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Development of a Risk-Based Maintenance Framework for Improving Human Reliability in Disc Brake Maintenance Using the HEART Method

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Abstract

Disc brake maintenance is a critical activity in ensuring the safety and reliability of passenger vehicles. In vocational automotive workshop environments, maintenance activities are vulnerable to human error due to limited operator experience, time pressure, and inadequate work procedures. This study aims to develop a Risk-Based Maintenance (RBM) framework for improving human reliability in disc brake maintenance using the Human Error Assessment and Reduction Technique (HEART) method. The research employed a mixed-methods approach with a sequential explanatory design. Quantitative analysis was conducted through Hierarchical Task Analysis (HTA), Generic Task Type (GTT) classification, identification of Error Producing Conditions (EPCs), Assessed Proportion of Effect (APOE) evaluation, and Human Error Probability (HEP) calculation. Qualitative data were collected through observations, interviews, and Focus Group Discussions (FGDs) involving vocational instructors and automotive technicians. The results showed that initial inspection (HEP = 2.49), brake disc inspection (HEP = 2.48), and brake pad and caliper reassembly (HEP = 1.81) were identified as the most critical maintenance activities. The dominant EPCs included time pressure, limited operator experience, poor work procedure quality, and the absence of independent checking. Based on these findings, an RBM framework was developed to prioritize risk control actions through improved supervision, enhanced practical training, refinement of standard operating procedures, and implementation of independent inspection mechanisms. The proposed framework integrates HEART-based human reliability assessment with RBM principles to support systematic maintenance risk control and human reliability improvement in vocational automotive workshop environments.

Keywords: Human reliability analysis, Human error assessment and reduction technique method, Risk-based maintenance, Disc brake maintenance, Human error, Vocational automotive workshop environments.

1 | Introduction

The growth of motor vehicle ownership has significantly increased transportation activity and traffic density, resulting in greater demands for vehicle operational safety and maintenance reliability. Brake systems play a critical role in ensuring vehicle safety because braking failure may directly contribute to traffic accidents and

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operational hazards. Among various braking technologies, disc brake systems are widely used in modern passenger vehicles due to their superior braking response, thermal stability, and heat dissipation capability [1]. However, braking performance reliability can only be maintained through proper and periodic maintenance procedures. Maintenance activities are highly dependent on human reliability because inspection, diagnosis, decision-making, and repair activities are directly performed by human operators [2], [3]. Previous studies reported that maintenance-related human error significantly contributes to operational failures, equipment damage, and safety incidents in industrial systems [4], [5]. Therefore, improving human reliability during maintenance activities is essential for ensuring maintenance effectiveness, operational safety, and system reliability.

In vocational automotive education environments, maintenance practices are routinely performed by students as part of practical competency training. Although these activities are essential for developing technical knowledge and practical skills, workshop-based maintenance activities remain vulnerable to operational errors because maintenance performance is strongly influenced by operator competence, training quality, and practical working conditions, while vocational workshop environments often face limitations in safety implementation and training resources [6], [7]. Previous studies have shown that poor adherence to maintenance procedures, inadequate operational supervision, and insufficient knowledge and experience are important contributors to human errors and procedural violations during maintenance operations [8]. Furthermore, maintenance activities conducted in educational workshop environments frequently involve variations in operator competence, procedural understanding, and safety awareness, which may influence maintenance reliability and operational safety [2], [9]. Preliminary observations conducted during vocational automotive workshop activities also identified several maintenance defects associated with incorrect tool usage, procedural violations, inaccurate measurements, improper component installation, and failure to follow safety procedures during disc brake maintenance activities.

Human Reliability Analysis (HRA) has been widely applied to identify, evaluate, and quantify human error in safety-critical operational systems because human performance significantly influences operational reliability and maintenance effectiveness [2], [5]. HRA provides systematic approaches for analyzing human contribution to operational failures and identifying workplace factors that may increase the probability of human error during task execution [4]. Among various HRA approaches, the Human Error Assessment and Reduction Technique (HEART) is widely recognized because of its practical implementation and ability to estimate Human Error Probability (HEP) based on Generic Task Types (GTTs) and EPCs influencing operator performance [10], [11]. Previous studies demonstrated that the HEART method can be effectively applied in maintenance and operational environments to identify critical tasks and dominant human error factors. For example, HEART has been applied in railway brake maintenance activities to evaluate human reliability during maintenance execution [12]. In maritime operational systems, HTA and HEART were integrated to identify critical human errors and support mitigation planning during emergency response activities [13]. Other studies also applied HEART in manufacturing and industrial operational systems to evaluate operator reliability and identify workplace conditions contributing to human error occurrence [14] [15]. Furthermore, several recent studies developed hybrid HEART approaches to improve the consistency and accuracy of HEP estimation under uncertain operational conditions [16], [17].

However, previous studies generally focused on industrial operations, maritime systems, railway maintenance, and manufacturing environments without specifically integrating HEART analysis into a Risk-Based Maintenance (RBM) framework within vocational automotive maintenance activities [12], [13]. Meanwhile, RBM approaches are increasingly important because maintenance planning should prioritize operational risks and allocate maintenance resources based on the probability and consequences of failure [18], [19]. Several studies also emphasized that maintenance-related risks may originate not only from equipment failure but also from human error during maintenance execution [2], [3]. Therefore, integrating HEART-based HRA into a RBM framework may support more systematic maintenance risk control and human reliability improvement in vocational automotive maintenance environments.

