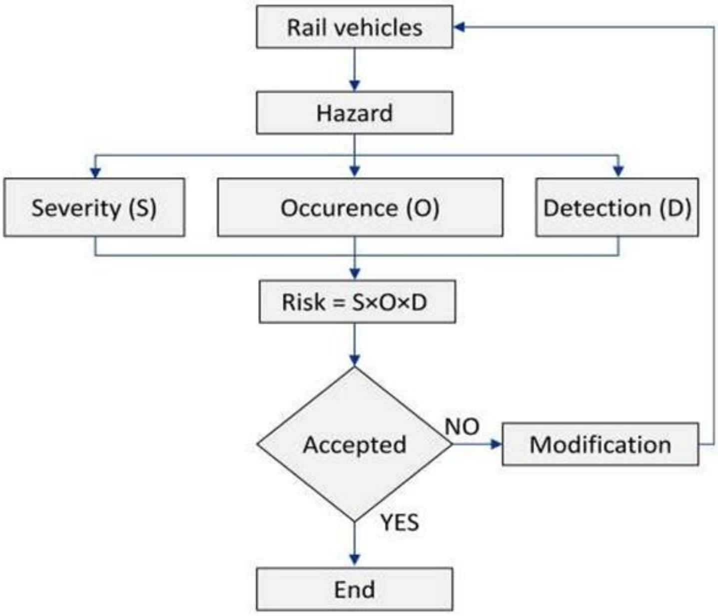

Fig. 1 *FMEA process*

3. Results and Discussion

3.1 Wear and Tear

The critical element of systematic data collection and precise analysis in the field of bogie wheel systems cannot be emphasized enough. The demand for accurate, detailed, and insightful data has grown increasingly urgent. This study aimed to contribute to the existing body of knowledge by conducting a comprehensive investigation into the safety and maintenance practices of the KTMB ETS Class 91-wheel system. The primary focus was an in-depth analysis of bogie wheel wear and tear, Failure Modes and Effects Analysis (FMEA), and maintenance procedures within the context of the KTMB ETS wheel system.

3.1.1 Preventive Maintenance

Over the four-year period from 2017 to 2020, a distinct trend emerged, showing that wheel skimming was the most frequent type of preventative maintenance in KTMB ETS Class 91-wheel repair procedures. This significant finding is visually depicted in Fig. 2, which offers a detailed breakdown of the preventative maintenance statistics for wheel skimming during the specified time frame.

