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Failure Analysis and Classification of Brake and Pneumatic Systems in Rolling Stock: A Comprehensive Approach to Enhancing Maintenance Efficiency

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Abstract

In modern railways, especially in the area of the brake and pneumatic environments, means that traditional maintenance techniques are becoming more inadequate. Therefore, need for a paradigm shift towards data-driven, predictive maintenance frameworks. The paper hence exhibits a broad examination of failures and a categorization scheme that would facilitate the advancement of maintenance performance in rail operation. Considering the historical information on maintenance, the investigation isolates a critical set of failure modes and makes use of the advanced tools of analysis, e.g., Visual Basic Applications (VBA) and RapidMiner, to design a hybrid analytical dashboard and predictive model. The step-by-step approach was used: the first stage was dedicated to the data collection, the second one was dashboard construction, and the third one was predictions based on machine learning (Decision Tree) algorithms. The outcomes show significant growth in the accuracy of identifying failures; the classification rate amounts to more than 85 %. With the VBA-RapidMiner integration, real-time visualization and predictive analytics became possible, therefore allowing the proactive maintenance planning and resource optimization. Despite the drawbacks of data completeness and standardization, the proposed framework has a scalable and smart-like way to handle the reliability of brakes and pneumatic systems. This paper contributes to the condition-based maintenance practice in railway engineering, thus ensuring safer, more dependable, and less expensive arrangements in the railways.

1. Introduction

The progressive modernization and urbanization growth that increased economic activities in modern societies have presented the rising need to have an effective and sustainable transportation system. Rail transport is one of the most reliable and energy-efficient modes, and it has a great role in this demand as it will provide mass transit solutions to reduce congestion, pollution of the environment and wastage of power in the form of energy. In spite of these advantages, the urban centers and the surrounding regions are suffering a lot from traffic jams occasioned by rising transportation demands and a shortage of infrastructure. To counter these problems, systems of public transport, especially the railway system, have taken the main focus on fulfilling economic and efficient mobility in the city regions. Brakes and pneumatic systems are considered to be some of the critical subsystems in the railway systems whose operations depend on the rolling stock, which includes passenger coaches, freight wagons, and locomotives, among others. Failure of such systems may mean operational inconveniences, or a high amount to be spent to provide maintenance, and a high security threat to passengers and personnel. Motions, pressures, and electronic interrelations within these subsystems are very intricate, making precise diagnostics of failures and the ability to predict them difficult. The conventional maintenance strategies mostly involve interventions depending on routine checks and fixing, which remain inefficient in meeting the current operations. To mine data contained in maintenance records, operation logs, and performance assessments, the sheer volume of data can inhibit and may frustrate conventional processing modalities and the traditional ways of processing large amounts of data, which can lead to inefficiencies and poor decision-making. There is therefore an unprecedented demand for database approaches to enhance failure analysis and allow predictive maintenance, particularly with the critical subsystems such as brakes and pneumatics. Data analytics and machine learning can be used to develop new opportunities to turn the current reactive approach to the maintenance of the railways industry into a proactive one, thus increasing its reliability and lowering expenses. Nevertheless, using these high-level techniques on rail-type systems, especially on those of brake and pneumatic subsystems, has not been widely possible as it is quite complex in nature as regards component interdependence and the absence of real-time monitoring solutions. This research study therefore offers a solution to these gaps in terms of an elaborated method that incorporates real-time data, advanced simulation, machine learning, and the hybrid analytical tools in an attempt to enhance the fault diagnosis, classification and prognosis. This way, it hopes to improve maintenance planning, resource management and performance and reliability of the railway operations.

