

Data Driven Predictive Maintenance Framework for Railway Safety in Indonesia

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Article Info

Article history:

Submission June 13, 2025

Revised July 16, 2025

Accepted August 22, 2025

Published September 22, 2025

Keywords:

Early Detection Systems

Railway Safety

Hot Box Detection

Hot Axle Detection

Vibration Sensors



ABSTRACT

Indonesia's railway network faces increasing operational pressures as passenger and freight volumes continue to rise, revealing the limitations of reactive maintenance approaches and emphasizing the need for predictive, data driven safety mechanisms. This study aims to **develop a conceptual** framework for a data-driven predictive maintenance system to enhance railway safety, reliability, and operational efficiency in Indonesia. A **Systematic Literature Review** (SLR) was conducted on international and national studies presents 25 key references published between 2016 and 2025 on early detection systems in railway, focusing on railway condition monitoring, IoT based maintenance, and AI driven safety analytics. The synthesized **findings** indicate that integrating IoT sensors, vibration monitoring, and hot box and hot axle detection systems supported by artificial intelligence and big data analytics can significantly improve early anomaly detection, predictive decision-making, and risk prevention. Nevertheless, several challenges remain, including limited technical capacity, fragmented regulations, and high implementation costs. **The proposed** data driven predictive maintenance framework positions early detection systems as strategic instruments for digital transformation in railway operations, strengthening risk management, promoting sustainable infrastructure, and aligning Indonesia's railway governance with global standards for intelligent and resilient transportation systems.

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DOI: <https://doi.org/10.34306/ajri.v7i1.1322>

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1. INTRODUCTION

Railway transportation holds a vital role in Indonesia's national mobility system, serving not only as a major mode of passenger travel but also as a key enabler of freight logistics across Java and Sumatra. Data from the Central Bureau of Statistics [1] show a steady rise in both passenger and cargo volumes, emphasizing the sector's expanding contribution to national economic activity. With more than 261.8 million passengers recorded in the first half of 2025 alone, railways remain a preferred mode of transportation, especially during peak seasons such as the eid exodus [2]. This continuous growth, however, places immense operational pressure on existing infrastructure, where high frequency and heavy load conditions accelerate mechanical fatigue, component wear, and system degradation.

As network expansion continues, ensuring safety and reliability has become increasingly critical for

maintaining public trust and operational sustainability. The transition from conventional, reactive maintenance practices toward predictive and data driven safety management is therefore imperative [3]. The implementation of Early Detection Systems (EDS) including hot box detectors, vibration sensors, and IoT based predictive maintenance platforms represents a strategic solution to detect anomalies before failures occur. Such systems enable a shift toward proactive safety governance, ensuring that Indonesia's railway modernization aligns with international standards for intelligent and sustainable transport operations [4].

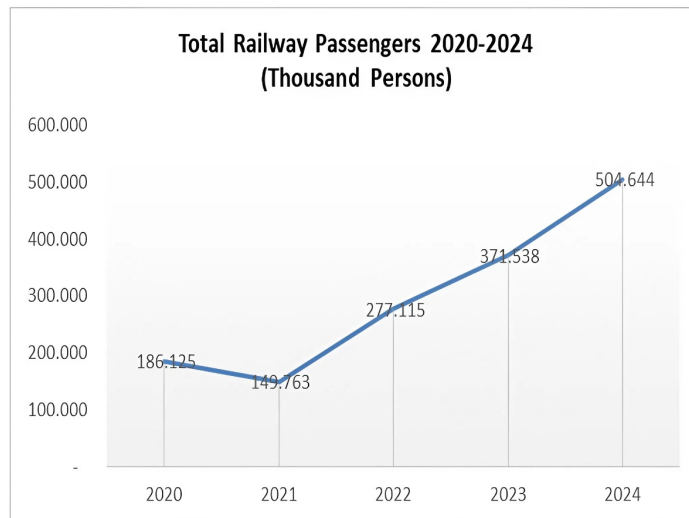


Figure 1. Total Railways Passengers 2020-2024
Sources: BPS, Data Processed

Figure 1 illustrates the dynamic growth of passenger numbers between 2020 and 2024. A decline occurred in 2021 (149.76 million passengers) due to mobility restrictions during the COVID-19 pandemic, representing a 19.5% decrease from 2020. However, recovery was swift: passenger numbers surged by 84.9% in 2022 to 277.12 million, increased by 34.1% to 371.54 million in 2023, and peaked at 504.64 million in 2024 a 35.8% rise from the previous year. This steady upward trajectory underscores the resilience of Indonesia's railway sector and its growing importance as a mass transportation backbone.

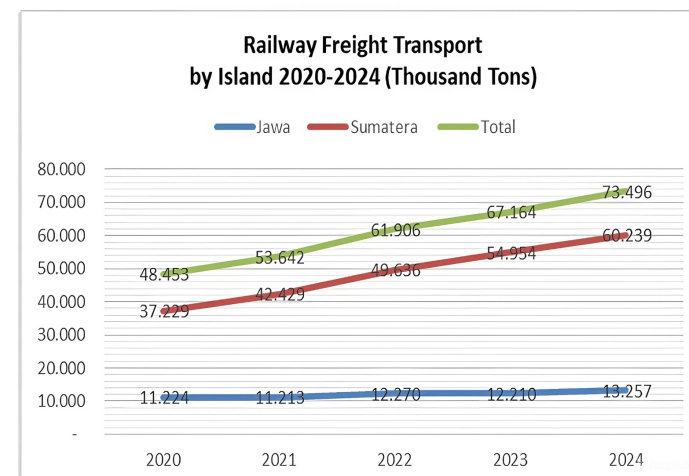


Figure 2. Railway Freight Transport by Island 2020-2024
Sources: BPS, Data Processed

Figure 2 presents freight transport performance by island from 2020 to 2024. The data reveal a consistent upward trend, with total freight volume rising from 48.45 million tons in 2020 to 73.50 million tons in

2024. Sumatra accounts for the largest share of freight activity, while Java demonstrates moderate yet steady growth. These figures highlight the railway's expanding role in supporting inter island logistics and industrial supply chains, further emphasizing the importance of reliable safety systems to sustain this momentum.

