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Evaluation of Additional Emergency Brake Button Installation to Reduce Risk Priority Number (RPN) for Main Emergency Brake Failure in a 350 HP Drawworks Rig

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Abstract
Introduction: *Emergency brake failure in a 350 HP drawwork rig poses significant operational and safety risks due to single-point-of-failure conditions within the braking system.* ***Objective:*** *This study aimed to evaluate the effectiveness of installing a secondary emergency brake system in reducing the Risk Priority Number (RPN) and mitigating the risk of primary emergency brake failure.* ***Method:*** *A quantitative evaluative approach was employed using integrated Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA), with data collected from maintenance records, inspection reports, failure records, and incident reports over a 12-month operational period.* ***Results and Discussion:*** *The results showed that the implementation of the secondary emergency brake significantly reduced RPN values by 55.6%-63.4% and decreased system failure probability by 63.8%73.3%, while improving system reliability, emergency response capability, and operational safety through the elimination of single-point-of-failure conditions using a dual pilot valve configuration. The integration of FMEA and FTA enabled a comprehensive assessment of critical failure modes, causal relationships, and risk mitigation priorities.* ***Conclusions:*** *The installation of a secondary emergency brake system is an effective risk mitigation strategy that enhances the safety, reliability, and operational performance of 350 HP drawwork rigs while providing a comprehensive framework for evaluating critical safety systems in drilling operations.*

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Introduction

The oil and gas industry is recognized as one of the highest-risk occupational sectors because drilling operations involve heavy equipment, high-energy systems, and hazardous working environments that expose workers to severe injuries and fatalities if safety systems fail. Occupational safety and health (OSH) is therefore essential for ensuring that operational hazards are systematically identified, controlled, and minimized through engineering controls, preventive maintenance, and structured risk management practices. The drawworks system is one of the main pieces of equipment used during drilling and workover operations because it controls the lifting and lowering of drill strings and other heavy loads. Failure of the drawworks braking system may result in uncontrolled load movement, equipment damage, environmental consequences, serious worker injuries, or fatalities, making emergency braking reliability an important component of occupational risk prevention (David & Emmanuel, 2025; IADC, 2015). Although the 350 HP drawworks rig is designed to safely handle substantial operational loads, its safety performance depends heavily on the reliability of its emergency braking mechanism (Hadid & Mohammed, 2022).

Occupational safety concerns related to hoisting and braking systems continue to be reported across the global oil and gas industry. According to the International Association of Drilling Contractors (IADC), 1,112 recordable incidents, 313 lost-time incidents, and 15 fatalities occurred during approximately 330 million working hours in 2022 (IADC, 2023). Although fatalities declined to 10 cases in 2023 and 8 cases in 2024, serious accidents associated with drilling operations remain a persistent challenge requiring continuous safety improvement (IADC, 2024; IADC, 2025). Likewise, the International Association of Oil and Gas Producers reported a 10% increase in the total recordable injury rate between 2020 and 2021, partly attributed to workforce restaffing after the COVID-19 pandemic, reduced training, and less frequent equipment inspections. Previous investigations also identified brake malfunctions involving linkage components and mechanical actuators as important contributors to hoisting-related incidents (IADC, 2019; Zulkarnain *et al*., 2024).

Various risk assessment methods have been developed to strengthen occupational safety by identifying hazards and prioritizing corrective actions in safety-critical industrial systems. Failure Mode and Effects Analysis (FMEA) is commonly applied to evaluate potential failure modes and prioritize risks through the Risk Priority Number (RPN), although its inductive approach limits the identification of causal relationships among failures. Conversely, Fault Tree Analysis (FTA) provides a deductive framework capable of identifying root causes, logical relationships, and minimal cut sets leading to system failures, but it does not directly prioritize risks using quantitative indicators such as RPN (Shafiee, Enjema, & Kolios, 2019). Previous studies have showed that integrating FMEA and FTA provides a more comprehensive evaluation of industrial safety systems, including subsea Blowout Preventers and manufacturing processes (Shafiee *et al*., 2019; Kutlu & Ekmekçioğlu, 2021). Nevertheless, limited studies have applied this integrated approach to emergency braking systems in medium-capacity 350 HP drawworks rigs, particularly for evaluating pneumatic secondary emergency braking configurations.