1.1 Problem Statement and Objectives

The effective operation of rolling stock and its reliability are associated with the effective functioning of braking systems and the pneumatic system, without which it is impossible to control locomotives, operators, and passengers and organize their stops and maintenance services with a schedule. And when rail networks expand in order to accommodate high-speed activity, the probability of them failing is also rising, bringing about the emergence of huge delays, safety risks, and high costs of maintenance. Conventional maintenance models- comprising mostly of either reactive repairs or preventive checks- fail to cope with the intricate nature of the mechanical and pneumatic dynamics of the modern rolling stock, and thus result in the occurrence of uncontrolled downtime periods, and wasteful drawbacks of the available resources. Moreover, there is no effective structure of failure classification and predictive analysis frameworks of brake and pneumatic systems; therefore, the effectiveness of maintenance methods based on the use of historical data, even a large amount of data on historical cases and advanced types of sensors, is limited. The drawbacks point to the necessity of a holistic approach, which will ensure that failure modes can be identified and classified, as well as predicted in new and different ways, with just the right combination of engineering and how we think of the data and modern data analytics. The major aim of such a study would be to increase the reliability and efficiency of maintenance through the aspects of the brake system as well as the pneumatic system. In particular, the study aims at cataloguing typical failure modes, at creating a strong failure prediction model which is specific to the railway operation and at demonstrating that the model is effective in improving the maintenance practice. The research, in this way, aims at strengthening the proactive, cost-efficient, and sustainable maintenance solutions of modern railway networks.

1.2 Literature Review

The maintenance aspect of railway engineering can only succeed in releasing sustained improvement on the built as long as its investigation and technological innovations focus on the crucial subsystems of the rolling stock, which are mainly in the braking and pneumatic systems. These systems are necessary to protect the safety, reliability of operations and their efficiency. The rolling stock is to be understood as a multi-constituent piece where the brake subsystem plays a central role in the management of speed and in the prevention of accidents. The elements within the hierarchies of the bogie, suspension and the system of naming the braking methods, i.e., adhesion-based and non-adhesion, are all of relevance towards constructing the element of comfort (of passengers) and safety in trains that run at high speeds. The results, as suggested by [13] and [14], show that the most frequent failures are about electropneumatic valve and air distributor subassemblies, and these researchers consider FMECA techniques as defining risk profiles and establishing maintenance priorities. The analyses support the necessity of real-time monitoring processes and predictive maintenance strategies to reduce the costs of failures and operations. Software. In this regard, tools that allow programming have gained more currency, like the Visual Basic for Applications (VBA) and RapidMiner. VBA allows one to perform the responsible entry and dashboard setup and failure codification tasks in the excel environment, whereas RapidMiner provides a machine-learning platform where various models, such as Decision Tree, Support Vector Machine, and Random Forest to predict the system degradation using the historical failure data, can be used. Taken together, these methods facilitate a mixed maintenance architecture that VBA supports user-interface processes and operations, as well as form-based workflows, and RapidMiner applies analytic depth to predictive initiatives and, therefore, builds a high-quality and extensive base through which one can enhance the stability and business effectiveness of the modern railways.

2. Methodology

This study is a systematic study and classification of malfunctions of brake and pneumatic systems of rolling stock, the goal of which is to raise the level of efficiency in operation and maintenance. In the study, a multi-phase approach is used that combines the data acquisition component, the dashboard creation process and the process of building a predictive model that will be based on machine-learning concepts.

2.1 Research Flowchart

Figure 1 illustrates the flow chart of the research followed, and that is how the issues were studied and developed to examine and improve maintenance work on the brake and pneumatic systems of rail-ways. This begins by the clearly stated central research question and the creation of specific project objectives. In order to put this question into its context, the researcher examines the existing literature and technical texts in order to evaluate the existing practices and issues associated with them. An operational data is then obtained in the form of train maintenance data records, which is virtually cleaned up and structured in Microsoft Excel to prioritize the relevant variables. A dashboard using excel along with VBA macros is then created to aid data visualization and management. The next step involves the use of machine-learning tools like RapidMiner to create predictive models that can foretell the occurrence of fail events. Just to make the models robust, a systematic evaluation and refinement is done. A final synthesis of the findings is done to develop a useful framework within which the train operators can schedule their maintenance, reduce unexpected breakdowns and in the process enhance both safety and functional efficiency.