The increasing operational demand reflected in the sharp rise of both passenger and freight volumes calls for the integration of advanced technologies to minimize mechanical risks and maintain service continuity [5]. EDS have thus become essential in reinforcing Indonesia's railway safety framework. Beyond their technical functions, these systems embody a strategic shift toward predictive maintenance and data driven decision making that supports modernization, efficiency, and long term reliability. Their implementation reflects a growing national commitment to building intelligent, sustainable, and resilient transport infrastructure that meets global standards of safety and operational excellence [6].

2. RESEARCH METHOD

The development of modern railway transportation demands safety systems that are no longer purely reactive but oriented toward preventive measures through the implementation of early detection of potential technical disruptions. EDS in the railway context are designed to recognize initial signs of damage in critical components, such as tracks, bearings, wheels, and braking systems, before these anomalies escalate into fatal failures that pose high operational safety risks [7]. This approach aligns with global trends in railway transformation, where wireless sensor technologies, machine learning, and deep learning are employed to enhance real time identification of track defects and signaling errors [8, 9]. The integration of these technologies not only improves detection speed and accuracy but also enables transport systems to respond predictively to potential hazards, reinforcing a preventive and intelligent maintenance safety paradigm within modern railway networks. Moreover, early detection systems provide not only technical benefits in damage prevention but also strategic advantages by optimizing maintenance costs and enhancing service reliability [10].

2.1. Hot Box Detection

Hot box detection represents one of the most essential technologies in modern railway safety systems. Its primary function is to monitor the temperature of wheel bearings, which are prone to overheating due to excessive friction, inadequate lubrication, or mechanical fatigue. Continuous temperature monitoring enables early identification of abnormal thermal patterns that may indicate internal damage or the onset of mechanical failure [11]. This early intervention capability helps prevent severe incidents such as bearing seizure, axle fractures, or derailments, which could otherwise cause significant operational disruptions and financial losses.

Beyond its basic temperature measurement function, the hot box detection system integrates advanced sensing elements, automated data transmission, and centralized analysis platforms to ensure real time monitoring and accurate fault prediction [12]. The deployment of these detectors along railway tracks or within rolling stock units allows maintenance teams to identify and isolate affected components before they reach a critical failure stage [13]. Over time, this technology has become a standard component of railway condition monitoring systems, contributing to enhanced safety performance, reduced maintenance costs, and improved reliability across both passenger and freight operations.

2.2. Hot Axle Detection

Hot axle detection serves as a critical complement to hot box detection by specifically targeting abnormal heat levels along the axle shaft an area that plays a central role in supporting wheel rotation and load transfer. Excessive heating of the axle often signifies frictional imbalance, insufficient lubrication, or bearing degradation, all of which may lead to structural damage or system failure if undetected. Through continuous temperature surveillance, hot axle detection enables early identification of potential hazards, allowing maintenance teams to address mechanical anomalies before they escalate into serious safety incidents.

In modern railway systems, hot axle detection operates through the integration of infrared imaging, thermal cameras, and automated alert mechanisms connected to centralized monitoring centers. These systems are capable of capturing high resolution thermal data in real time, even under high speed operational conditions. The collected information is then processed using digital analytics to determine whether temperature deviations exceed safety thresholds. This predictive capability supports a shift from reactive maintenance to proactive safety management, minimizing unscheduled downtime while extending the operational lifespan of rolling stock components [14]. As a result, hot axle detection has evolved into a fundamental component of smart railway infrastructure, enhancing both the efficiency and safety reliability of train operations.

2.3. Vibration Monitoring with Accelerometer Sensors

Vibration monitoring is a vital element of early detection systems, employing accelerometer sensors to capture vibration intensity, frequency, and displacement in railway components. Using high sensitivity Micro-Electro-Mechanical Systems (MEMS), these sensors detect early structural anomalies in rails, wheels, and bearings under high speed or heavy load conditions. The system enables real time monitoring and supports predictive maintenance by identifying irregularities before serious failures occur. Its practical applications focus on two main aspects:

- **Structural Health Assessment:** Continuous vibration data provide insight into the physical condition of rails, joints, and crossings, allowing early detection of stress or wear.
- **Predictive Maintenance Optimization:** Vibration data analyzed through digital platforms help forecast potential failures, minimize downtime, and extend the service life of railway assets.

Overall, vibration monitoring using accelerometer sensors serves as a vital predictive tool in railway safety systems. By providing accurate and continuous feedback on structural conditions, it supports informed decision making, enhances maintenance efficiency, and reinforces the overall reliability of railway infrastructure.

2.4. IoT based predictive maintenance

Furthermore, digital transformation through IoT based predictive maintenance introduces a new paradigm in early detection systems. This technology integrates smart sensors with Internet of Things (IoT) platforms to enable real time condition monitoring and support predictive maintenance [13]. Through this approach, anomalies in infrastructure or rolling stock can be detected earlier via automated data analysis, even before disruptions occur. [15] emphasize that IoT based monitoring systems can prevent derailments by detecting rail defects at an early stage, while [16] highlight that IoT connectivity in the railway industry fosters the concept of smart trains that are safer, more efficient, and more reliable. In summary, the theoretical foundation of early detection systems demonstrates that technologies such as hot box detectors, hot axle detection, vibration monitoring with accelerometers, and IoT based predictive maintenance share a common objective: detecting failures at an early stage to enhance safety, efficiency, and reliability in railway systems. These approaches are also in line with the broader framework of Condition Based Monitoring (CBM) as mandated in ministry of transportation regulation number 60 of 2020, which underscores the importance of preventive mechanisms in Indonesia's railway safety strategy.

2.5. Method

To address the research questions and achieve the stated objectives, this study employs a systematic literature review with a narrative descriptive presentation to examine early detection systems in railway transportation. The review focuses on four core technologies outlined in the conceptual framework, namely hot box detection, hot axle detection, vibration monitoring, and IoT based predictive maintenance. A systematic approach was selected as it ensures procedural clarity in the selection and analysis of literature, while also enabling the integration of theoretical and empirical findings from diverse academic sources [17]. Accordingly, this review not only maps the global development of early detection technologies but also connects them with the challenges and opportunities of implementation within the Indonesian context.