Therefore, this study aims to develop a RBM framework for improving human reliability in disc brake maintenance activities using the HEART method within vocational automotive maintenance environments. The study integrates Hierarchical Task Analysis (HTA), HEP evaluation, Error Producing Condition (EPC) identification, and risk prioritization processes to identify critical maintenance activities vulnerable to human error [12]. Unlike previous studies that mainly focused on human error quantification in industrial operational systems, this study emphasizes the integration of HEART-based HRA with RBM principles to support systematic maintenance risk control, maintenance reliability improvement, and human-centered maintenance supervision within vocational automotive practical activities [2]. The main contribution of this study is the integration of HEART-based HRA with RBM principles to develop a structured framework for maintenance risk prioritization and human reliability improvement in vocational automotive workshop environments.

2 | Literature Review

2.1 | Human Error and Human Reliability Analysis

Human error has been recognized as one of the dominant contributors to operational failures, maintenance-related accidents, and safety degradation in complex industrial systems [2], [5]. In maintenance activities, human error may occur because maintenance tasks frequently involve inspection, diagnosis, decision-making, procedural execution, and verification processes performed directly by human operators under varying workplace conditions [3]. Previous studies explained that factors such as limited operator competence, inadequate supervision, procedural deficiencies, time pressure, and unfavorable working environments may substantially increase the probability of maintenance-related human error occurrence [8], [9]. Consequently, maintenance reliability is influenced not only by equipment condition and technical performance but also by human reliability and workplace factors affecting maintenance execution [4], [20].

HRA is a systematic approach used to identify, evaluate, and reduce the probability of human error within operational systems [4]. HRA methods have been widely applied in manufacturing systems, healthcare, transportation, aviation, maritime operations, and industrial maintenance activities to identify and evaluate human reliability within operational systems. Several HRA approaches commonly used in operational risk analysis include THERP, HEART, CREAM, SPAR-H, and Bayesian-based reliability models [5], [21].

Among various HRA approaches, the HEART is widely recognized because of its practical implementation, relatively simple analytical structure, and capability to estimate HEP under operational workplace conditions [4], [10]. The HEART method evaluates human reliability by combining nominal task error probabilities derived from GTTs with workplace performance factors represented by EPCs and Assessed Proportion of Effect (APOE) values influencing operator performance [11]. Compared with several other HRA approaches, HEART has been extensively applied in maintenance activities and operational systems because it allows systematic identification of critical tasks, dominant workplace factors, and human performance vulnerabilities during operational execution [16], [21]. Several recent studies also demonstrated that hybrid HEART approaches may improve the consistency and accuracy of HEP estimation under uncertain operational conditions [16], [17].

2.2 | Risk-Based Maintenance Framework

RBM is a maintenance strategy that prioritizes maintenance planning and corrective actions based on the level of operational risk associated with equipment failure and maintenance-related consequences [18], [19]. RBM supports maintenance decision-making processes by integrating failure probability, operational consequences, safety impact, and maintenance criticality into systematic maintenance planning activities [22]. Unlike conventional maintenance strategies that mainly focus on scheduled maintenance intervals, RBM emphasizes maintenance prioritization based on risk severity to improve operational reliability, maintenance effectiveness, and resource allocation efficiency [23], [24].

In maintenance systems, operational risks may originate not only from equipment degradation and component failure but also from human error during maintenance execution [2], [3]. Several previous studies emphasized that maintenance-related human error may significantly affect operational reliability, maintenance effectiveness, workplace safety, and maintenance decision-making processes [9], [25]. Consequently, integrating HRA into RBM strategies is important for identifying maintenance activities with high human error vulnerability and prioritizing corrective actions based on operational risk severity [18], [19]. Human-centered maintenance approaches also highlighted that maintenance systems should not only focus on technical reliability but also consider operator competence, workplace conditions, procedural quality, and supervision mechanisms affecting maintenance performance [26], [27].

Despite extensive studies regarding HEART and RBM applications in industrial systems, limited research has specifically integrated HEART-based HRA into RBM framework development within vocational automotive maintenance activities [12], [16]. Most previous studies primarily focused on industrial operations, maritime systems, railway maintenance, power plants, and process industries rather than maintenance training environments involving relatively inexperienced operators [11], [13]. In addition, previous RBM studies generally emphasized equipment reliability, maintenance optimization, and maintenance scheduling without specifically addressing human reliability vulnerability during practical maintenance execution [18], [22]. Therefore, integrating HEART-based HRA with RBM principles may provide a more systematic approach for identifying maintenance-related human error risks, prioritizing corrective maintenance actions, and improving maintenance reliability within vocational automotive practical environments.

3 | Research Methodology

This study employed a mixed-methods approach with a sequential explanatory design to analyze human reliability during disc brake maintenance activities and develop a RBM framework based on HEART analysis [28]. The quantitative phase was conducted to evaluate HEP values through HTA, GTT classification, EPC identification, and HEP calculation using the HEART method. The qualitative phase was subsequently conducted to support interpretation of the quantitative findings, validate operational workplace conditions, and formulate corrective maintenance strategies based on expert judgment and practical observations.

The object of this study was front disc brake maintenance activities performed within vocational automotive practical training environments. The study focused on maintenance practices involving inspection, brake pad replacement, brake disc inspection, brake caliper reassembly, and final brake system verification activities conducted by vocational automotive students during practical workshop sessions.

