

Comparative Analysis of the Effectiveness of Wayside and Onboard Systems for Condition Monitoring and Fault Detection

Nafiz Idlan Salman¹, Musli Nizam Yahya^{1*}, Norazman Abu Hassan¹

¹ Department of Transportation Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Muar, 84600, Pagoh, Johor, MALAYSIA

*Corresponding Author: musli@uthm.edu.my

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Abstract

This research study compares onboard and wayside condition monitoring of railways in light of three key features: real-time condition monitoring, ability to detect faults, and cost. A qualitative theme analysis of 52 literature samples was conducted, with evidence of both onboard and wayside systems to provide a balanced perspective. The data was organized in repeated readings, presented in visual tools such as bar charts to display frequency trends and thematic focuses. Findings show that onboard systems are very valuable as they enable real-time and continuous data collection techniques, and discrete fault detection, making them very useful for predictive maintenance and safety. In contrast, wayside systems had more relationship with cost efficiency because of their centralized capability that can monitor many trains without onboard costs; however, wayside systems seemed less capable of detecting changing, in-service anomalies. It is suggested that an onboard monitoring system is the best option for today's railway operations, particularly when referring to safety, rapid diagnostics, and reliability. The advice to the railway operators was to utilize onboard technology as part of their scheduled preventative maintenance, since there are high costs in a way that would be considered an investment in order to reduce unexpected failures and improve performance. In this sense, the research supports good decision-making in railroad asset management and strategically expresses the value of modern monitoring technology onboard.

1. Introduction

Condition monitoring plays an important role in assuring the safety and efficiency of rail operations. Two common technologies utilized for condition monitoring are onboard and wayside systems. Wayside systems are trackside installations that collect data as trains transit, and they typically have lower cost installations, and they can cover an entire fleet of trains. However, they also collect data at irregular intervals, and they may miss issues that may occur between the places where the data is collected. In contrast, onboard systems are physically mounted to rolling stock, and they provide continuous, real-time monitoring of train wheels, brakes, and bearings. These systems enable quick actions to be taken, but they usually require more expensive installations and have higher maintenance costs. Each provided method has certain advantages as well as limitations. Wayside systems offer advantages for standard process inspections and centralized monitoring, while onboard systems have some of the best fault detection and predictive maintenance options. As the rail sector moves towards data-driven maintenance, hybrid options that utilize both methods are increasing. This

paper will assess the effectiveness of onboard and roadside systems related to real-time monitoring, fault detection, and costs, to provide recommendations on the way to achieve more efficient and sustainable maintenance practices.

1.1 Problem Statement and Objectives

Today's railway networks depend on condition monitoring and fault detection to operate safely, effectively, and continuously. Wayside and onboard systems are the two main approaches to condition monitoring and fault detection technologies for detecting failures in the key railway components - wheels, brakes, and bearings. Wayside condition monitoring systems consist of trackside sensors that detect or monitor trains as they pass and therefore provide a periodic snapshot of the component's condition at designated checkpoints along the track. Whereas onboard condition monitoring systems are sensors installed on trains, which provide continuous and real-time monitoring and condition status of components under inspection while the train is operating. The two systems offer unique advantages and disadvantages with respect to data coverage, cost, operating frequency, and reliability, and this can make it difficult for rail operators when evaluating what approach (or combination) best meets their operating and maintenance requirements. Both systems similarly have their pros and cons, and their particular advantages are still uncertain with respect to which system is superior for predictive maintenance. As a response to this knowledge gap, this study will evaluate and compare the two different condition monitoring methods focusing on their respective advantages or disadvantages as well as performance from a fault detection, cost-effectiveness and efficiency of maintenance perspective. The aims of this study will be to: report on the condition monitoring and fault detection capabilities of both systems; compare maintenance impact, cost-effectiveness and reliability; and investigate if there is potential for hybrid use of onboard and wayside systems that may deliver benefits to railway performance.