The review process was conducted through a comprehensive search strategy across internationally recognized databases such as Scopus, Web of Science, Springer, and Emerald, complemented by nationally indexed journals in SINTA. The search was limited to the period 2016–2025 using keywords including railway hot box detection, axle monitoring, vibration fault detection, and IoT predictive maintenance. Inclusion criteria were restricted to peer reviewed articles in English or Indonesian with conceptual or empirical relevance to railway safety issues. Studies failing to meet academic standards, lacking evidence based foundations, or unrelated to the research focus were excluded from analysis [18]. The selection process involved screening titles and abstracts, followed by an in depth review to extract patterns of findings. The synthesized results were then formulated to explain the contributions of the four technologies in shaping effective early detection systems, while also providing a conceptual basis for developing implementation strategies in Indonesia.

3. FINDINGS

The findings of this study emphasize that EDS play a central role in advancing the safety and reliability of Indonesia's railway network. The systematic analysis of recent literature indicates that technological integration particularly through thermal detection, vibration monitoring, and IoT based maintenance has significantly transformed traditional safety practices into predictive and data driven models [1]. Each technology contributes to early fault identification, reduced accident potential, and improved operational decision making. Together, these components create an interconnected safety framework that supports the transition toward intelligent and sustainable railway operations. The conceptual structure of these relationships is illustrated in Figure 3, which demonstrates how four major technologies collectively enhance railway safety and system resilience.

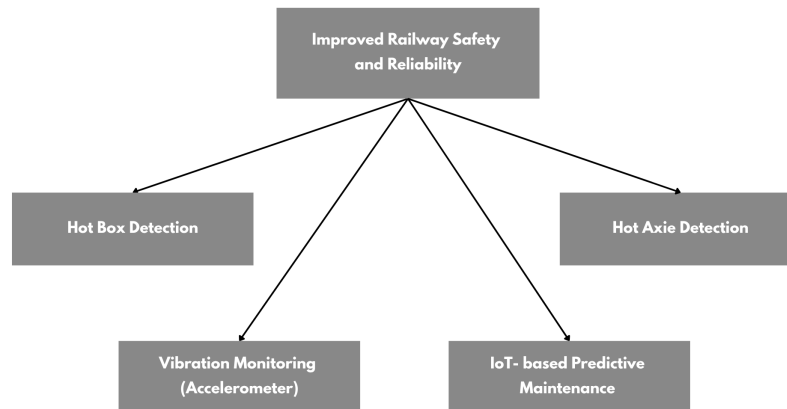


Figure 3. Conceptual Framework: Early Detection System in Railways Safety

The conceptual framework of this study positions EDS as a primary instrument for enhancing railway safety and reliability. Four technologies, hot box detection, hot axle detection, vibration monitoring, and IoT based monitoring, are represented as supporting elements that collectively contribute to the goal of improved railway safety and operational dependability. Figure 3 illustrates the interaction among these technologies, ranging from the prevention of mechanical failures and the early detection of structural anomalies to real time, data-driven decision making. This framework emphasizes the integration of both technical and strategic dimensions of EDS into railway operations and safety policies, thereby minimizing failure risks and reinforcing operational reliability.

Furthermore, hot box detection functions to identify rising wheel bearing temperatures that may indicate severe damage if left unaddressed. Second, hot axle detection complements this function by focusing on axle temperature monitoring, thereby anticipating potential mechanical failures in both bearings and wheels. Third, vibration monitoring using accelerometer sensors adds another dimension by capturing real time vibration patterns from both infrastructure and rolling stock, enabling the early identification of structural anomalies. Fourth, IoT based predictive maintenance introduces digital integration through smart sensors and Internet of Things (IoT) platforms, facilitating continuous monitoring and predictive maintenance.

Although differing in technical approaches, these four technologies share a common thread: the early detection of damage to prevent major failures, minimize accident risks, and enhance operational efficiency. Thus, the conceptual framework demonstrates that the integration of early detection technologies is not only relevant as a technical solution but also as a systemic strategy to build a safer, more efficient, and sustainable railway service.

To strengthen the conceptual framework and ensure its alignment with the Indonesian context, Table 1 presents 25 key references published between 2016 and 2025 on early detection systems in railways [19]. The literature is organized into four main clusters, hot box detection, hot axle detection, vibration monitoring, and IoT based predictive maintenance, that form the core of this study. Each reference was analyzed based on its methodology, key findings, and practical relevance to Indonesia's railway system. Through this mapping, the study establishes a solid foundation for linking international insights with national needs, particularly in relation to PT KAI's digital transformation and the improvement of rail based transportation safety.

Table 1. Theoretical Mapping of Selected References on Early Detection Systems in Railways

No.	Author(s) (Year)	Detection System	Method	Key Findings	Relevance to Indonesia
1	J. Dumoulin, B. Merainani, and T. Toullier, 2024 [9]	Hot Box Detection	Real-time thermal imaging on moving trains	Detects abnormal axle heat at high speed	Suitable for dense tropical railways like Java
2	C. Tarawneh, B. Wilson, and B. Porter, 2024 [20]	Hot Box Detection	Experimental way-side system analysis	Optimizes detector placement and thresholds	Basis for PT KAI calibration under local climate
3	J.-H. Lee, K. H. Cho, and K. Cho, 2023 [3]	Hot Box Detection (Domestic)	Comparative heat sensor analysis	Notes variation in sensitivity; promotes multi-sensor use	Strengthens local detection systems
4	M. Z. Shaikh, Z. Ahmed, B. S. Chowdhry, 2023 [21]	Hot Axle Detection	Review of sensor-based studies	Highlights AI-assisted axle and wireless sensors	Supports AI- and IoT-based monitoring in Indonesia
5	L. Ariani, F. Winjaya, and N. F. Rachman, 2024 [5]	Hot Axle Detection (KNN)	KNN classification of axle data	Accurately separates normal vs faulty patterns	Enables data-driven detection for PT KAI
6	E. Tudor, I. Vasile, D. Lipcinski, 2025 [22]	Vibration Monitoring	Review of MEMS and piezo sensors	Detects micro-vibration and early resonance	Basis for predictive maintenance program
7	J.-Y. Shih, P. Weston, M. Entezami, C. Roberts, and M. O'Callaghan, 2024 [23]	Vibration Monitoring (Field)	Field test with multi-axis MEMS sensors	Captures subtle track vibration patterns	Useful for Jabodetabek line degradation monitoring
8	E. Jansson, N. O. Olsson, and O. Fröidh, 2024 [1]	Vibration Monitoring (Smart Infra)	MEMS validation on rail systems	Confirms low-cost predictive maintenance potential	Adaptable for modernization projects
9	A.-Q. O. Gbadamosi, 2023 [13]	IoT-Based Predictive Maintenance	IoT, cloud, and AI integration	Detects degradation; cuts downtime by 35%	Supports condition-based maintenance programs
10	N. Davari, B. Veloso, G. d. A. Costa, 2021 [8]	IoT-Based (Data-Driven)	ML framework using sensor data	Enables automatic failure prediction	Aligns with Indonesia's Smart Rail initiatives
11	W. T. Adi, B. R. Nugroho, and H. W. Puruhita, 2025 [2]	IoT-Based (Track Inspection)	IoT-GPS track monitoring	Detects voids with 90% accuracy	Strengthens domestic IoT inspection capability
12	H. U. R. Siddiqui, A. A. Saleem, M. A. Raza, 2022 [24]	IoT-Based (Fault Detection)	Acoustic AI-based localization	High-accuracy fault detection in real time	Ideal for Smart Rail and remote operations