Despite advances in braking technology and reliability assessment, important research gaps remain regarding occupational safety improvement through redundant emergency braking systems in drilling operations. Previous studies have examined modified FMEA approaches for drilling risk assessment (Hatefi & Balilehvand, 2023), methodological developments of Fault Tree Analysis (Pan *et al*., 2022), brake material degradation (Yusubov, 2025), and braking technologies in automotive and railway applications (Haus *et al*., 2019; Han *et al*., 2019; Belhocine & Abdullah, 2020; Günay *et al*., 2020; Cicchino, 2022; Stender *et al*., 2021). Although these studies contribute valuable knowledge regarding braking performance and reliability, they do not specifically evaluate occupational safety improvements achieved through pneumatic secondary emergency braking systems installed on 350 HP drawworks rigs. Moreover, most existing studies rely on either FMEA or FTA individually, limiting their ability to simultaneously prioritize risks and identify causal failure mechanisms. However, evidence regarding the effectiveness of installing an additional emergency brake button as a redundancy-based safety intervention remains limited. Further evaluation is needed to determine whether this intervention can reduce emergency brake failure and improve occupational safety during drilling operations.

The importance of improving emergency braking systems is further supported by actual incidents occurring during drilling operations. On 6 April 2024, a near-miss event occurred at Rig XYZ when the travelling block gradually descended approximately 10 feet and reached the rotary table because the primary emergency braking system failed. Investigation results showed that the failure was associated with a loose linkage connection between the female and male brake components, while the absence of an alternative emergency brake button outside the driller's console delayed emergency response (IADC, 2006; IADC, 1999). Industry reports further show that approximately 23% of drilling rig incidents involve braking system failures, with linkage mechanisms and actuators representing common sources of failure (IADC, 2019; Zulkarnain *et al*., 2024). A similar accident on 10 February 2023 resulted in a fatality following the uncontrolled fall of a travelling block during an onshore workover operation, emphasizing the consequences of single-point failure systems. Therefore, this study evaluates the effectiveness of installing an additional emergency brake button as a Secondary Emergency Brake (SEB) by integrating FMEA and FTA to determine its impact on reducing the Risk Priority Number (RPN), minimizing emergency brake failure risk, and strengthening occupational safety in 350 HP drawworks rig operations.

Method

This study employed a quantitative evaluative research design to assess the effectiveness of installing an additional emergency brake button in reducing the risk of primary emergency brake failure in a 350 HP drawworks rig through an integrated Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) approach. The design was selected because the study aimed to evaluate a technical intervention using measurable indicators, including changes in Risk Priority Number (RPN), system failure probability, and system availability before and after the implementation of the Secondary Emergency Brake (SEB), consistent with the post-positivist paradigm emphasizing objective measurement, empirical verification, and replicability (Creswell & Creswell, 2018). Similar applications of integrated FMEA-FTA for industrial safety and reliability evaluation have been reported by Shafiee *et al*. (2019). To ensure validity and reliability, FMEA scoring was conducted using an expert panel consensus approach involving a driller, a mechanical maintenance engineer, and an HSE officer, with Severity (S), Occurrence (O), and Detection (D) scores independently assessed and averaged to obtain consensus values following the recommendations of Lavasani *et al*. (2015) and Wang and Chin (2011).

The scoring criteria were adapted from the AIAG and VDA FMEA Manual (2019), while inter-rater agreement was evaluated using Kendall's coefficient of concordance with a minimum acceptable threshold of 0.70 (Schmidt, 1997). The study utilized maintenance records, failure records, inspection reports, incident reports, near-miss reports, and technical specifications collected over a twelve-month period (April 2023-April 2024) from a 350 HP drawworks rig owned by PT. XYZ within the operational area of PT. XXX. The research focused on the pneumatic Primary Emergency Brake (PEB) system, consisting of the brake chamber, pilot valve, linkage mechanism, brake drum, and brake lining, while the evaluated intervention was the installation of an independent push-button Secondary Emergency Brake (SEB) connected to the same pneumatic circuit as an additional safety layer. The study population consisted of forty 350 HP drawworks rigs operating within the PT. XXX working area, and five rigs meeting predefined criteria including complete maintenance records, SEB installation, and documented brake-related incidents were selected through purposive sampling as the research sample as showed in Table 1.