2. Literature Review: Wayside Monitoring Systems

Wayside monitoring systems help to operate the railways safely and efficiently by providing real-time information, allowing for the quick identification of problems or defects in rolling stock and track infrastructure. Wayside monitoring systems use various types of sensors placed at fixed positions along the track to assess the condition of the operating trains. The system will also enable the planning of preventive maintenance samplings, enhancing the assurance of serviceability. HotBox Detectors (HBD), a key element of wayside monitoring systems, use non-contact infrared sensors to identify overheated axle bearings. These sensors are necessary contributors to help detect high-risk problems that can result in derailments [1]. The Wheel Impact Load Detector (WILD) is another key sensor used within railway monitoring systems that identifies and quantifies the dynamic loads being applied by wheels on the track. The WILD systems identify problems like flat and out-of-round wheels, and the data will help schedule maintenance quickly in response to those detections to prevent breakdowns [2]. Acoustic detection systems, such as the Trackside Acoustic Detection System (TADS), monitor the sounds emitted by worn train parts (and especially bearings) using an array of microphones and algorithms to process variables in the signals. Typically, wayside systems are able to detect deviations from normal sound patterns that denote a developing condition. Interpreting these changes in sound may be complicated by the addition of background noise or the presence (in some cases) of the Doppler effect, which changes the sound patterns [3]. While these and other impediments complicate the acoustic analysis made by the waysides, they nonetheless remain an important area of railway operation management that provides critical information to equip the railway with technologies that provide safety, performance, and accident-avoidance information.

2.1 Literature Review: Onboard Monitoring Systems

Onboard monitoring systems are paramount in improving the safety, efficiency, and reliability of rail operations. Onboard monitoring systems use different sensors placed onto trains or rolling stock as well as smart features to continuously monitor the health or state of many items on an operational vehicle, and then data ingestion, collection, and analysis occur. Vibration sensors are one of the most utilized onboard sensors to track issues associated with the wheels and bearings. Vibration sensors capture vibrations in train components and, using the data, track frequency and amplitude to determine abnormal patterns that may be an indicator of problems in their early stages. Onboard vibration as a tool—algorithms and scoping data—offers valuable insights into the health of components and plans for maintenance ahead of time [4]. Temperature sensors are also a significant element of onboard systems. These sensors track axle bearing hot spots, helping to discover a case of possible overheating and to detect the first occurrence of breakdown before it leads to catastrophic brake failure. With onboard technology, the temperature sensors can also be integrated into the existing braking systems on the train and confirm that brake disc temperature is not in an unsafe range, reducing the effect known as brake tag on maintenance schedules, as they will perform better overall [5]. Onboard systems can also give braking wear information and ultimately both pad and disc wear details. With modern algorithms, this information could initiate a predictive maintenance model that can dramatically reduce the chances of brake failure. Onboard

monitoring systems provide comprehensive continuous diagnostics, which means that the railway operators can implement preventative maintenance, which can make railway operations a safer, efficient, and overall more effective mode of travel [6].

2.2 Methodology

The study used a qualitative comparative analysis methodology that included a full literature review and thematic analysis of the existing research literature. The aim was to review and compare the effectiveness of onboard and wayside condition monitoring systems for railway maintenance and problem finding. A qualitative method was selected to explore the discussion of the variety of monitoring systems in the executive, academic, and technical research literature to provide a complete understanding of performance, cost, safety, and operational feasibility. The study drew on secondary data available in peer-reviewed journals, technical papers, and industrial sources rather than collecting primary data using interviews or field measurements. This analysis at a distance provided the opportunity to seek out different perspectives and case-specific data, which was very useful for investigating systems that had been implemented across different rail networks internationally. This method would also avoid the limitations of gaining access to commercially confidential railway locations. The design features allow for identifying trends, defining themes, and making systematic comparisons between the technologies. This interpretive analysis focused on the strengths, weaknesses, and integration potential of the two systems. Thematic analysis was done using a structured framework, which helps in synthesizing and comparing. The reported findings are designed to help railway operators and maintainers make informed decisions on condition monitoring strategies.