Early detection systems serve as a cornerstone of Indonesia's railway safety, particularly amid ongoing digital transformation. The Hot Box Detection cluster plays a critical role in identifying abnormal temperature rises in axle bearings before catastrophic mechanical failures occur. As shown in Table 1, studies by [25] introduced way side thermal infrared imaging capable of precisely detecting excessive heat even at high train speeds. This non contact technology is highly relevant for intercity passenger trains in Java and Sumatra, as well as for KRL Jabodetabek, which require automated inspections without disrupting operations. By research [26] emphasize the importance of optimizing sensor locations and temperature thresholds to support condition based maintenance, particularly for heavy freight trains over long routes with extreme temperature variations. Locally, by research [25] demonstrated the effectiveness of thermal sensors on the Surabaya–Madiun line, highlighting the need for multi sensor integration to accelerate response times. Furthermore, studies by [27] with the OPTIBOX device and [28] using unattended mainline system log analysis reinforce the significance of data analytics and adaptive sensor distribution. Consequently, the development of Hot Box Detection in Indonesia should focus on sensor positioning, calibration, and data integration to enhance operational safety across all train types, from intercity and commuter lines to MRT, LRT, high speed rail, and freight transport.

The Hot Axle Detection cluster emphasizes real time monitoring of axle temperatures and bearing conditions to prevent overheating, wheel sliding, and structural failures. By research [29] developed an automatic method using thermal imagery to detect sliding railway wheels and hot bearings, enabling early identification of friction induced damage that could threaten operational safety. According to Table 1, by [21] highlight the transition to wireless systems based on the Internet of Things (IoT) and Artificial Intelligence

(AI), which significantly reduce axle failure rates. These systems are especially suitable for high speed trains on the Jakarta–Bandung corridor and KRL Jabodetabek, which require continuous automated diagnostics.

Local research by [5] reinforces contextual relevance through K-Nearest Neighbors (KNN) machine learning experiments to detect anomalous axle patterns with high accuracy, making it suitable for intercity trains with long routes and high wear levels. By [9] combine thermal infrared imaging with Kalman filters for rapid axle tracking, ideal for high speed modes. The MAXBE project by [30] highlights energy efficiency through low power smart sensors, relevant for freight trains on logistic routes and areas with limited electricity supply. Overall, Hot Axle Detection has evolved into an intelligent, data and AI driven system adaptable to various train types, including intercity lines in Java and Sumatra, LRT, MRT, high speed rail, and freight, and the tropical conditions of Indonesia, thereby enhancing both safety and operational reliability.

The Vibration Monitoring cluster occupies a strategic position within early detection systems in Indonesian railways due to its capacity to identify structural anomalies before they escalate into critical failures. This system analyzes changes in vibration patterns of bearings, wheels, rails, and track joints as early indicators of dynamic wear. According to Table 1, [22] demonstrate that Micro Electro Mechanical Systems (MEMS) accelerometers are a core component of condition based monitoring, providing precise observation of vehicle and infrastructure dynamics. These sensors can capture high frequency resonances indicative of potential cracking, making them highly relevant for intercity passenger trains in Java and Sumatra, as well as high speed freight trains with heavy loads.

By study [23] expand the application of MEMS sensors to switches and crossings, areas susceptible to complex vibrations caused by wheel direction changes. Their findings highlight the ability of these sensors to detect micro displacements and subtle vibration patterns that conventional devices cannot capture, suitable for KRL Jabodetabek, MRT Jakarta, and LRT Jabodebek operating on densely trafficked lines requiring high track stability. [30] mark the early implementation of MEMS for smart railway infrastructure, evidencing that compact, energy efficient sensors can transmit real time data to control centers, aligning with PT KAI's planned control monitoring system. [31] further introduced self powered triboelectric nano vibration accelerometers, ideal for logistical routes outside Java with limited power supply.

By research [32] emphasize the reliability of MEMS accelerometers in detecting multi-directional vibrations in humid tropical environments such as Indonesia, while [3] confirm their effectiveness on high speed trains like Jakarta–Bandung. By study [5] extend axle vibration detection through inductive sensors, and [24] demonstrate that vibration disturbances can impact the accuracy of axle counter systems across PT KAI networks. Collectively, these studies indicate that vibration based monitoring is not merely a technical instrument but forms the foundation of predictive safety systems. The combination of MEMS sensors, intelligent algorithms, and IoT data transmission paves the way for a digital maintenance ecosystem adaptable to the operational characteristics of diverse train modes in Indonesia.