These maintenance activities were selected because they involve operational procedures requiring inspection accuracy, procedural compliance, technical judgment, and operator concentration during maintenance execution. Data collection was conducted through direct observation, interviews, documentation studies, and Focus Group Discussions (FGDs) involving vocational instructors and automotive maintenance practitioners. Observation activities were performed to identify maintenance task sequences, workplace conditions, operational behaviors, maintenance defects, and procedural deviations occurring during disc brake maintenance practices. Interviews and FGDs were subsequently conducted to validate GTT classifications, identify relevant EPCs, and determine APOE values based on expert judgment and operational experience.

The research procedure began with HTA to decompose disc brake maintenance activities into operational stages and detailed maintenance sub-tasks. Each identified sub-task was subsequently classified into an appropriate GTT according to HEART guidelines based on task complexity, operational characteristics, and cognitive demands during maintenance execution. After task classification, relevant EPCs influencing operator performance were identified based on workplace observations, operational conditions, and maintenance behaviors observed during practical maintenance activities.

The influence level of each identified EPC was evaluated using APOE values obtained through expert judgment during FGDs and maintenance observations. HEP values were subsequently calculated by combining nominal task error probabilities derived from GTTs with the influence levels of relevant EPCs affecting operator performance during maintenance execution. The HEP calculation process was conducted to determine maintenance activities with the highest human error vulnerability levels and identify critical maintenance tasks requiring priority corrective actions.

The HEART calculation used in this study is expressed as follows:

$$\mathrm{HEP} = \mathrm{Base\ Hep} \times \prod_{i=1}^{n} [1 + \mathrm{APOE_i} \times (\mathrm{ME_i} - 1)]. \quad (1)$$

where:

HEP = HEP.

Base HEP = GTT nominal probability.

APOEi = APOE for EPC-i.

MEi = Maximum effect multiplier of EPC-i.

i = Index of each identified EPC.

n = Total number of identified EPCs.

The calculated HEP values were subsequently analyzed to identify critical maintenance activities with the highest human error vulnerability levels. Maintenance activities with higher HEP values were prioritized for corrective maintenance planning and RBM development.

The calculated HEP values were analyzed to identify critical maintenance activities with high human error vulnerability levels during disc brake maintenance practices. Pareto analysis, scatter plot visualization, and risk ranking techniques were subsequently employed to evaluate dominant EPCs, compare maintenance defect frequencies, and determine maintenance activities requiring priority corrective actions. Quantitative data processing and graphical visualization were performed using Microsoft Excel to support systematic analysis of maintenance-related human error risks and operational vulnerability patterns.

Based on the HEART analysis results, a RBM framework was developed to support maintenance risk control and improve human reliability in vocational automotive workshop environments.

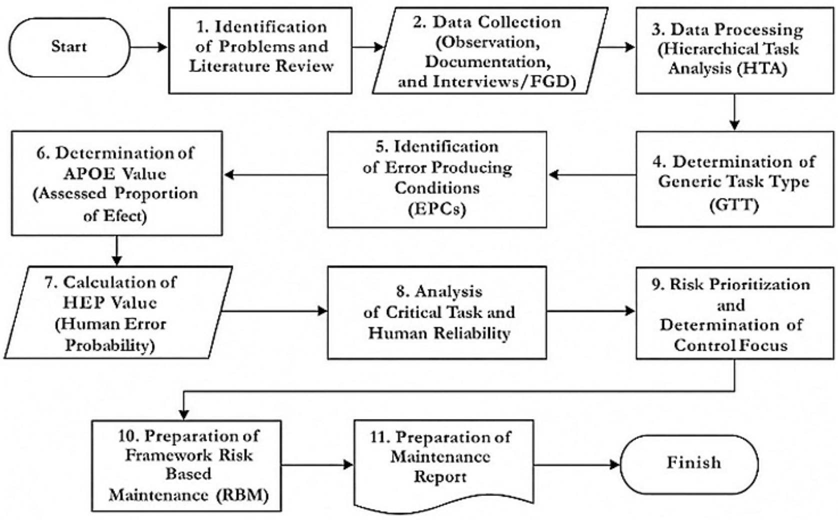

Fig. 1. Research procedure flowchart.

Fig. 1 illustrates the overall research procedure, beginning with maintenance task decomposition using HTA and continuing through HEART analysis, risk prioritization, and development of the proposed RBM framework.

4 | Result

4.1 | Hierarchical Task Analysis and Task Classification

The front disc brake maintenance activity was first analyzed using HTA to identify operational work sequences and critical maintenance sub-tasks. The HTA process decomposed the maintenance activity into several operational stages, including wheel removal, brake caliper opening, brake pad inspection, brake pad replacement, brake disc inspection, brake caliper installation, wheel installation, and final brake system inspection.

The HTA results indicated that maintenance activities involving component reinstallation and final verification required higher concentration levels and procedural accuracy compared with routine inspection activities. Improper execution during these stages may directly affect braking performance and operational safety. Tasks involving routine preparation and simple operational activities were generally classified into lower-risk GTT categories, while inspection and verification activities requiring higher cognitive judgment were categorized into higher nominal HEP classifications. These findings indicate that maintenance activities involving inspection, verification, and component reassembly are more vulnerable to human error because such activities require higher cognitive attention, procedural consistency, and operational judgment during maintenance execution. Similar findings were also reported in previous HEART-based maintenance studies, where inspection and verification tasks frequently demonstrated higher human error vulnerability compared with routine operational activities [12], [21].