2.3 Research Flowchart

The research flowchart illustrates the sequential order of steps taken in the study, as shown in Figure 1. The process begins with identifying research goals, which are described by three central themes: real-time monitoring, fault detection, and cost-effectiveness. Secondary data was accessed through academic databases such as Google Scholar and Science Direct. Each type of literature was reviewed to find relevant snippets. The excerpts were categorized in Microsoft Excel by system type, code, and theme, where applicable. A decision point determined if the snippet matched any of the established code. If there was a mismatched coding, the snippet was re-conceptualized or recategorized. After the decisions were made, the data was coded and themed to recognize patterns between on-board and wayside monitoring devices. A thematic analysis was completed next to assess performance across the three focus areas. Results were organized in charts for comparison and interpretation. Finally, the conclusions were drawn from the summary of key evidence findings to produce recommendations that aligned with the research objectives. Overall, the study's systematic process enabled consistency, reliability, and logical flow for finishing the investigation.

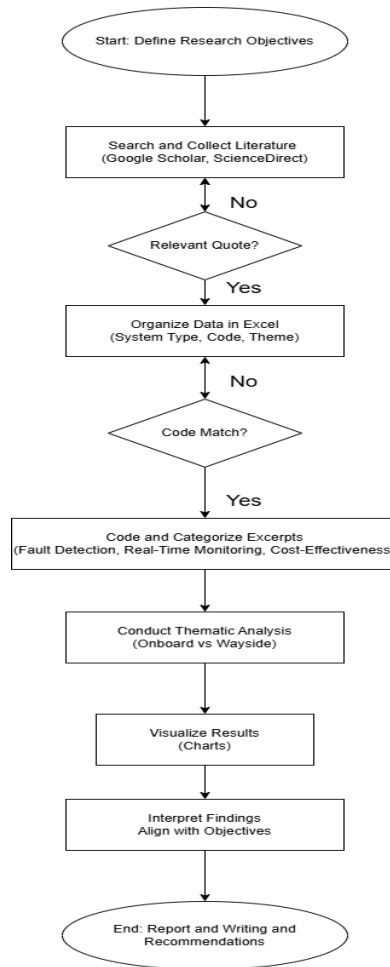


Fig 1: Flowchart for each step from defining objectives to the final reporting stage.

2.4 Data Collection

This study used solely secondary sources from peer-reviewed journals, technical reports, and conference papers published between 2010-2024. The data were collected using academic search engines like Google Scholar and ScienceDirect with keyword searches including “onboard condition monitoring,” “wayside monitoring systems,” “railway fault diagnosis,” and “predictive maintenance in railways.” The collected data is illustrated in Table 1, showing how the quotes were excerpted and classified based on system type and thematic relevance. In total, 52 extracts related to the keywords were included, 26 related to onboard systems and 26 related to wayside systems, to provide a balanced comparison analysis. Each excerpt was read to locate all relevant extracts, extracted, and classified using a Microsoft Excel spreadsheet with metadata from the article, including the published date, author, and the type of monitoring system used. This process permitted a standardized format for coding, thematic classification, and improving the reliability and tractability of the results.

Table 1: Some of Collected and Coded Qualitative Data for Onboard and Wayside Monitoring Systems

No	Source	Excertps/Quotes	Code	Theme	System Type
1	Fu et al.,2023	Real-time monitoring of the operating environment of high-speed trains is critical, as it directly influences safety during transit.	Real-Time Monitoring	Performance	Onboard
2	Li et al.,2024	Accurate, real-time data collection enables operators to mitigate risks associated	Real-Time Monitoring	Performance	Onboard

with pantograph failures.