The IoT Based Predictive Maintenance cluster represents the most advanced stage in the evolution of condition monitoring based early detection systems. By integrating wireless sensors, real time data processing, and machine learning algorithms, these systems continuously monitor infrastructure and rolling stock conditions, shifting the paradigm from repair after failure to repair before failure. By research [13] demonstrate that IoT based predictive systems in the UK can reduce downtime by up to 35% through a combination of smart sensors, cloud analytics, and AI, a model highly relevant for intercity and freight trains across Indonesian provinces. By study [8] highlight machine learning frameworks that transform sensor data into predictive insights about asset conditions, supporting automated decision making within PT KAI's digital systems. Local research by [33] presents an IoT based Railway Track Void Meter capable of detecting sleeper gaps with over 90% accuracy, accelerating the identification of potential track failures.

In addition, by [24] introduce non invasive acoustic monitoring methods suitable for both passenger and freight trains, providing an alternative for early fault detection without operational disruption. By [34] emphasize derailment prevention systems based on wireless sensors, enhancing safety for urban and intercity networks. By [19] underline the importance of interoperability among sensor systems, supporting the integration of KRL Jabodetabek, MRT Jakarta, LRT Jabodebek, and logistic routes into a centralized control ecosystem. The research [35] demonstrate the use of deep learning for real time railway signal recognition, enhancing operational safety, while [33] implement GPS IoT to continuously monitor moving assets. By study [17] further highlight innovative IoT applications for machinery fault detection in PT KAI depots. Collectively, the integration of these technologies and approaches not only strengthens the safety and reliability of passenger trains, KRL, MRT, LRT, and freight services but also supports the vision of an efficient, resilient, and sustain-

able national predictive maintenance system. The application of this principle is crucial for linking intercity rail monitoring, KRL, MRT, LRT, and logistic lines into a single centralized control ecosystem, realizing the vision of a robust and sustainable national predictive maintenance framework.

As illustrated in Table 1, the synergy between thermal sensors, accelerometers, and IoT systems forms a comprehensive theoretical mapping for the implementation of condition based monitoring (CBM) early detection systems across Indonesia's national railway network. The integration of Hot Box Detection, Hot Axle Detection, and Vibration Monitoring establishes a multi sensor system capable of precisely identifying structural anomalies, enhancing real time diagnostics, and improving maintenance efficiency and operational safety across all train modes in Indonesia, from KRL Jabodetabek, MRT Jakarta, and LRT Jabodebek to high speed trains Jakarta-Bandung, intercity services in Java and Sumatra, as well as provincial freight transport.

This literature mapping underscores two key points. First, the effectiveness of early detection systems depends heavily on the collaboration of multi modal sensors (thermal, accelerometer, and IoT), which not only minimize false alarms but also accelerate the detection of potential failures. Second, the successful implementation of CBM relies not only on technology but also on institutional readiness, digital infrastructure, and operational regulations in Indonesia [27]. Integrating these perspectives opens avenues for further research, aiming not merely to replicate global models but to design adaptive, contextually relevant strategies for the national railway system transformation, including urban modes such as KRL, MRT, and LRT.

Globally, the evolution of early detection systems reflects a shift toward real time monitoring, IoT integration, and AI-driven predictive analytics. This approach enhances the accuracy of axle overheating detection, reduces the risk of false negatives, and strengthens condition based maintenance with the support of big data analytics. Nevertheless, challenges such as false alarms caused by extreme conditions and environmental variability remain critical issues, particularly for high frequency systems like KRL Jabodetabek, where schedule stability and operational reliability are paramount. Thus, the success of CBM is measured not solely by technological sophistication but also by its ability to balance detection precision, data stability, and systemic integration readiness. The combination of technical and institutional aspects is key for Indonesia to develop an adaptive, predictive, and safety oriented early detection system across all railway modes.

Currently, PT KAI and urban rail operators in Indonesia still rely on manual inspections and reactive approaches to technical disruptions. Such systems carry high risk, especially on densely trafficked intercity routes in Java and urban lines in Jabodetabek, which serve millions of passengers daily. Local studies, including [36], demonstrate early steps toward algorithm based detection systems, though these remain limited. Observing this trend, there is significant potential to integrate early detection systems into the digital transformation agenda of PT KAI and urban operators. For instance, the deployment of low cost accelerometer sensors [22, 23] on KRL tracks or the use of IoT based asset tracking [33] on MRT and LRT lines can enable faster fault detection while supporting the smooth daily operation of public transport. Furthermore, Indonesia's railway infrastructure differs from that of developed countries: many intercity lines utilize older rails, whereas MRT and LRT lines are constructed with modern infrastructure. This implies that technology deployment strategies must be differentiated, strengthening legacy systems while fully integrating new systems.

Indonesia already has a relatively strong regulatory framework for railway safety, including law number 23 of 2007 on railways, government regulation number 72 of 2009 on railway traffic and transport, and several ministry of transportation regulations such as permenhub number 60 of 2012, number 63 of 2019, and number 60 of 2020 on Railway Digitalization. These frameworks cover the development and implementation of digital systems, including real time monitoring, operational data integration, and the use of sensors and IoT for enhancing safety and efficiency. However, practical implementation remains limited: most inspections and safety routines are still conducted manually due to uneven digital infrastructure, limited technical capacity, and the absence of a comprehensive national roadmap with secured funding for EDS deployment.

The integration of these approaches aligns closely with Condition Based Monitoring (CBM), which leverages sensor data and IoT connectivity to support real time decision making in infrastructure and rolling stock management. Within the framework of Ministry of Transportation Regulation number 60 of 2020, CBM provides not only a technical but also a regulatory basis for embedding early detection systems into Indonesia's railway safety strategy, ensuring that operational growth is matched with stronger preventive mechanisms. Consequently, policy directions must be reinforced through regulatory updates that accommodate global technological developments, such as technical standards for real time monitoring, certification of safety sensors and software, the preparation of a national roadmap for EDS adoption across all railway modes (KRL, MRT, LRT), investment in technology, collaborative research among academia, operators, manufacturers, and industry as-

sociations, as well as strengthening cybersecurity to protect IoT based operational data. In this way, regulation would not only be normative but also adaptive to technological innovation and the safety needs of modern transportation.