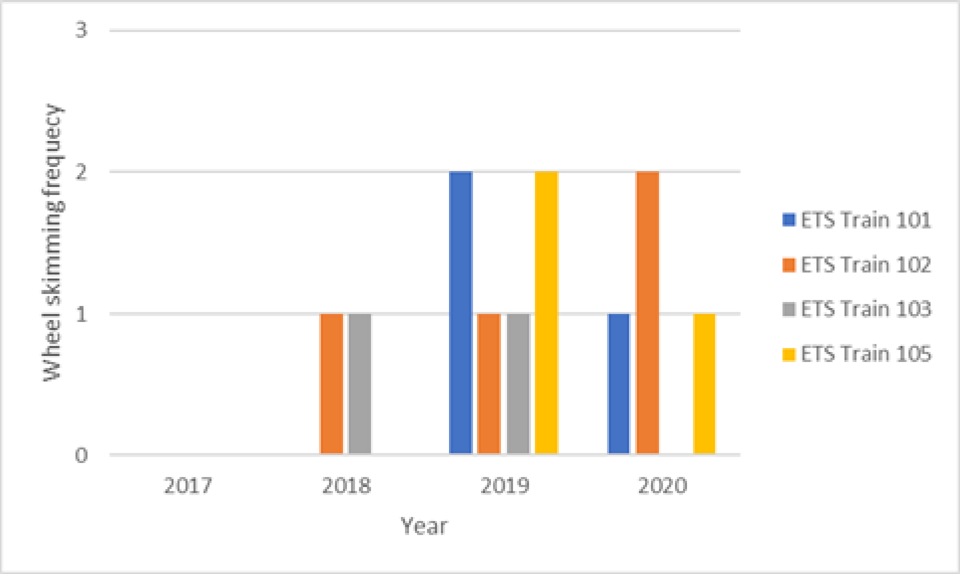

Fig. 2 *Wheel skimming frequency for KTMB ETS Class 91 trains*

3.1.2 Corrective Maintenance

Corrective maintenance aims to optimize the efficiency of all critical installations, prevent failures and costly repairs, and minimize deviations from optimal operating conditions. It is a reactive process that involves identifying, isolating, and repairing faults within a unit to restore it to its operational state within the tolerances or limits set for on-site repair. This often requires equipment reconstruction due to incidents such as collisions, emergencies, corrections, and repairs. When a system is shut down for repairs, corrective maintenance can be carried out either rapidly or slowly, depending on the severity of the issue.

The most commonly replaced parts between 2017 and 2020 were the WPS sensor, axle carbon brush bolt, axle carbon brush, axle, wheel, and cover axle as presented in Fig. 3. The brakes and wheels of rolling stock are particularly prone to wear due to the constant pressure of rapid acceleration and deceleration, as well as the braking systems along the railway track (Buchheit, 2018).

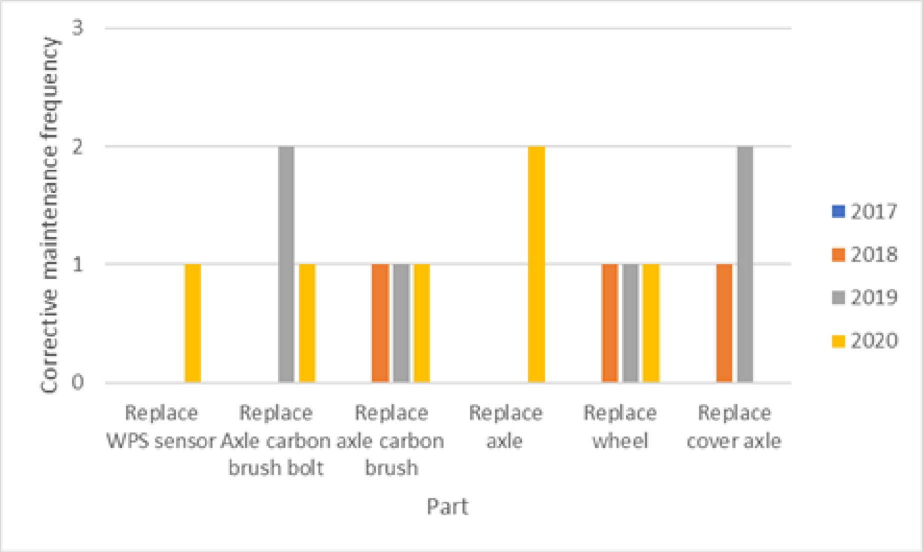

Fig. 3 *Corrective maintenance activities for KTMB ETS Class 91 trains*

3.2 FMEA

In the context of KTMB ETS, failure modes for rolling stock wheels have been identified based on two primary defects: (1) Worn Out Wheels: This refers to the gradual degradation of the wheel surface due to continuous contact with the rail, leading to a reduction in the wheel's diameter or the formation of flat spots, which can affect the smooth operation of the train; (2) Broken Wheels: This represents a more severe condition where the wheel suffers structural damage, such as cracks or complete fractures, which can pose significant safety risks and lead to operational failures.

The FMEA will focus on the following conditions: (1) Wheel Re-skimming after 200,000 km: Re-skimming involves machining the wheel surface to restore its profile and remove any defects that have developed over time. This process is typically required after the wheel has covered 200,000 km to ensure it remains within the operational tolerance and continues to perform safely and efficiently; (2) Wheel Replacement after 900,000 km: Complete wheel replacement is considered necessary after 900,000 km. At this point, the wheel may have experienced significant wear or accumulated damage that cannot be corrected by re-skimming alone, making replacement essential to maintain safety and performance. Before calculating the Risk Priority Number (RPN), the severity, occurrence, and detection criteria will be established using the MIL-STD-1629A standard. Table 1, Table 2, and Table 3 provide the ranking criteria for these factors.