3	Tsunashima et al., 2018	Wayside systems... utilizing data from probe vehicles equipped with sensing technologies, can precisely identify maintenance needs along tracks in real time.	Real-Time Monitoring	Performance	Wayside
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3. Results

The study presents the results of a thematic analysis of 52 academic excerpts, 26 on onboard condition monitoring systems and 26 on wayside condition monitoring systems. The analysis was based on three core themes: real-time condition monitoring, fault detection, and cost-effectiveness, consistent with the purpose of the study. Each excerpt was grouped by system type and thematically coded using Microsoft Excel. The coding would suggest that onboard condition monitoring systems are most often associated with continuous, real-time diagnostics and problem detection, while wayside condition monitoring systems are identified with cost-effective solutions for condition monitoring based on centralized infrastructure. Summaries of the coded frequencies can be found in Table 2, and a visual comparison can be seen in Figure 2. The following sections will discuss each theme in detail.

Table 2: Frequency of Coded Excerpts by Theme and System Type

Code	Onboard	Wayside
Real-Time Monitoring	10	8
Fault Detection	10	7
Cost-Effectiveness	6	11

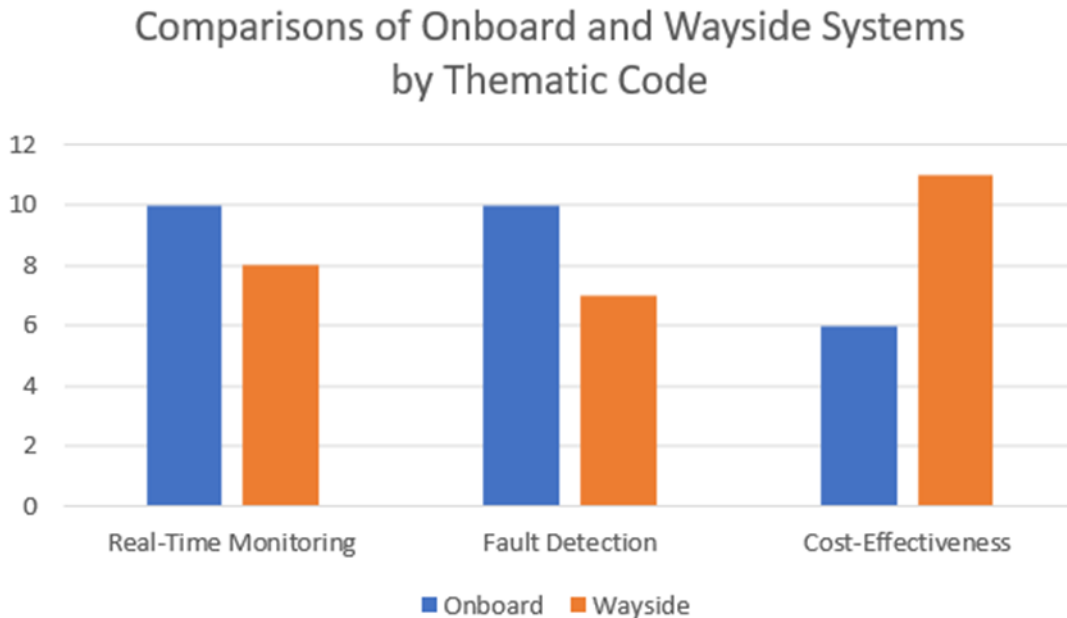


Fig 2: Illustrates the comparative emphasis between onboard and wayside monitoring systems based on 52 excerpts. Onboard systems are more often associated with Real-Time Monitoring and Fault Detection, while wayside systems show higher frequencies in Cost-Effectiveness.