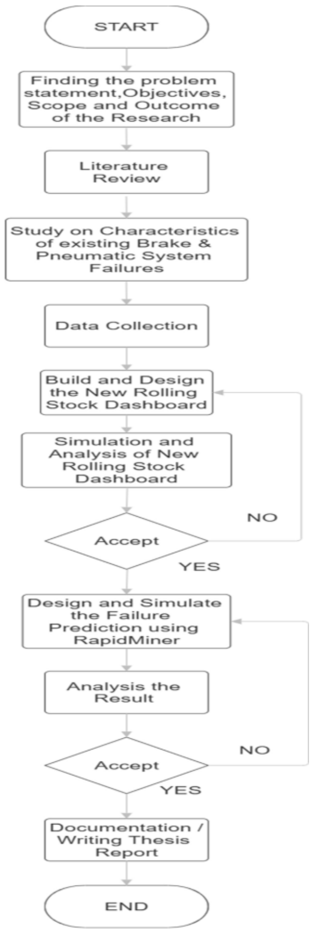

Fig.1 Research Flowchart

2.2 Rolling Stock Dashboard Flowchart

A flow diagram of the Rolling Stock Dashboard is a comprehensive description of activities of developing a macro-based analytical tool aimed at the enhancement of failure classification and maintenance planning optimization in the brake and pneumatic networks. As shown in Figure 2 the work flow that has been documented used to start the work by articulating the objectives and requirements, followed next by obtaining the data, then it continues through other processes such as cleaning, designing of dashboards, developing a visual basic for applications (VBA) module, testing and debugging the module, and verifying the complete system. Every step is directly connected with both the reliability of operations of the dashboard in use and the accuracy of analysis. The investigation of the macro implementation shows that VBA used in Microsoft Excel allows automating information processing, creation of dynamic graphs, and reporting with the in-time factor, which minimizes the possibility of errors in manual operation and promotes more effective decision-making. In turn, the introduced iterative and modular development architecture does not only promote the predictive maintenance strategies, but also fulfills the demands of the industry in scalable, convenient-to-use tools that allow managing assets in the intelligence way, in the context of the rolling-stock system.

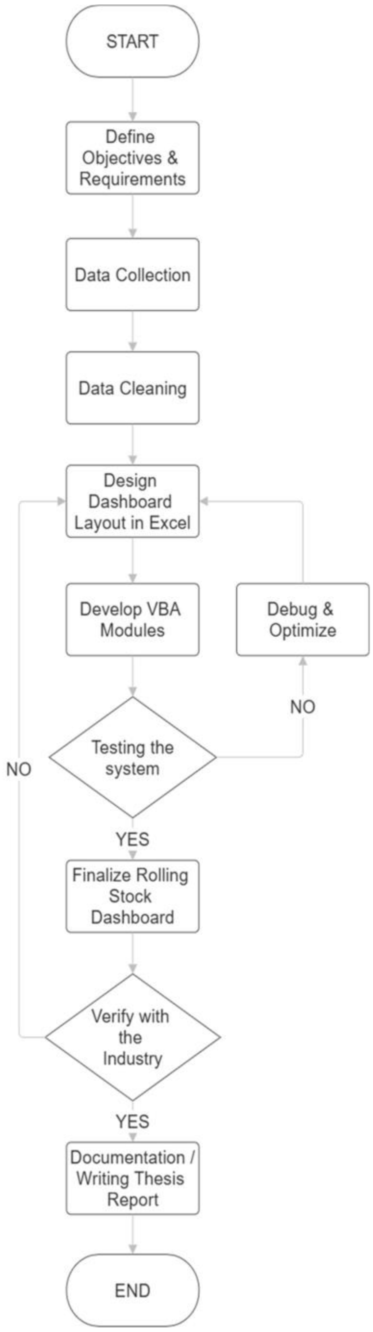

Fig.2 Rolling Stock Dashboard Flowchart

2.3 Prediction Model Flowchart

Figure 3 represents the flowchart of the prediction model, where a logical sequential process of building a predictive maintenance model based on machine learning is presented using brake and pneumatic systems in rolling stocks as an example. The evidence presented in the diagram shows a sequential organization of a set of events starting with the statement of prediction goals, then the gathering of data, intensive preprocessing, and separation of the data into training and testing sets. This is closed by the construction of a model based on the Decision Tree algorithm, the performance validation, and deployment in the environment of real-time prediction. Structural study of this workflow has shown that every phase preserves the integrity of data, promotes model accuracy, and continues to remain operably relevant, especially when it comes to the identification of failure trends and how a pre-failure state can be detected easily. It follows that the method couples substantive expertise with data-based methods, ensuring that the model is not only technically robust but also relevant to applications. Finally, such a predictive framework enables a shift to a proactive maintenance process, increases the system reliability, addresses capacity in case of downtimes, and is consistent with the overall purpose of intelligent asset management in railway operations.