Table 1 *MIL-STD-1629A – Severity (Szkoda & Kaczor, 2015)*

Rate	Description	Criteria
1	Minor	A failure could only result in unplanned repair without serious damage or people injury
2	Marginal	A failure could result in minor system damage, losses in availability or mission delay
3	Critical	A failure could result in serious damage and improper operation of the system
4	Catastrophic	A failure could result in death or losses of some system equipment

Table 2 *MIL-STD-1629A – Occurrence (Szkoda & Kaczor, 2015)*

Rate	Description	Criteria
1	Extremely unlikely	A single probability of failure occurrence is less than 0.001 of the overall probability of failure in the specific period of time.
2	Remote	A single probability of failure occurrence is more than 0.001 but less than 0.01 of the overall probability of failure in the specific period of time.
3	Occasional	A single probability of failure occurrence is more than 0.01 but less than 0.1 of the overall probability of failure in the specific period of time.
4	Reasonably probable	A single probability of failure occurrence is more than 0.1 but less than 0.2 of the overall probability of failure in the specific period of time.
5	Frequent	A single probability of failure occurrence is more than 0.2 of the overall probability of failure in the specific period of time

Table 3 *MIL-STD-1629A – Detection (Szkoda & Kaczor, 2015)*

Rate	Description	Criteria
1	Almost certain	Probability of early detection of the failure is close to 1
2	Very high	Probability of early detection of the failure is very high
3	High	Probability of early detection of the failure is high
4	Moderately high	Probability of early detection of the failure is moderately high
5	Medium	Probability of early detection of the failure is moderately medium
6	Low	Probability of early detection of the failure is moderately low
7	Slight	Probability of early detection of the failure is moderately slight
8	Very slight	Probability of early detection of the failure is moderately very slight
9	Remote	Probability of early detection of the failure is moderately remote
10	Almost impossible	Probability of early detection of the failure is close to 0

The RPN is a numerical score used to prioritize potential failure modes based on their risk, determined by multiplying the severity, occurrence, and detection ratings (Equation 1). The following algorithm is applied to identify high-risk failure types that could disrupt train operations. For this study, occurrence data was referenced from KTMB ETS Class 91 failure evaluations conducted during the project stage. This data provides insight into the frequency of these failures, helping to assess the likelihood and impact of each failure mode. Table 4 represent the FMEA analysis of KTMB ETS Class 91-wheel system.

$$\text{RPN} = \text{Severity x Occurrence x Detection} \tag{1}$$

3.3 Wheel Maintenance Schedule

The maintenance plan outlined in Table 5 details various operational maintenance grades for a vehicle's wheelset. These grades, ranging from Safety Check (SCH) to F inspection, are assigned based on specific inspection intervals or mileage thresholds. For instance, a Safety Check is recommended every 1 day or 500 km, while an F inspection is advised every 6 years or 1,000,000 km. Each maintenance grade corresponds to a particular set of inspections identified by specific markings.

Table 6 provides a comprehensive overview of the wheel maintenance schedule, detailing inspections for various wheelset components. Both the wheelset inspection and the wheelset detail inspection, which are performed visually, are marked with a "●" and are required for all maintenance grades from SCH to F inspection. Other inspections, such as those for the journal box and journal bearing, involve measurements and are indicated accordingly. The maintenance plan also includes overhauls for the wheel and axle, as well as the wheel flange lubricator, which are also marked with a "●" in the maintenance grade column. This detailed maintenance plan ensures that routine checks and necessary overhauls are conducted at specified intervals, enhancing the wheelset's overall reliability and safety.