3.1 Real-Monitoring

Real-time monitoring is a significant performance metric in condition monitoring systems. Of the 18 linked passages, 10 referenced onboard systems while 8 referenced wayside systems. Onboard systems demonstrated a stronger connection to real-time diagnosis, likely because they can monitor components continuously via activated sensors (GPS and accelerometers) in transit. Thus, onboard condition monitoring systems have advantages, as early fault detection can take place and the reaction time can be much more immediate. Wayside systems are limited by snapshots in time when a train collects data as it travels between specified checkpoints. In terms of systems configuration, onboard systems are attached directly to the rolling stock as shown in Figure 3, often in axle-box, monitoring index bodies for vibration, temperature, and rotational speed in real time, during the whole journey of the train. Wayside systems consist of fixed sensor units attached to the track (like hot bearing detectors, wheel defect detectors, and vehicle identification systems) that are triggered by the passing train, as shown in Figure 4. Wayside devices provide real-time data, but only when a train passes (and not continuous data). Because of the limited and intermittent nature of wayside coverage, they are not as responsive as onboard systems with continuous real-time monitoring. Onboard systems allow for continuous real-time diagnostics, especially to assess defects which occur between.

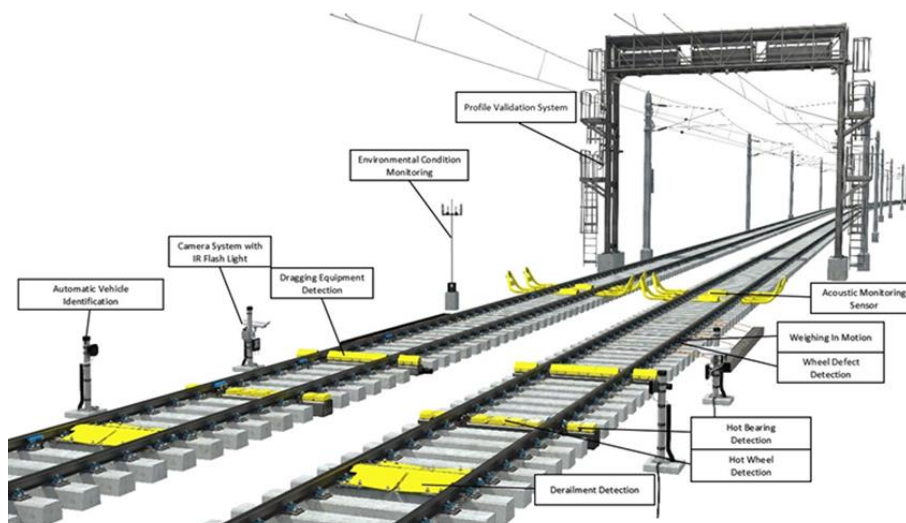


Fig 3: Modular Wayside Diagnostic System integrating multiple sensor types at a fixed trackside location.

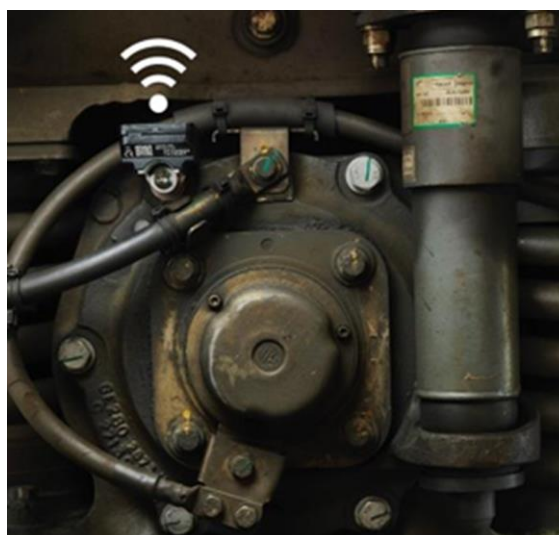


Fig 4: Example of onboard monitoring system sensor installed at a train axle-box for continuous real-time diagnostics.