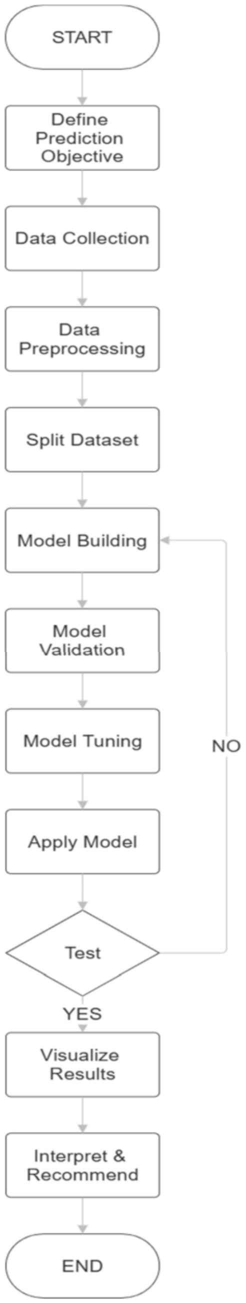

Fig.3 Failure prediction Flowchart

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3. Result

The results section will be used to evaluate how efficient the integrated dashboard and predictive model will be to increase efficiency of maintenance of the brake and pneumatic systems in the rolling stock.

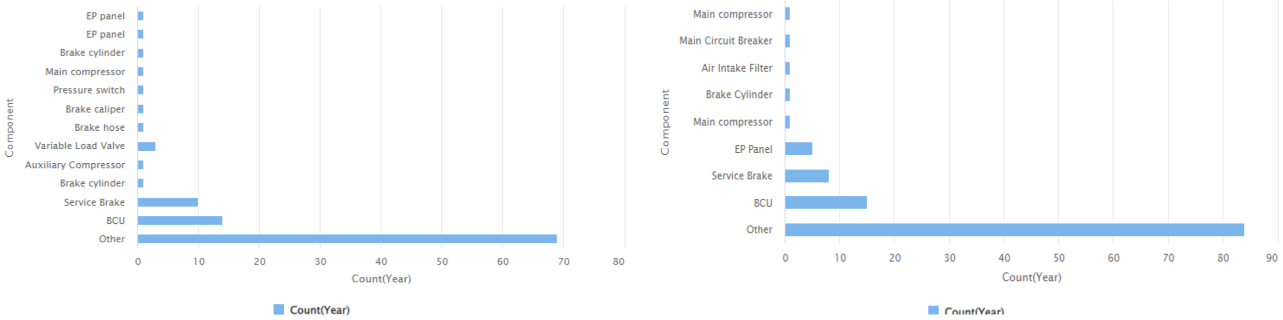
3.1 Result of Rolling Stock Dashboard

The implementation of the Rolling Stock Dashboard that is presented in Figure 4 has significantly increased possibilities to track, analyze and enhance rail-vehicle performance. Based on a dataset of 38,172 notifications, the dashboard is one of the core elements of the Maintenance Intelligence Framework, showing a complete picture of the failure trends and the challenges of the system. An outstanding discovery is that 34.2% of the notifications fall under the Non-Descriptive (ND) category, thus reflecting an important shortcoming of the existing set of codes that do not allow clear faulting and specific remedy. Improving failure codes in terms of structure and consistency becomes imperative in making engineers capable of identifying and resolving serious problems (particularly in such essential systems like brakes and pneumatics) more effectively. The dashboard also enables analyzing the trend based on failure rates per type of train in each month to help identify the operational risk early and schedule the maintenance before it presents operational risks. Moreover, the visual analytics using the same system reveal significant issues in passenger control systems and traction converters, which point to the necessity of intensive diagnostic work and evaluations of reliability in the respective spheres. Combined with data from brake and pneumatic systems, these insights create a comprehensive image of the interaction between subsystems and their deterioration. The Rolling Stock Dashboard serves, therefore, not only as an effective reporting and monitoring tool but also as a tool that facilitates the process of strategic decision-making; hence, the instrument serves the purpose of the study, which aims at creating a systematic method of handling railway failures and improving the effectiveness and reliability of rail operations.