Table 4 *FMEA analysis of KTMB ETS Class 91-wheelset*

	Hazard Category	Cause of Failure	Local Effect (Effect of the failure to the subsystem)	Operation Effect (Effect to the train operation)	Subsystem Effect	Availability / Safety / None	Repairable / Replaceable	Failure Detectability	Severity	Detectability	Occurrence	RPN
Replace WPS Sensor	Mechanical	Broken	Brake	Wheel Slide	Wheel and brake	Safety	Replace	Wear and Tear	3	5	3	45
Replace Axle Carbon Brush Bolt	Mechanical	Broken	Bogie	Damage to axle end	Wheel and axle bearing	Safety			3	3	5	45
Replace Axle Carbon Brush	Electrical	Broken	Bogie	Damage to axle end	Wheel and axle bearing	Safety			3	3	5	45
Replace Axle	Mechanical	Worn out	Bogie	-	Wheel and axle	Safety			4	2	4	32
Replace Wheel	Mechanical	Worn out	Bogie	-	Wheel and axle	Safety / Availability			4	1	6	24
Replace Cover Axle	Mechanical	Broken	Bogie	Damage to axle end	Wheel and axle bearing	Safety			1	3	5	15

Table 5 *Running maintenance grades*

Name	Inspection periods	Marking
Safety check	1 days or 500 km	SCH
A inspection	10 days or 5000km	A
B inspection	3 months or 45,000 km	B
C inspection	6 months or 90,000 km	C
D inspection	1 year or 180,000 km	D
E inspection	3 years or 500,000 km	E
F inspection	6 years or 1,000,000 km	F

Table 6 *Summary of wheel maintenance schedule*

Part	Description of inspection	Manner of inspection	Maintenance grade						
			SCH	A	B	C	D	E	F
Wheelset	Wheelset inspection	Visually	●	●	●	●	●	●	●
	Wheelset detail inspection	Visually		●	●	●	●	●	●
	Journal box	By measurement	●	●	●	●	●	●	●
	Journal bearing	Visually		●	●	●	●	●	●
Wheel flange lubricator	Wheel flange lubricator	Visually		●	●	●	●	●	●
Sensors	Sensors	Visually		●	●	●	●	●	●
Wheel and axle	Overhaul	Overhaul						●	●
Wheel flange lubricator	Overhaul	Overhaul						●	●

3.4 Wheel Maintenance Process Flow

In this study, the analytical process involved a thorough collection of maintenance requirements for the bogie wheelset, using KTMB's comprehensive Operations and Maintenance Manual as a primary source. This detailed manual served as the key repository of essential information, guiding the extraction of relevant data crucial for understanding the complexities of bogie wheelset maintenance routines. Subsequently, a detailed flowchart was meticulously developed to visually represent and simplify the procedural complexities, as illustrated in Fig. 4. This flowchart was carefully designed to highlight and address the various bogie subsystems that require specific modifications or inspections, thereby enhancing the clarity and thoroughness of the maintenance activities involved.