Table 1. Summary of HTA and generic task type classification.

Task Code	Maintenance Sub-Task	GTT	Base HEP
T1	Initial inspection	D	0.09
T2	Prepare tools and equipment	E	0.02
T3	Use Personal Protective Equipment (PPE)	E	0.02
T4	Install protective cover	E	0.02
T5	Lift the vehicle	F	0.003
T6	Remove the wheel	E	0.02
T7	Inspect brake pad thickness	D	0.09
T8	Open brake caliper	F	0.003
T9	Inspect/replace brake pads	F	0.003
T10	Inspect brake disc	C	0.16
T11	Reassemble brake pad and caliper	C	0.16
T12	Install the wheel	E	0.02
T13	Lower the vehicle	F	0.003
T14	Tighten wheel nuts	C	0.16
T15	Check brake fluid	D	0.09
T16	Check brake pedal	D	0.09
T17	Remove protective cover	E	0.02
T18	Clean and organize tools	E	0.02
T19	Road test	D	0.09

The HTA decomposition and GTT classification presented in *Table 1* demonstrate that maintenance activities involving inspection, verification, and component reassembly were generally associated with higher nominal HEP values compared with routine preparation activities. *Fig. 2* further illustrates the hierarchical structure of disc brake maintenance activities and the operational relationship among maintenance sub-tasks identified during the HTA process.

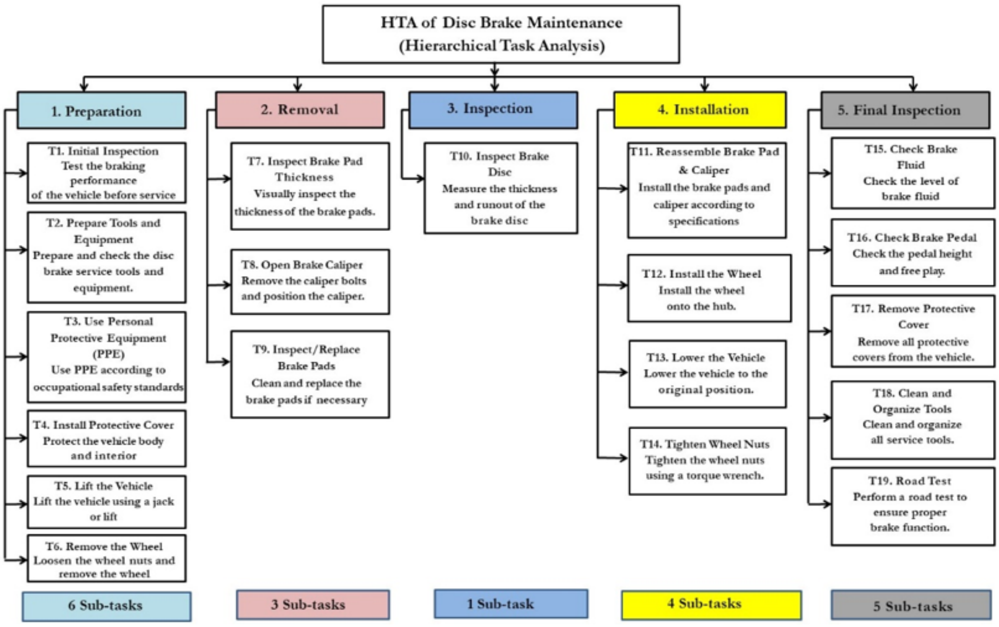

Fig. 2. Hierarchical task analysis of disc brake maintenance.

Fig. 2 presents the hierarchical structure of disc brake maintenance activities used to support GTT classification and HEART-based HRA.

4.2 | Identification of Error Producing Conditions

Observation activities and expert evaluations indicated that several EPCs significantly influenced maintenance performance during disc brake maintenance practices. The identified EPCs reflected operational, procedural, cognitive, and environmental factors that potentially increased human error vulnerability during vocational automotive workshop activities. The dominant EPCs identified included limited operator experience, mismatch between perceived and actual risk, inadequate procedures, time pressure, and absence of independent checking mechanisms.

These findings indicate that maintenance reliability in vocational workshop environments is strongly influenced by operator competency, procedural compliance, and supervision quality during maintenance execution. Limited practical experience and insufficient understanding of operational risks may increase the possibility of procedural deviations, inaccurate inspections, and improper component installation during maintenance activities. Similar findings were also reported in previous maintenance human reliability studies, where inadequate operational supervision, limited operator competence, and unfavorable workplace conditions were identified as dominant contributors to maintenance-related human error [2], [6].

The identified dominant EPCs and their frequency distributions are presented in *Table 2*.

Table 2. Dominant error producing conditions identified during disc brake maintenance activities.