Fig.4 Rolling Stock Dashboard Interface

3.2 Result of Prediction Model

A forecast of the Decision Tree model described patterns of major links of braking systems and pneumatic systems in a transit and express train with a high degree of accuracy. Fig. 5 (a) results show that in the transit network, Other types of failure are the most common types of failures, then followed by the components that are the most serious, like the Brake Control Unit (BCU), Service Brake and Brake Cylinder. This distribution implies that many of the failures can be somehow rooted in subsystems that are not monitored enough or failure classification that that are not consistent. A similar trend can be seen in the Fig. 5 (b) displaying a sharp failure rate of express trains falling within the category of Other in which significant breakdowns take place in the BCU and Service Brake and Main Compressor. These results serve as an acknowledgment of the weakness of major segments and further substantiates the importance of specific maintenance planning. Its interpretability allowed the maintenance personnel to isolate the path level of failures and in turn prioritize an intervention. Overall, the evidence indicates that the model can be used to plan condition-based maintenance and decrease the amount of downtime of operations and increase the reliability of rolling-stock by making data-based decisions.



(a) **(b)**

Fig.5 Component failure for Brake and Pneumatic System from 2016 to 2024 (a) Transit (b) Express

The current research has considered the efficiency of a Decision Tree model to predict failure modes in brake and pneumatic components of rolling stock (mainly, transit and express trains). The conclusions which are reflected in Figures 6 and 7 illustrate the finding that the model showed high classification accuracy of 87.10 % on transit trains and 85.71 % on express trains thus ensuring strong predictive capability. On further examination of the confusion matrices, superior results can be inferred in Service Failure (SF) detection (recall values of 96.15 % and 100.00 %, respectively), whereas results of Maintenance Repair (MR) predictions are relatively inferior (recall values of 40 % in case of transit and 0 % (by express trains)). This indicates that it is a case of classes being imbalanced and having overlapping feature sets which limits the generalization across the types of failures. Still, the model is effective in terms of maintenance programming because it allows detecting faults at an early stage and prioritizing the most important parts. Thus, the main finding is that Decision Tree model will be useful to classify SF; however, the model should be improved using feature engineering and data rebalancing to make perfect MR predictions to create more balanced and reliable predictive maintenance plan.

accuracy: 87.10%

	true Service Failure (SF)	true Maintenance Repair (MR)	class precision
pred. Service Failure (SF)	25	3	89.29%
pred. Maintenance Repair (MR)	1	2	66.67%
class recall	96.15%	40.00%	

Fig.6 Confusion Matrix for Transit Train

accuracy: 85.71%

	true Service Failure (SF)	true Maintenance Repair (MR)	class precision
pred. Service Failure (SF)	30	5	85.71%
pred. Maintenance Repair (MR)	0	0	0.00%
class recall	100.00%	0.00%	

Fig.7 Confusion Matrix for Express Train

3.3 Benefit Integration Between VBA and RapidMiner

The aim of combining Visual Basic for Applications (VBA) and RapidMiner would be to create an end-to-end analytical system that would bring both the descriptive and the predictive approach to maintenance of rolling-stock systems. As shown in Table 1, empirical evidence demonstrates that VBA can ease the tedious task of entering structured data, validation and visualization through custom GUI forms in Excel, and thus allow the maintenance workers to log and retrieve the failure records efficiently. In parallel, rapid-Miner extends this framework by providing advanced predictive modeling features with the help of machine-learning models, including Decision Trees Model, which will allow predicting the component failures accurately. An evaluation of the merger places one on the opinion that there exists a synergistic alliance between the user-friendly interface and tight analytics offered by VBA and RapidMiner platforms, respectively, which contributes to the viability of condition-based maintenance, reduction of unexpected downtimes, and optimizing of the decision-making process in general. Finally, the dual-tool ecosystem is not just about the improvement of the quality and accessibility of data but also about the consistency of the aim of increasing the reliability and sustainability of brake and pneumatic systems in rolling stock and overall working performance of the vehicle.