Table 1
Sampled Rig Units

No.	Rig Name	Location/Area	Owner Company	Selection Rationale
1	Rig Alpha	DSF 5G-0911B	PT. XYZ	Experienced a near-miss event in April 2024 and possesses complete 12-month maintenance records
2	Rig B	PT. XXX Operational Area	PT. XXX	Secondary emergency brake installed and complete operational records available
3	Rig C	PT. XXX Operational Area	PT. XXX	Secondary emergency brake installed and complete operational records available
4	Rig D	PT. XXX Operational Area	PT. XXX	Meets SEB configuration requirements and possesses complete historical records
5	Rig E	PT. XXX Operational Area	PT. XXX	Meets selection criteria and contains documented risk-related incidents

Fault Tree Analysis (FTA) was employed to complement the FMEA assessment by identifying causal relationships among system failures, quantifying the probability of total emergency brake failure, and determining critical failure pathways through AND/OR logic gate modeling. Failure probabilities for each basic event were estimated from actual maintenance and failure records using an exponential failure distribution model, following the methodology proposed by Ruijters and Stoelinga (2015) and applied in oil and gas safety systems by Shafiee *et al*. (2019). The integrated FMEA-FTA framework enabled the prioritization of failure modes through Risk Priority Number (RPN) values while simultaneously identifying minimal cut sets and critical failure combinations that may not be revealed by FMEA alone, consistent with findings reported by Kutlu and Ekmekçioğlu (2021). The study examined Severity, Occurrence, Detection, Risk Priority Number, response time, braking capacity, and system availability, with analysis conducted by comparing the primary emergency brake system before and after the installation of the Secondary Emergency Brake (SEB). FMEA procedures included failure mode identification, S-O-D scoring, RPN calculation, and risk categorization, whereas FTA was used to estimate top-event probabilities and quantify risk reduction. Intervention effectiveness was evaluated using mean RPN reduction, FTA-based risk reduction, and system availability, while research validity was strengthened through triangulation of maintenance records, failure records, incident reports, and comparison with previous integrated FMEA-FTA studies by Shafiee *et al*. (2019) and Kutlu and Ekmekçioğlu (2021). The operational definitions of the research variables are showed in Table 2.

Table 2
Operational Definition of Variables

Variable	Definition	Measurement	Scale	Measurement Outcome
Severity (S)	Magnitude of failure consequences	FMEA scoring	Ordinal (1-10)	Score
Occurrence (O)	Frequency of failure occurrence	Failure records and FMEA scoring	Ordinal (1-10)	Score
Detection (D)	Ability to detect failure before impact	FMEA scoring	Ordinal (1-10)	Score
RPN	Risk Priority Number	S × O × D	Ratio	1-1000
Response Time	Secondary brake activation time	Technical data	Ratio	Seconds (<2 s target)
Braking Capacity	Load holding capability	Technical data	Ratio	Percentage of hook load (≥150% target)
System Availability	Operational readiness of the braking system	MTBF / (MTBF + MTTR)	Ratio	Percentage (≥99.9% target)

Result and Discussion

1. Result

The Failure Mode and Effects Analysis (FMEA) was conducted to identify and prioritize potential failure modes associated with the emergency braking system of 350 HP drawworks rigs. The assessment was performed by an expert panel consisting of a driller, a maintenance engineer, and an HSE officer. Three principal parameters were evaluated, namely Severity (S), Occurrence (O), and Detection (D), and the Risk Priority Number (RPN) was calculated as the product of these parameters. The evaluation focused on four critical components of the emergency braking system: the Primary Brake Chamber (BC-P), Secondary Brake Chamber (BC-S), Primary Pilot Valve (PV-P), and Secondary Pilot Valve (PV-S). Prior to the implementation of the Secondary Emergency Brake (SEB), risk levels varied across the studied rigs, with several components categorized as high-risk due to elevated occurrence frequencies and limited detection capability.

Table 3
Severity Rating Matrix

Score	Criteria	Impact Description
10	Extremely Hazardous	Fatal accident or major system damage
9	Hazardous	Potential serious injury or total system failure

8	Very High	Complete operational shutdown and major damage
7	High	Major operational disruption requiring extensive repair
6	Moderate-High	Significant performance degradation
5	Moderate	Operational disturbance but system remains functional
4	Low-Moderate	Minor system disturbance
3	Low	Minor impact and easily repairable
2	Very Low	Negligible operational effect
1	No Effect	No operational impact

The severity matrix shown in Table 3 was used to assess the consequences of each identified failure mode. Severity scores remained unchanged throughout the study because the intrinsic consequences of a failure event are independent of corrective actions.