EPC Code	Description	Frequency (f)	Percentage (%)	Cumulative Percentage (%)
EPC-15	Lack of operator experience	53	32.52	32.52
EPC-12	Mismatch between perceived risk and actual risk	41	25.15	57.67
EPC-3	Low signal-to-noise ratio	21	12.88	70.55
EPC-28	Task is meaningless or overly monotonous	20	12.27	82.82
EPC-24	Need to make judgments beyond operator capability or experience	15	9.2	92.02
EPC-2	Shortage of time available for error detection and correction	10	6.13	98.15
EPC-17	No independent checking	3	1.85	100

The analysis demonstrated that EPC-15 contributed most significantly to maintenance-related human error during workshop practices. This finding reflects the limited practical experience and technical judgment capability of vocational students during maintenance execution. Similarly, EPC-12 was frequently observed because several students underestimated the operational risks associated with improper maintenance procedures. EPC-3 also indicated that unclear operational signals and limited communication during practical activities contributed to maintenance inaccuracies and increased the possibility of procedural mistakes. Similar findings were reported by Walter and Drury, who emphasized that limited operator competence, insufficient maintenance training, and ineffective communication may substantially increase maintenance-related human error during technical maintenance activities [6], [20].

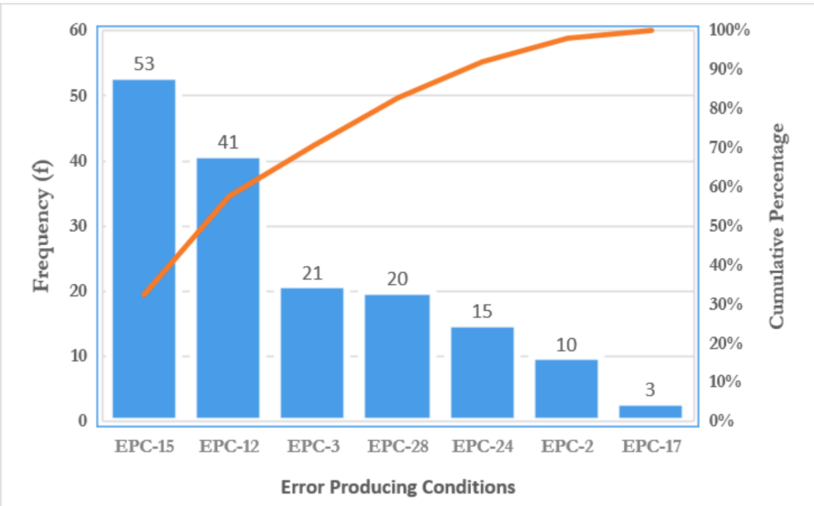

Fig. 3. Pareto diagram of error producing conditions.

Fig. 3 illustrates the cumulative contribution of dominant EPCs influencing maintenance-related human error during vocational automotive workshop practices. The Pareto analysis demonstrated that a small number of dominant EPCs contributed to most maintenance-related errors observed during practical maintenance activities. EPC-15 and EPC-12 showed the highest cumulative contribution, indicating that operator experience and risk perception were the most influential factors affecting maintenance reliability during maintenance execution. These findings indicate that improving operator competency, strengthening supervision, and increasing operational risk awareness are important factors for reducing maintenance-related human error during vocational maintenance activities. Similar findings were also reported in previous maintenance reliability studies, where operator competence and workplace conditions significantly influenced maintenance quality and operational safety performance [2], [20]. Therefore, corrective actions focusing on dominant EPCs may significantly improve maintenance reliability, operational safety, and human reliability performance within vocational automotive maintenance environments.

4.3 | Human Error Probability Analysis

HEP values were calculated for each maintenance sub-task using the HEART method. The calculation process combined nominal probability values derived from GTTs with the influence of relevant EPCs and APOE values obtained through expert judgment and workshop observations. This approach enabled a systematic evaluation of human reliability by considering both task characteristics and workplace factors affecting maintenance performance during disc brake maintenance activities. The analysis identified several maintenance activities with relatively high HEP values, indicating that these sub-tasks were highly vulnerable to human error in vocational automotive workshop environments. Activities involving inspection, verification, component reassembly, and final operational checking generally demonstrated higher HEP values because they required high concentration, procedural accuracy, and technical judgment during maintenance execution. These findings suggest that maintenance tasks requiring technical assessment and verification should receive greater attention within maintenance risk control programs because errors occurring during these activities may directly affect maintenance quality, operational reliability, and safety performance. Table 3 presents the human error probability results.

Table 3. Human error probability results for critical disc brake maintenance activities.

Task Code	Maintenance Sub-Task	HEP Value
T1	Initial inspection	2.49
T10	Inspect brake disc	2.48
T11	Reassemble brake pad and caliper	1.81
T7	Inspect brake pad thickness	0.97
T15	Check brake fluid	0.84
T16	Check brake pedal	0.82
T19	Road test	0.79
T14	Tighten wheel nuts	0.74

The results showed that T1 (Initial Inspection) and T10 (Inspect Brake Disc) produced the highest HEP values among all maintenance sub-tasks. These activities required careful observation, accurate technical assessment, and high operator concentration during maintenance execution. Improper inspection at these stages may significantly affect braking system reliability and operational safety because maintenance defects may remain undetected and continue into subsequent maintenance stages. The high HEP values identified in these activities were consistent with the dominant EPCs identified in Section 4.2, particularly limited operator experience and mismatch between perceived and actual risk. Similar findings were reported by Lin et al. [29], who emphasized that tasks involving inspection, decision-making, and technical evaluation generally impose higher cognitive workload and are therefore more vulnerable to operational errors.