Table 1: Comparative Benefits of VBA and RapidMiner Integration

RapidMiner	Aspect	VBA
Predictive modeling and advanced analytics	Primary Function	Data entry, validation, and visualization in Excel
Drag-and-drop interface for workflow design	User Interface	Custom GUI forms for data input and search
Handles large datasets with complex preprocessing capabilities	Data Handling	Structured data entry and real-time visualization
Supports decision trees, SVMs, neural networks, and more	Machine Learning Capability	Limited to Excel functions and macros
Enables predictive maintenance and failure forecasting	Integration in Maintenance	Supports descriptive analytics and failure tracking
Provides high-accuracy predictions and actionable insights	Accuracy and Insights	Improves data accuracy and categorization
Enhances decision-making and maintenance efficiency through prediction	Overall Contribution	Enhances data quality and accessibility

3.4 Limitations

Although this study provides valuable insights to understand how failure analysis of brake and pneumatic systems in rolling stock is conducted, there is a number of limitations that are required to be mentioned. A major limitation is on the nature and completeness of the available failure data, where limited failure records contained more precise identification of the name of specific components (valves, air compressors, brake actuators, connecting hoses) and therefore restricted the accuracy of the failure classification and root cause analysis. Also, a great deal of the information used was historical and could have lacked consistency, lacked entries, or differed greatly in terms of terminology between different maintenance teams, which can add bias to results and decrease the ability to generalize the results. The use of tools in the data analysis, including simple pivot tables, also impede the ability to dive deep into the trend analysis and real-time diagnostics due to limited capabilities to deal with large amounts of data with multiple different types of failure and variable interconnections. Moreover, although the suggested framework has potential, it is necessary to prove whether it can be applied to various rail models and operational settings. Effective integration with the already existing Computerized Maintenance Management Systems (CMMS), as well as proper training of the staff and interoperability of the system, is a feasible challenge. Future activities should aim at creating reliable data collection mechanisms, adoption of high-value analytical tools, and joint testing of theory with advanced business partners to resolve these problems and make the framework effective in the long run.

4. Conclusion

The current study was organized to provide the systematic improvement of the brake and pneumatic systems reliability in rolling stock using the data-based approach. Maintenance and repair records of past years were reviewed to clarify the common modes of failure and identify the dangerous weak areas in these systems. After this, a customized failure modeling formula, which combined the statistical analyses and critical input of the engineers, was developed, which could be used to predict errors and to enable proactive maintenance planning. Efficiency of the model was supported by increased accuracy of prediction, optimal resource deployment, and minimized cases of unexpected service interruptions. Overall, the research provides a structured platform of fault examination and provides a practical tool of planning preventive maintenance, which would make railway operations safer, more reliable, and cost-efficient.

4.1 Recommendations

The current study makes a number of recommendations that can be used to improve the level of reliability, safety, and cost effectiveness of rolling stock maintenance. To begin with, the proposal is made that railway operating companies find proactive approach to addressing the problem of obsolete and ageing parts, especially when it comes to the critical systems like the Brake Control Unit (BCU). It is advisable to identify at-risk component and continuously analyze supplier availability, prioritize replacements based on criticality and failure trends, and reassess causing alternative solutions such as reverse engineering, redesign, and new retrofit technology. There is also the boosted implementation of digital inventory systems and predictive maintenance tools to match procurement and actual maintenance needs. It is also proposed to set up a special obsolescence review board that would give thought to matters of strategy and ensure that the cross-functional resource reserves are correctly apportioned to undertake the replacement of components at an appropriate moment.

Second, a high recommendation is necessary as far as failure log structure standardization at the component and subcomponent level is concerned to enhance the accuracy and usability of maintenance data. There should be a standardized, hierarchical way to record the events of failure, including the detailed nomenclature, failure modes, cause, severity, to have such practice throughout the organization. Application of this standardized architecture in a digitalized failure logging platform would provide improved data quality, a more accurate diagnosis of the faults or abnormalities, the opportunity to establish an effective predictive maintenance programming, and the capability of long-term performance tracking and reliability development in railway activities. Taken together, these guidelines are aimed at enhancing maintenance practices, building the capacity of informed decisions to make the railway perhaps more resilient and more sustainable.

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Conflict of Interest

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

Author Contribution

The author confirms contribution to the paper as follows: **Failure Analysis and Classification of Brake and Pneumatic Systems in Rolling Stock: A Comprehensive Approach to Enhancing Maintenance Efficiency**: Mohamad Nazmi Ariqrullah bin Salim, **Supervisor**: Dr. Nurul Farhanah binti Muarat and Ir. Ts. Norazman bin Abu Hassan. All authors reviewed the results and approved the final version of the manuscript.

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