Existing literature also reveals a gap in contextual research within Indonesia, both on intercity lines and urban rail networks. Much of the scholarship originates from developed countries with modern infrastructure, making direct adoption difficult without adaptation. Thus, pilot studies are needed on major intercity routes, such as Jakarta–Surabaya, and on urban systems like KRL Jabodetabek, MRT Jakarta, and LRT Jabodebek, to evaluate detector performance under tropical conditions and high traffic intensity. Further research should also advance toward the integration of artificial intelligence and big data analytics to enable system failure prediction rather than mere detection. Cost benefit analyses will be equally crucial to assess the feasibility of investment compared to the potential economic and social losses from accidents or service disruptions. On the technical side, the development of energy efficient sensors, such as self powered devices, is essential for deployment in remote tracks or areas with limited electricity supply. Moreover, capacity building in human resources, including technician training, data scientist integration, and knowledge management systems, is a prerequisite to ensure sustainable implementation. Finally, social aspects must also be considered, as the adoption of EDS could enhance public trust in rail based transport, encourage a shift from private vehicles to mass transit, and support the broader agenda of green mobility and national transport sustainability.

4. MANAGERIAL IMPLICATION

The implementation of EDS in Indonesia's railway sector carries significant strategic implications for managerial decision making, particularly for PT KAI and urban rail operators such as MRT Jakarta and LRT Jabodebek. Management should view EDS not merely as a technological project but as a long term risk management instrument that can reduce accident potential, extend infrastructure lifespan, and enhance service reliability. Investment decisions should prioritize systems capable of cross subsystem integration ranging from hot box detectors and vibration sensors to IoT based predictive platforms to create a comprehensive safety chain. Accordingly, budget allocation and investment priorities must be based not only on initial costs but also on long term value creation in the form of maintenance savings, operational efficiency improvements, and strengthened public trust and reputation.

For operational managers, EDS implementation demands organizational transformation and human resource capability development. Sensor and IoT based detection systems generate large volumes of data that require advanced analytical skills and data driven decision making. Therefore, management should establish dedicated safety monitoring units, train technicians and analysts in predictive maintenance, and develop rapid response protocols for anomaly detection. These measures not only improve the effectiveness of detection systems but also ensure that technological investments are strategically aligned with the organization's mission to minimize downtime and sustain the reliability of mass transportation services.

From a policy and inter institutional collaboration perspective, senior management must foster strategic partnerships among regulators, operators, and technology providers to build a sustainable safety ecosystem. Developing Public Private Partnership (PPP) models can serve as an innovative financing mechanism to address the high initial investment barriers. In addition, management should promote the harmonization of technical and safety standards across operators while ensuring that EDS implementation aligns with national regulations such as Ministry of Transportation Regulation number 60 of 2020 on Railway Digitalization. Through such collaborative and adaptive approaches, EDS can function not only as a technical safeguard but also as a managerial catalyst that accelerates Indonesia's transition toward a safer, more efficient, and globally competitive railway system.

5. CONCLUSION

This study demonstrates that early detection systems in railways cannot be viewed merely as additional technical devices, but as integral elements of the modern transport safety ecosystem. International literature highlights how technologies such as hot box detectors, hot axle detectors, accelerometer based vibration sensors, and IoT driven predictive maintenance have shifted safety paradigms from reactive responses toward proactive and predictive approaches. As part of the implementation of Ministry of transportation regulation number 60 of 2020 on Railway Digitalization, the adoption of Condition Based Monitoring (CBM) has become a strategic instrument to leverage sensor data and IoT connectivity for real time monitoring of infras-

structure and rolling stock, enabling the identification of anomalies before they escalate. Each technology plays a distinct role: thermal detection prevents catastrophic bearing failures, vibration monitoring uncovers structural anomalies before they reach critical stages, while IoT and CBM provide real time analytics that support faster and more accurate decision making. Despite their technical differences, all converge on the same goals: ensuring safety, enhancing reliability, and improving operational efficiency.

In Indonesia, the urgency of adopting these systems is particularly pronounced in high frequency urban networks such as KRL Jabodetabek, MRT Jakarta, and LRT Jabodebek, where large passenger volumes amplify the risks of undetected failures. While the regulatory framework for railway safety is relatively well established, its focus remains on manual inspections a model that is no longer sufficient for addressing the demands of modern, data driven transport systems. Policy updates are therefore imperative, encompassing real time monitoring standards, certification of safety technologies, and the formulation of a national roadmap for sustainable predictive maintenance.

Nevertheless, adoption is far from straightforward. Key challenges include high upfront investment costs, limited technical capacity, fragmented regulatory responsibilities, and cybersecurity vulnerabilities in IoT based systems. Overcoming these barriers requires multi stakeholder collaboration among regulators, operators, academics, technology providers, and industry associations to ensure knowledge transfer, contextual adaptation, and policy synchronization. At the same time, sustainable financing models, supported by cost benefit analyses, must underscore that initial investments in early detection technologies are substantially lower than the potential economic, social, and psychological costs of accidents or service disruptions.

Within this framework, the practical implications of this study become evident. For regulators, early detection systems call for a paradigm shift from manual inspections and post incident responses to a model of proactive, predictive, and data driven regulation. This entails not only establishing certification mechanisms and legal safeguards against technological risks but also fostering innovative financing schemes to distribute the costs of major safety investments more equitably. In doing so, regulators would assume the role of catalysts, creating not only rules but also an enabling ecosystem for innovation and safety transformation in Indonesia's railway sector.

The adoption of early detection systems presents both opportunities and challenges for various stakeholders in Indonesia's railway sector. Operators are required to integrate modern devices into daily operations, strengthen human resource capacity, and foster an organizational culture that prioritizes safety as a strategic value rather than an administrative obligation. Successful implementation enhances efficiency, reduces service disruptions, and sustains public trust. Such success depends on viewing investment in detection technologies not as a financial burden but as a long-term strategy to consolidate their position amid growing customer expectations and global competition. For technology providers, the findings highlight the need for innovations that are not only technically advanced but also contextually adapted to Indonesia's tropical climate, rail infrastructure, and dense urban operations. Their role extends beyond equipment provision to becoming strategic partners in knowledge transfer, after-sales services, and long-term technical support, thereby shifting relationships with operators and regulators from transactional to collaborative and strengthening the overall safety ecosystem. For academia, this study opens wide avenues for research on transport safety technologies, assessing the field effectiveness of early detection systems, conducting comprehensive cost-benefit analyses, and exploring societal dimensions such as public trust in mass transport technologies. Academia also plays a pivotal role in capacity building through education, training, and collaborative research that bridges theory and practice, ensuring a robust knowledge base for the continuous development of Indonesia's railway sector.