T11 (Reassemble Brake Pad and Caliper) also demonstrated a relatively high HEP value because the activity involved precise component positioning, procedural compliance, and proper tightening accuracy during reassembly. Errors during this stage may directly influence braking performance and operational safety. The findings indicate that maintenance activities involving both technical judgment and component verification represent critical stages requiring enhanced supervision and procedural control to minimize maintenance-related human error. Several calculated HEP values exceeded 1.0 due to the combined influence of multiple EPCs with high effect multipliers and APOE values. In the HEART methodology, values exceeding 1.0 may occur when several dominant workplace factors simultaneously influence task performance and substantially increase human error vulnerability. Therefore, HEP values greater than 1.0 in this study were not interpreted as absolute mathematical probabilities but rather as indicators of highly critical maintenance activities with elevated human error susceptibility. Similar interpretations have been reported in previous HEART applications, where high HEP values reflected the substantial influence of human-related and operational risk factors on task performance [16], [30]. These findings indicate that critical maintenance activities should receive priority attention within maintenance risk control programs to reduce the likelihood of maintenance-related errors and improve operational safety.

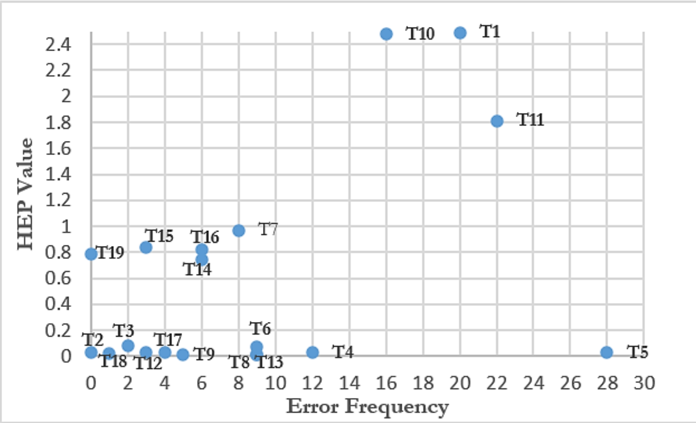

Fig. 4. Scatter diagram of error frequency versus HEP values.

The scatter diagram analysis presented in *Fig. 4* generally demonstrated that maintenance activities with higher HEP values tended to exhibit higher observed error frequencies in vocational automotive workshop environments. Several critical sub-tasks, particularly T1 (Initial Inspection), T10 (Inspect Brake Disc), and T11 (Reassemble Brake Pad and Caliper), showed both high HEP values and relatively high maintenance defect frequencies. These findings indicate that maintenance activities identified as highly vulnerable through HEART analysis were also associated with frequent maintenance errors during practical workshop implementation. However, the scatter diagram also indicated that certain activities, such as T5 (Lift the Vehicle), exhibited relatively high error frequencies despite having low HEP values. This finding suggests that error occurrence may be influenced not only by estimated human error vulnerability but also by task repetition, operator familiarity, and the frequency with which activities are performed during maintenance practices. Therefore, both HEP values and actual error frequencies should be considered when prioritizing maintenance risk control actions and developing corrective strategies. Overall, the results demonstrate that HEART analysis effectively identified critical maintenance activities requiring priority supervision, procedural improvement, and competency enhancement within vocational automotive workshop environments.

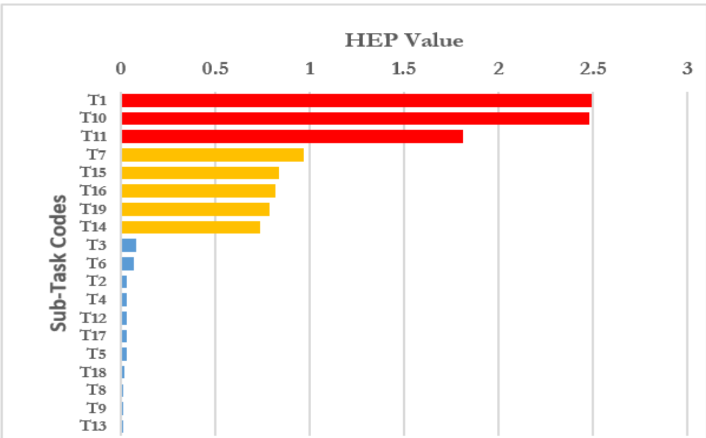

Fig. 5. Risk ranking diagram of maintenance sub-tasks.

The risk ranking analysis identified several critical maintenance activities requiring priority risk control actions, particularly T1 (Initial Inspection), T10 (Inspect Brake Disc), and T11 (Reassemble Brake Pad and Caliper), which demonstrated the highest HEP values among all maintenance sub-tasks. These activities involved inspection accuracy, technical judgment, and precise component reassembly processes that were highly vulnerable to human error during vocational automotive workshop activities. The findings support the implementation of RBM principles by prioritizing supervision, procedural improvement, operator competency development, and independent checking mechanisms on maintenance activities with the highest human error vulnerability levels.

4.4 | Development of Risk-Based Maintenance Framework

Based on the HEART analysis results, a RBM framework was developed to improve human reliability and maintenance risk control in vocational automotive workshop environments. The framework was formulated to address dominant human error factors, prioritize critical maintenance activities, and support systematic corrective actions based on HEP values obtained from HEART analysis. In accordance with RBM principles, maintenance resources and corrective actions should be prioritized according to risk severity and criticality levels to improve maintenance effectiveness and operational reliability [19], [31]. Therefore, HEP values were utilized as indicators of human error vulnerability to prioritize maintenance control actions and determine corrective strategies for critical maintenance tasks. This approach supports more effective maintenance decision-making by focusing improvement efforts on activities with the highest human error vulnerability. The proposed RBM framework is illustrated in *Fig. 6*.