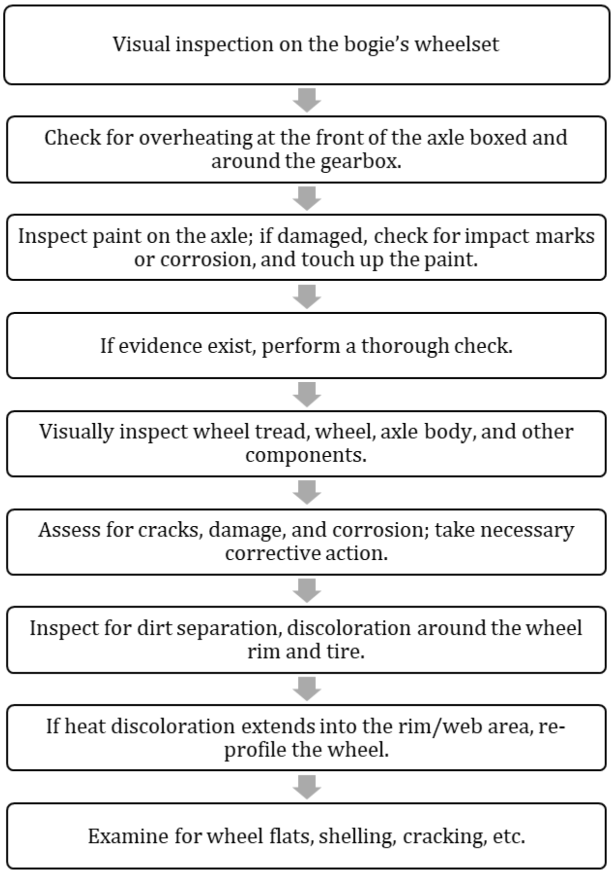

Fig. 4 *Wheel maintenance process flow for visual check*

The inspection procedure outlined here is a systematic approach to ensuring the operational integrity of a wheelset. It begins with the "Visual inspection of wheelset," focusing primarily on detecting any signs of relative movement between the wheels and the axle, which is crucial for maintaining the wheelset's stability and functionality. Following this, the "Axle check" involves a dual inspection: one for overheating at the front of the axle boxes and around the gearbox, and another visual inspection of the axle's paint for signs of corrosion. If any damage is found, further investigation into impact marks or corrosion is necessary, followed by appropriate touch-up treatments. The procedure also includes a branch for "Wheel overheating or derailment," recommending a thorough inspection if any indications of these issues are present.

4. Conclusion

Railway systems, such as KTMB ETS, are critically dependent on the reliability of their wheels. This study systematically evaluates and aims to enhance the maintenance procedures related to wheel wear and tear in the KTMB ETS Class 91. The first objective of this research was to assess the various maintenance strategies employed for KTMB ETS wheels, with a particular focus on understanding and mitigating wear and tear issues. This involved a detailed analysis of current maintenance practices, their effectiveness, and their impact on the longevity and performance of the wheels within the ETS system. The second objective was to conduct an in-depth analysis of the primary failure modes associated with KTMB ETS wheels using the Failure Modes and Effects Analysis (FMEA) methodology. By systematically identifying potential failure modes, their causes, and their effects, this study provides valuable insights into the vulnerabilities of the wheel system, contributing to the enhancement of preventive and corrective maintenance strategies. The final objective was to propose an optimized approach for improving the KTMB ETS wheel maintenance process. This involved developing recommendations and best practices based on the assessment of maintenance strategies and the critical failure mode analysis. The proposed recommendations aim to optimize the wheel maintenance process, ensuring greater reliability and operational efficiency for the KTMB ETS.

To reduce wheel reprofiling maintenance costs for intercity train sets, several innovative strategies can be implemented, focusing on optimization and condition-based maintenance. First, by implementing condition monitoring at regular intervals allows for timely interventions, reducing unnecessary maintenance and extending wheel service life. Secondly, combining periodic inspections with preventive maintenance can decrease maintenance costs by over 27% while prolonging wheel lifespan (Zhang *et al.* 2022). In contrast, traditional fixedinterval maintenance strategies may lead to higher costs and increased wear, highlighting the need for adaptive approaches in wheel maintenance. In conclusion, this study offers a comprehensive evaluation of KTMB ETS Class 91-wheel maintenance, identifies key failure modes, and suggests improvements. The findings provide actionable insights that can inform future maintenance policies, ultimately contributing to a more robust and reliable railway system for KTMB ETS.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Muhammad Iqmal Syahmi Mohd Zaid, Mohamad Ali Selimin, Nor Aziati Abdul Hamid, Nuramira Najihah Baharin, Amirul Afif Jumiran;* ***data collection:*** *Muhammad Iqmal Syahmi Mohd Zaid, Nuramira Najihah Baharin;* ***analysis and interpretation of results:*** *Muhammad Iqmal Syahmi Mohd Zaid, Mohamad Ali Selimin, Nor Aziati Abdul Hamid, Nuramira Najihah Baharin, Amirul Afif Jumiran;* ***draft manuscript preparation:*** *Muhammad Iqmal Syahmi Mohd Zaid, Mohamad Ali Selimin, Nor Aziati Abdul Hamid, Nuramira Najihah Baharin. All authors reviewed the results and approved the final version of the manuscript.*

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