Finally, for society, transport safety must be seen not merely as a technical issue behind the scenes but as a collective right. Early detection systems provide shared protection, ultimately enhancing the sense of security in daily mobility. By recognizing that these technologies are designed to safeguard lives, the public can build greater trust in rail based mass transport while also participating in public oversight and safety advocacy. This trust not only strengthens the user operator relationship but also grants social legitimacy for regulators and government to expand safety innovations across the transport sector.

This study underscores that early detection systems are not merely technical instruments, but reflections of institutional readiness, policy adaptability, and social commitment to public safety. In the Indonesian context, their implementation represents more than regulatory compliance; it signals a broader transformation toward predictive, globally aligned transport governance. When advanced technologies are embedded within adaptive policy frameworks and supported by socio cultural contexts, early detection systems elevate railway safety from a procedural requirement to a shared value that enhances operational reliability and rebuilds public

trust. Ultimately, safety must be understood not only as the execution of technical protocols, but as a collective manifestation of values that unite regulators, operators, industry, academia, and society in shaping a safer, more reliable, and globally competitive future for rail transport.

6. DECLARATIONS

6.1. About Authors

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6.2. Author Contributions

Conceptualization: SB; Methodology: DP; Software: SB; Validation: DP and SB; Formal Analysis: DP and SB; Investigation: DP; Resources: SB; Data Curation: DP; Writing Original Draft Preparation: SB and DP; Writing Review and Editing: SB and DP; Visualization: SB; All authors, DP and SB, have read and agreed to the published version of the manuscript.

6.3. Data Availability Statement

The data used in this study can be obtained from the corresponding author upon a reasonable request. All information analyzed in this paper was derived from credible academic and institutional sources relevant to the study objectives.

6.4. Funding

This research was carried out independently without any external financial support or sponsorship. No grants or funding were received during the stages of research, writing, or publication of this article.

6.5. Declaration of Conflicting Interest

The authors declare that there are no potential conflicts of interest, financial connections, or personal relationships that could have influenced the work presented in this paper. All authors have approved the final version and are collectively responsible for its content.

REFERENCES

- [1] E. Jansson, N. O. Olsson, and O. Fröidh, "Trackside sensors in unattended train mainline systems—a case study of alarm logs from Sweden," *Transportation Research Procedia*, vol. 78, pp. 151–157, 2024.
- [2] W. T. Adi, B. R. Nugroho, and H. W. Puruhita, "Accuracy assessment of railway track inspection equipment 'void meter' based on the Internet of Things," *SAINSTECH NUSANTARA*, vol. 2, no. 3, pp. 46–57, 2025.
- [3] J.-H. Lee, K. H. Cho, and K. Cho, "Emerging trends in soft electronics: integrating machine intelligence with soft acoustic/vibration sensors," *Advanced Materials*, vol. 35, no. 32, p. 2209673, 2023.
- [4] I. Sasono and M. Aman, "Framework of master data management in banking using consolidation and Jaro-Winkler algorithm," *International Journal of Cyber and IT Service Management (IJCITSM)*, vol. 5, no. 2, pp. 186–197, 2025.
- [5] L. Ariani¹, F. Winjaya, and N. F. Rachman, "Check for updates detection of railways through axle detection patterns using inductive proximity sensors," in *Proceedings of the 2nd International Conference on Railway and Transportation 2023 (ICORT 2023)*, vol. 231. Springer Nature, 2024, p. 204.
- [6] A. Booth, M. Martyn-St James, M. Clowes, and A. Sutton, "Systematic approaches to a successful literature review," 2021.
- [7] A. Kadim, I. Yusnita, A. Sutarman, R. Lesmana, and F. A. Ramahdan, "Assessing the impact of corporate governance and strategic leadership on economic growth and market stability," *IAIC Transactions on Sustainable Digital Innovation (ITSDI)*, vol. 6, no. 2, pp. 177–187, 2025.