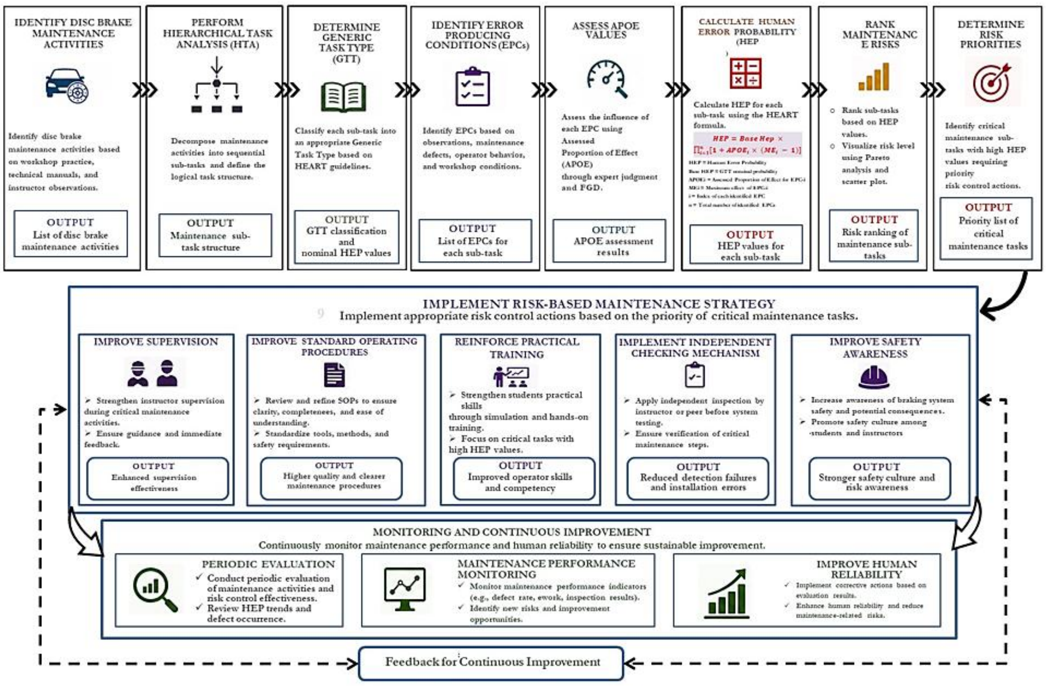

Fig. 6. Proposed risk-based maintenance framework.

The framework begins with maintenance activity decomposition using HTA to systematically identify maintenance stages and detailed operational sub-tasks. This stage provides a structured representation of the maintenance process and enables the identification of activities that may contribute to maintenance-related risks. By decomposing disc brake maintenance into sequential tasks and sub-tasks, the framework establishes a foundation for subsequent human reliability assessment and risk evaluation. The HTA results also facilitate the identification of critical maintenance activities requiring further analysis within the RBM process.

The second stage involves HRA using the HEART method to evaluate human error vulnerability during maintenance execution. Relevant EPCs are identified based on workplace observations, operator behavior, and maintenance performance factors observed during practical activities. The influence of each EPC is subsequently assessed using APOE values obtained through expert judgment and FGDs. HEP values are then calculated to quantify the level of human error vulnerability associated with each maintenance sub-task. These HEP values provide an objective basis for identifying critical maintenance activities and support risk-informed decision-making within the proposed RBM framework.

The third stage focuses on risk evaluation and prioritization based on the HEART analysis results. In accordance with RBM principles, maintenance activities are prioritized according to their relative risk levels to ensure that corrective actions and maintenance resources are directed toward the most critical activities [19], [31]. Pareto analysis, scatter diagram analysis, and risk ranking techniques are employed to identify dominant EPCs and maintenance sub-tasks with the highest HEP values. Based on the results presented in *Figs. 3–5*, critical maintenance activities such as initial inspection, brake disc inspection, and brake pad and caliper reassembly were identified as priority maintenance tasks requiring immediate corrective actions to reduce human error vulnerability.

The fourth stage involves the implementation of RBM control strategies aimed at reducing maintenance-related human error risks. Corrective actions are developed based on the dominant EPCs identified during the HEART analysis. Enhanced practical training programs are proposed to address the lack of operator experience (EPC-15), while strengthened supervision and safety awareness initiatives are intended to reduce the mismatch between perceived and actual risk (EPC-12). Improvements to standard operating procedures and maintenance guidance are designed to support decision-making during complex maintenance activities, whereas independent checking mechanisms are introduced to minimize verification-related errors and procedural deviations. This risk-based approach ensures that corrective actions are directly aligned with the most influential human error factors affecting maintenance performance and operational safety.

The final stage emphasizes monitoring and continuous improvement through periodic maintenance evaluation, operational performance monitoring, and continuous human reliability assessment. The effectiveness of implemented corrective actions should be regularly reviewed to ensure that maintenance risks remain under control and that human reliability performance continues to improve over time. This stage also supports the identification of newly emerging human error factors and changing workplace conditions that may influence maintenance performance. Consistent with human-centered maintenance principles, continuous monitoring and feedback mechanisms are essential for sustaining maintenance effectiveness and improving long-term operational reliability [26]. Therefore, the framework promotes an ongoing improvement cycle that enables corrective actions to remain effective, adaptive, and aligned with operational requirements within vocational automotive workshop environments.