3.2 Fault Detection

Fault detection systems, both onboard and wayside monitoring systems, have an advantage in this study, with 10 extracts versus 7. Onboard systems ultimately utilize sensors such as vibration sensors and temperature sensors that provide real-time information regarding overheating, part wear, and mechanical issues. These devices provide accurate train-specific diagnostics that enhance safety and improve reaction time. Wayside systems, while less frequently shown, are important for fleet monitoring functions because, as trains pass by fixed detection devices, wayside systems can find wheel flats, overheated bearings, and misaligned axles. Although wayside systems are fleet-wide and reduce manual inspections, their passive and periodic nature prevents real-time responses. An important application of onboard defect detection is the IMx-Rail system, which is shown in Figure 5, including vibration sensors to assess infrastructure health in the normal course of service. This instrumentation records real-time vibration data whilst trains are in motion and relays the data wirelessly to back-office software that is being designed to diagnose and locate the defect without GPS. Visual dashboards, as shown in Figure 6, indicated the fault severity and fault location by color coding the amplitude of the fault.

Bound 1				Bound 2			
Station of departure	Number of exceptions	Vibration amplitude	Station of arrival	Station of departure	Number of exceptions	Vibration amplitude	Station of arrival
Sant Antoni	3	Green	Universitat	Badalona	0	Green	Pep Ventura
Universitat	3	Yellow	Passeig de Gràcia	Pep Ventura	0	Green	Gorc
Sagrada Família	3	Yellow	Encants	Gorc	0	Green	Sant Roc
Paral·lel	1	Green	Sant Antoni	Sant Roc	0	Green	Artigues-St. Adrià
Tetuan	1	Yellow	Monumental	Artigues-St. Adrià	0	Green	Veneda
Passeig de Gràcia	0	Green	Tetuan	Veneda	0	Green	La Pau
Monumental	0	Green	Sagrada Família	La Pau	0	Yellow	Sant Martí
Encants	0	Green	Clot	Sant Martí	0	Green	Bac de Roda
Clot	0	Yellow	Bac de Roda	Bac de Roda	0	Green	Clot
Bac de Roda	0	Yellow	Sant Martí	Clot	0	Green	Encants
Sant Martí	0	Orange	La Pau	Encants	0	Yellow	Sagrada Família
La Pau	0	Yellow	Veneda	Sagrada Família	0	Yellow	Monumental
Veneda	0	Yellow	Artigues-St. Adrià	Monumental	0	Orange	Tetuan
Artigues-St. Adrià	0	Orange	Sant Roc	Tetuan	0	Green	Passeig de Gràcia
Sant Roc	0	Green	Gorc	Passeig de Gràcia	0	Yellow	Universitat
Gorc	0	Green	Pep Ventura	Universitat	0	Green	Sant Antoni
Pep Ventura	0	Green	Badalona	Sant Antoni	0	Green	Paral·lel
				Paral·lel	0	Green	Centre Siding
				Centre Siding	0	Green	Paral·lel 1

Fig 5: Dashboard summary of vibration-based condition monitoring across metro line segments, indicating fault levels by color coding (green = normal, yellow = moderate, red = critical)

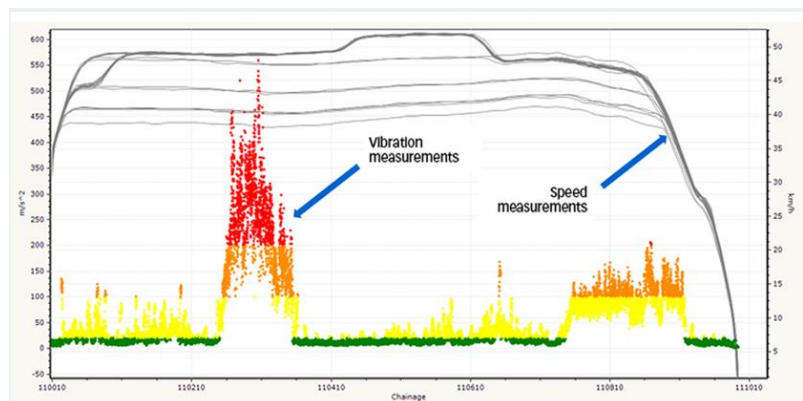


Fig 6: Scatter chart correlating vibration amplitude and train speed during live operation. High peaks in vibration indicate potential track faults that require targeted maintenance.