- [8] N. Davari, B. Veloso, G. d. A. Costa, P. M. Pereira, R. P. Ribeiro, and J. Gama, "A survey on data-driven predictive maintenance for the railway industry," *Sensors*, vol. 21, no. 17, p. 5739, 2021.
- [9] J. Dumoulin, B. Merainani, and T. Toullier, "Study of hot box detection on moving targets using way side thermal infrared camera and image processing methods: application to railway infrastructures," in *European Geosciences Union*, 2024.
- [10] U. Rahardja and Q. Aini, "Evaluating the effectiveness of digital marketing campaigns through conversion rates and engagement levels using anova and chi-square tests," *Journal of Digital Market and Digital Currency*, vol. 2, no. 1, pp. 26–45, 2025.
- [11] A. Eduard, D. Urazayev, A. Sabyrbek, D. Orel, and D. Zorbas, "Ad-hoc train-arrival notification system for railway safety in remote areas," *Internet of Things*, vol. 25, p. 101062, 2024.
- [12] Q. Aini, P. Purwanti, R. N. Muti, E. Fletcher *et al.*, "Developing sustainable technology through ethical ai governance models in business environments," *ADI Journal on Recent Innovation*, vol. 6, no. 2, pp. 145–156, 2025.
- [13] A.-Q. O. Gbadamosi, "An internet of things enabled system for real-time monitoring and predictive maintenance of railway infrastructure," Ph.D. dissertation, Dissertation, University of the West of England, Bristol, 2023.
- [14] D. Sunaryo, E. P. Lestari, S. Puryandani, and H. Hersugondo, "Driving shareholder value through technopreneurship innovation," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 7, no. 3, pp. 751–765, 2025.
- [15] N. F. Hadi and N. K. Afandi, "Literature review is a part of research," *Sulawesi Tenggara Educational Journal*, vol. 1, no. 3, pp. 64–71, 2021.
- [16] A. Sutarman, R. Aprianto, R. Adyatama, K. C. Pokkali, and M. Yusup, "Influence of digital technology & data analytics on strategic decision making," *Startupreneur Business Digital (SABDA Journal)*, vol. 4, no. 1, pp. 12–23, 2025.
- [17] F. Hendra, R. Effendi *et al.*, "The implementation of innovative iot models in machine failure detection and risk mitigation," *Journal of Energy, Mechanical, Material, and Manufacturing Engineering*, vol. 9, no. 2, pp. 121–130, 2024.
- [18] M. Yusup, S. V. Sihotang, M. Sunengsih, L. Devi, and P. A. Sunarya, "Optimizing graduate competitiveness through service with mathematical economics and obe: Optimalisasi daya saing lulusan melalui pengabdian dengan matematika ekonomi dan obe," *ADI Pengabdian Kepada Masyarakat*, vol. 5, no. 2, pp. 92–103, 2025.
- [19] Y. Wang, B. Miao, Y. Zhang, Z. Huang, and S. Xu, "Review on rail damage detection technologies for high-speed trains," *Applied Sciences*, vol. 15, no. 14, p. 7725, 2025.
- [20] C. Tarawneh, B. Wilson, and B. Porter, "Historical implications of wayside detector systems and their ability to detect hot bearing derailments," in *ASME/IEEE Joint Rail Conference*, vol. 87776. American Society of Mechanical Engineers, 2024, p. V001T07A002.
- [21] M. Z. Shaikh, Z. Ahmed, B. S. Chowdhry, E. N. Baro, T. Hussain, M. A. Uqaili, S. Mehran, D. Kumar, and A. A. Shah, "State-of-the-art wayside condition monitoring systems for railway wheels: A comprehensive review," *IEEE Access*, vol. 11, pp. 13 257–13 279, 2023.
- [22] E. Tudor, I. Vasile, D. Lipcinski, C. Dumitru, N. Tănase, F. Drăghici, and G. Popa, "Accelerometers in monitoring systems for rail vehicle applications: A literature review," *Applied System Innovation*, vol. 8, no. 3, p. 70, 2025.
- [23] J.-Y. Shih, P. Weston, M. Entezami, C. Roberts, and M. O'Callaghan, "Experiences using mems accelerometers on railway bearers at switches and crossings to obtain displacement—awkward situations," *Infrastructures*, vol. 9, no. 6, p. 91, 2024.

- [24] H. U. R. Siddiqui, A. A. Saleem, M. A. Raza, K. Zafar, K. Munir, and S. Dudley, "Iot based railway track faults detection and localization using acoustic analysis," *IEEE Access*, vol. 10, pp. 106 520–106 533, 2022.
- [25] B. Merainani, T. Toullier, and J. Dumoulin, "Moving train wheel axles automated detection, counting, and tracking by combining ai with kalman filter applied to thermal infrared image sequences," in *Multimodal Sensing and Artificial Intelligence: Technologies and Applications III*, vol. 12621. SPIE, 2023, pp. 24–32.
- [26] F. A. Baso, S. L. Sitorus, V. Meilinda, S. A. Anjani, and M. Rodriguez, "Analysis of omni channel strategy in digital retail on modern indonesian consumer behavior: Analisis strategi omni channel dalam ritel digital terhadap perilaku konsumen indonesia modern," *ADI Bisnis Digital Interdisiplin Jurnal*, vol. 6, no. 1, pp. 66–76, 2025.
- [27] T. S. Goh, D. Jonas, B. Tjahjono, V. Agarwal, and M. Abbas, "Impact of ai on air quality monitoring systems: A structural equation modeling approach using utaut," *Sundara Advanced Research on Artificial Intelligence*, vol. 1, no. 1, pp. 9–19, 2025.
- [28] D. Novitasari, F. S. Goestjahjanti, U. Rahardja, S. Santoso, S. V. Sihotang, N. A. Santoso, and G. P. Cesna, "Optimizing msme performance through marketing capabilities and digital marketing adoption," in *2025 4th International Conference on Creative Communication and Innovative Technology (ICCIT)*. IEEE, 2025, pp. 1–7.
- [29] S. E. Minson, E. S. Cochran, S. Wu, and S. Noda, "A framework for evaluating earthquake early warning for an infrastructure network: An idealized case study of a northern california rail system," *Frontiers in Earth Science*, vol. 9, p. 620467, 2021.
- [30] H. Qizhou, F. Xin, and B. Lishuang, "Natural disaster warning system for safe operation of a high-speed railway," *Transportation safety and environment*, vol. 3, no. 4, p. tdab019, 2021.
- [31] R. Anindita, V. H. Prastowo, and J. Parker, "Reinforcing the role of cyber village in improving indonesia msms through an exploratory study," *Aptisi Transactions on Technopreneurship (ATT)*, vol. 7, no. 3, pp. 726–737, 2025.
- [32] A. E. Widjaja, M. Mulyati, D. Supriyanti, I. N. Hikam, F. S. Goestjahjanti, K. Kamar, and J. Nathalie, "Implementation of cloud-based information management to enhance work efficiency in information technology companies," *International Transactions on Artificial Intelligence*, vol. 3, no. 2, pp. 150–160, 2025.
- [33] S. Suakanto, T. A. Nugroho, E. Nuryanto, S. N. Lathifah, and H. Nuraliza, "Moving asset tracking using gps sensor and internet of things," *Jurnal Telematika*, vol. 19, no. 2, pp. 65–71, 2024.
- [34] N. Lutfiani, I. Sembiring, I. Setyawan, A. Setiawan, U. Rahardja, and S. Sulistio, "Exploring the relationship between artificial intelligence and business performance," *IJCCS (Indonesian Journal of Computing and Cybernetics Systems)*, vol. 19, no. 1, pp. 1–12, 2025.
- [35] A. Staino, A. Suwalka, P. Mitra, and B. Basu, "Real-time detection and recognition of railway traffic signals using deep learning," *Journal of big data analytics in transportation*, vol. 4, no. 1, pp. 57–71, 2022.
- [36] A. R. Dina, N. Alifah, L. Paz *et al.*, "Leveraging big data for student success and institutional growth: Memanfaatkan big data untuk kesuksesan mahasiswa dan pertumbuhan institusi," *Jurnal MENTARI: Manajemen, Pendidikan dan Teknologi Informasi*, vol. 3, no. 2, pp. 147–156, 2025.