Table 4
Occurrence Rating Matrix

Score	Probability	Frequency Description
10	Very Frequent	Occurs almost continuously
9	Very High	Occurs very frequently
8	High	Occurs routinely
7	Moderately High	Occurs several times during operation
6	Moderate	Occurs occasionally
5	Moderate-Low	Rare occurrence
4	Low	Low probability
3	Very Low	Very rare
2	Almost Never	Nearly impossible
1	Impossible	Practically impossible

The occurrence matrix showed in Table 4 was used to quantify the likelihood of each failure mode based on historical maintenance and failure records collected during the observation period. Then Table 5 shows detection rating matrix in this study.

Table 5
Detection Rating Matrix

Score	Detection Capability	Description
10	Undetectable	No detection system available
9	Extremely Difficult	Detection is almost impossible
8	Difficult	Very limited detection capability
7	Low	Low probability of detection
6	Moderate-Low	Occasionally detectable
5	Moderate	Adequate detection capability
4	Moderate-Good	Generally detectable
3	Good	Effective monitoring system
2	Very Good	Almost always detected
1	Certain Detection	Automatically detected by the system

FMEA Results Before Corrective Actions

The initial FMEA assessment revealed that primary emergency brake components generally exhibited higher risk levels than secondary components. The highest RPN values were associated with Brake Chamber Primary and Pilot Valve Primary failures, particularly in Rig Alpha, Rig C, and Rig D.

Table 6
FMEA Results Before Corrective Actions

Rig	Component	S	O	D	RPN	Category
Alpha	Brake Chamber Primary	8	4	3	96	High
Alpha	Brake Chamber Secondary	9	2	3	54	Medium
Alpha	Pilot Valve Primary	8	3	3	72	High
Alpha	Pilot Valve Secondary	9	1	3	27	Low
B	Brake Chamber Primary	8	3	3	72	High
B	Brake Chamber Secondary	9	2	3	54	Medium
B	Pilot Valve Primary	8	3	3	72	High
B	Pilot Valve Secondary	9	1	3	27	Low
C	Brake Chamber Primary	8	4	3	96	High
C	Brake Chamber Secondary	9	2	3	54	Medium
C	Pilot Valve Primary	8	4	3	96	High
C	Pilot Valve Secondary	9	1	3	27	Low
D	Brake Chamber Primary	8	3	3	72	High
D	Brake Chamber Secondary	9	2	3	54	Medium
D	Pilot Valve Primary	8	4	3	96	High
D	Pilot Valve Secondary	9	1	3	27	Low
E	Brake Chamber Primary	8	3	3	72	High
E	Brake Chamber Secondary	9	2	3	54	Medium
E	Pilot Valve Primary	8	3	3	72	High
E	Pilot Valve Secondary	9	1	3	27	Low

Prior to corrective actions, total RPN values ranged from 225 to 273 across the five rigs. Rig C recorded the highest cumulative risk score, indicating a greater likelihood of failure occurrence within its emergency braking system.

FMEA Results After Corrective Actions

Corrective actions focused on reducing Occurrence and Detection values through enhanced preventive maintenance programs, installation of pressure alarms, routine functional testing, and emergency simulation exercises.

Table 7
FMEA Results After Corrective Actions

Component	S	O	D	RPN	Category
Brake Chamber Primary	8	2	2	32	Low
Brake Chamber Secondary	9	1	2	18	Low
Pilot Valve Primary	8	2	2	32	Low
Pilot Valve Secondary	9	1	2	18	Low

Comparison of FMEA Results Before and After SEB Implementation

A comparative analysis was conducted to quantify the effectiveness of the Secondary Emergency Brake implementation.

Table 8
RPN Before and After SEB Implementation

Rig	Total RPN Before	Total RPN After	Reduction (%)
Rig Alpha	249	100	59.8
Rig B	225	100	55.6
Rig C	273	100	63.4
Rig D	249	100	59.8
Rig E	225	100	55.6

The average cumulative RPN before implementation was 244.2, whereas the average post-implementation value decreased to 100. The percentage reduction ranged from 55.6% to 63.4%, with an average reduction of 58.8%. These findings show that the SEB installation substantially improved emergency braking system reliability and reduced operational risk.

Fault Tree Analysis Results

Fault Tree Analysis was subsequently conducted to identify the causal pathways leading to total emergency brake failure. The top event was defined as the inability of the emergency braking system to stop the travelling block under emergency conditions. The fault tree structure comprised multiple intermediate and basic events derived from maintenance records, incident investigations, and operational data.