3.3 Cost-Effectiveness

Wayside monitoring systems are very popular due to their effectiveness and cost-effective performance. By using centralized infrastructure, systems can reduce the need to station inspectors at many places, thereby

allowing monitoring of many trains with fewer sensors. Although wayside requires a large upfront capital investment to install and calibrate in one-off set-ups, it can be cost-effective over time by reducing wear and improving predictive maintenance, so that it tends to be beneficial for operators of large fleets. Onboard systems, while rarely discussed in terms of cost, provide savings due to the cost of unscheduled maintenance avoided, and faster defects being detected. Implementing systems on many trains is costly, even though they can be more convenient, where constantly monitoring high-value or high-speed operations is vital to manage the risk of catastrophic failures. A cost comparison for six years was analyzed as shown in Table 3 to show that the total cost of wayside systems is RM 1,475,520 (including installation and yearly maintenance) as opposed to RM 4,194,000 for the onboard system with larger recurrent maintenance costs per trainset. This example supports the case that wayside systems are cost-effective for larger fleets, and onboard systems are indicated if there is a demand for continuous monitoring and if there are regulatory safety obligations.

Table 3: Comparison of six-year lifecycle cost between wayside and onboard monitoring systems

Cost Details	Wayside System (RM)	Onboard System (RM)
Upfront Cost – 1st year	948,880	294,000 (49k per month)
2nd year	105,328 (Annual)	780,000 (65k per month)
3rd year	105,328 (Annual)	780,000 (65k per month)
4th year	105,328 (Annual)	780,000 (65k per month)
5th year	105,328 (Annual)	780,000 (65k per month)
6th year	105,328 (Annual)	780,000 (65k per month)
Total	1,475,520	4,194,000

4. Conclusion

This research achieved its research objectives, by completing a qualitative thematic analysis of the 52 extracts from the academic literature to analyze and compare onboard and wayside condition monitoring systems. Findings suggest that onboard monitoring systems outperform wayside monitoring systems in both real-time monitoring and fault-finding attributes, providing dynamic, in-transit, on-demand diagnostics that facilitate predictive maintenance and enhance operational safety. In their ongoing diagnostics, onboard systems allow for the proactive identification of defects followed by remediation before failures can impact railway schedules. This proactive approach effectively increases railway service reliability.

Wayside systems have the lower installation cost and proficiency to monitor multiple trains, with lower operating costs for all trains in a centralized infrastructure condition, but both the intermittent and discrete nature of data collection and reporting in wayside systems reduce their overall impact, particularly in the higher demand or higher speed environments. Onboard systems have higher up-front costs, but they are assessed with better long-term value by offering lower risks of unplanned downtime and lower risks associated with catastrophic failures.

In summary, onboard condition monitoring systems are positioned to meet operational realities for condition-based maintenance in a railway setting where safety, performance, and real-time diagnostics are paramount. It is advised that operators and planners consider investing in onboard technology for their pure technical capability, and for the overall operational and safety benefits they espouse. To assist in its suitability, maintenance professionals would require training, and defined diagnostic procedures. While the initial investment to onboard monitoring systems could be expensive, the investment return, through the reduced failures, extended asset life, enhanced service reliability, unmistakably justify proactive procurement of more onboard systems.

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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 author confirm contribution to the paper follows: **Comparative Analysis Of The Effectiveness Of Wayside And Onboard Systems For Condition Monitoring And Fault Detection**: Nafiz Idlan Bin Salman, **Supervisor**: Prof. Madya Ir. Ts. Dr. Musli Nizam bin Yahya and Ir. Ts. Norazman Bin Abu Hassan. All authors reviewed the results and approved the final version of the manuscript.

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