The proposed framework extends previous HEART applications by transforming HEP assessment results into a structured RBM decision-making process. While most previous HEART studies primarily focused on identifying human error vulnerability and estimating HEP values, the present framework links HRA with maintenance risk prioritization, corrective action planning, and continuous performance improvement. Through the integration of HTA, HEART analysis, risk evaluation, and targeted maintenance control strategies, the framework provides a systematic mechanism for translating human reliability assessment results into practical maintenance management actions. This approach is consistent with RBM principles that emphasize maintenance prioritization based on risk severity and operational criticality [19], [31]. Therefore, the proposed framework contributes both theoretically and practically by integrating human reliability considerations into maintenance decision-making and maintenance risk control within vocational automotive workshop environments.

5 | Discussion

The findings of this study confirm that human error represents a significant risk factor in vocational automotive maintenance activities. Similar findings have been reported in previous maintenance reliability studies, where limited operator experience, inadequate procedures, and unfavorable workplace conditions were identified as important contributors to human error and maintenance-related failures [12]. These findings indicate that vocational automotive workshop environments involve substantial cognitive and procedural challenges because maintenance activities are frequently performed by relatively inexperienced operators under practical learning conditions. Consequently, maintenance tasks requiring inspection accuracy, technical judgment, and procedural compliance become more vulnerable to human error than routine operational activities.

The results also demonstrate that the HEART method is effective for identifying critical maintenance tasks and evaluating human reliability within vocational automotive workshop environments. The dominance of inspection and component reassembly activities indicates that maintenance tasks involving technical evaluation, verification processes, and procedural precision are particularly sensitive to human error vulnerability. These findings suggest that maintenance activities requiring greater cognitive involvement and decision-making tend to present higher levels of human error susceptibility than routine operational tasks. Compared with previous studies that primarily focused on industrial and maintenance operations, this study extends the application of HEART into vocational automotive education environments through the integration of human reliability assessment and RBM framework development.

From a practical perspective, the proposed RBM framework may support vocational institutions in improving maintenance safety, strengthening maintenance supervision systems, and enhancing students' practical competencies. The framework may also assist vocational instructors and workshop managers in prioritizing preventive supervision, competency reinforcement, and operational monitoring on maintenance activities with the highest human error vulnerability levels. Consistent with RBM principles, maintenance resources and corrective efforts should be directed toward activities with the greatest risk and operational criticality to improve maintenance effectiveness and safety performance [31]. Therefore, the proposed framework provides a practical decision-support tool for identifying priority maintenance activities and implementing targeted risk control actions within vocational automotive workshop environments.

The study contributes theoretically by extending the application of HEART-based HRA into vocational automotive maintenance environments through its integration with RBM principles. Unlike previous studies that primarily focused on human error identification and HEP estimation, the present study demonstrates how human reliability assessment results can be systematically translated into maintenance risk prioritization and corrective action planning. Practically, the proposed framework provides a structured approach for improving maintenance safety, strengthening supervision, enhancing operator competency, and supporting maintenance risk control within educational workshop activities.

Several limitations of this study should be acknowledged. First, the study was limited to front disc brake maintenance activities and may not fully represent other automotive maintenance systems with different operational characteristics and risk profiles. Second, the research was conducted within a vocational automotive workshop environment involving student operators, which may limit the generalizability of the findings to industrial maintenance settings involving experienced technicians. Third, the proposed RBM framework was developed based on analytical findings and has not yet been evaluated through long-term implementation and performance measurement. Therefore, future studies may validate the framework in industrial maintenance environments, apply the approach to other automotive maintenance systems, and assess its effectiveness in reducing human error and improving maintenance reliability over extended operational periods.

6 | Conclusion

This study demonstrated that human reliability represents a critical factor influencing maintenance safety and operational reliability during disc brake maintenance activities in vocational automotive workshop environments. The HEART analysis identified several critical maintenance activities with high HEP values, particularly initial inspection, brake disc inspection, and brake pad and caliper reassembly processes. The findings also revealed that limited operator experience, inadequate procedural control, time pressure, and the absence of independent checking mechanisms were dominant factors contributing to maintenance-related human error during practical maintenance activities. Based on these findings, a RBM framework was developed by integrating maintenance task identification, human reliability assessment, risk prioritization, and corrective action planning into a systematic maintenance risk control process. The framework emphasizes supervision enhancement, practical training improvement, procedural reinforcement, and implementation of independent checking mechanisms to reduce human error vulnerability in critical maintenance activities. The proposed framework provides a structured approach for improving human reliability and supporting maintenance risk control within vocational automotive workshop environments. By prioritizing maintenance activities according to their human error vulnerability levels, the framework may assist vocational institutions, instructors, and workshop managers in enhancing maintenance safety, operational reliability, and practical competency development during automotive maintenance training activities.

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Author Contribution

Conceptualization, D.A. and H.H.P.; Methodology, D.A.; Validation, D.A. and H.H.P.; Formal analysis, D.A.; Investigation, D.A.; Writing original draft preparation, D.A.; Writing review and editing, H.H.P.; Visualization, D.A.; Supervision, H.H.P. All authors have read and agreed to the final version of the manuscript.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare no conflict of interest.

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