Table 9

FTA Basic Events and Failure Probabilities

Event ID	Basic Event	Failure Probability
BE-01	Loose linkage pin due to vibration	0.0060
BE-02	Corrosion of linkage pin	0.0040
BE-03	Primary brake chamber diaphragm seal leakage	0.0040
BE-04	Secondary brake chamber activation failure	0.0015
BE-05	Brake lining thickness below 3 mm	0.0030
BE-06	Brake drum overheating (> 200°C)	0.0020
BE-07	Primary pilot valve response time > 1.5 s	0.0025
BE-08	Secondary pilot valve non-response	0.0010
BE-09	Driller unable to reach console during emergency	0.0050
BE-10	Pneumatic supply pressure below 6.0 bar	0.0020

Among all identified basic events, the highest failure probability was associated with loose linkage pins caused by vibration (BE-01 = 0.0060), followed by the inability of the driller to reach the console during emergency situations (BE-09 = 0.0050) and corrosion of linkage pins (BE-02 = 0.0040).

Fault Tree Analysis Quantification and Minimal Cut Set Identification

The Fault Tree Analysis (FTA) was performed to quantify the probability of emergency brake system failure and to identify the most critical combinations of basic events contributing to the top event. The top event was defined as the inability of the emergency braking system to stop the travelling block under emergency operating conditions.

Table 10

FTA Results as Failure Probability and Critical Minimal Cut Sets

Rig	Failure Probability Before	Failure Probability After	Risk Reduction	Critical Minimal Cut Set
Rig Alpha	0.0180 (1.80%)	0.0054 (0.54%)	70.0%	(BE-01)/(BE-02)
Rig B	0.0165 (1.65%)	0.0055 (0.55%)	66.7%	(BE-01)/(BE-02)

Rig C	0.0195 (1.95%)	0.0052 (0.52%)	73.3%	(BE-01)/(BE-02)
Rig D	0.0180 (1.80%)	0.0056 (0.56%)	68.9%	(BE-01)/(BE-02)
Rig E	0.0160 (1.60%)	0.0058 (0.58%)	63.8%	(BE-01)/(BE-02)

The results show that the dominant critical pathway was consistently associated with linkage pin deterioration, reshowed by vibration-induced loosening (BE-01) and corrosion of linkage connections (BE-02). Following implementation of corrective measures, including double-locking mechanisms and corrosion-resistant linkage materials, the probability of system failure decreased substantially across all rigs. Risk reduction ranged from 63.8% to 73.3%, with Rig C exhibiting the highest improvement. Moreover, all post-improvement failure probabilities were reduced to below 0.60%, indicating a significant enhancement in overall system reliability.

Reliability and System Availability

Reliability analysis was conducted using Mean Time Between Failure (MTBF), Mean Time to Repair (MTTR), and system availability calculations derived from operational records covering 8,760 operating hours. The objective was to evaluate the long-term impact of preventive maintenance improvements and secondary emergency brake implementation on emergency braking system performance.

Table 11
Reliability Analysis of Emergency Brake Components

Rig	MTBF Before	MTBF After	Availability Before	Availability After	Primary Brake Response Time
Rig Alpha	4,380 h	8,760 h	99.86%	99.95%	1.5 to 0.7 s
Rig B	4,380 h	8,760 h	99.84%	99.93%	1.4 to 0.8 s
Rig C	4,380 h	8,760 h	99.82%	99.92%	1.5 to 0.9 s
Rig D	4,380 h	8,760 h	99.83%	99.91%	1.6 to 0.8 s
Rig E	4,380 h	8,760 h	99.80%	99.90%	1.5 to 0.9 s

As shown in Table 11, MTBF doubled from 4,380 hours to 8,760 hours across all rigs following the implementation of enhanced preventive maintenance strategies. System availability increased to values ranging from 99.90% to 99.95%, reflecting a highly reliable operational condition. Furthermore, the response time of the primary emergency brake improved significantly, decreasing from 1.4-1.6 seconds to 0.7-0.9 seconds after maintenance optimization.

Comparison of Emergency Brake Configurations

To evaluate the operational benefits of redundancy, the original single-brake configuration was compared with the newly implemented redundant braking architecture.

Table 12
Comparison Between Single and Redundant Brake Systems

Aspect	Single Brake System	Redundant Brake System
Number of Systems	1 (Primary Brake)	2 (Primary + Secondary)
Failure Risk	High	Lower
Backup System	Not Available	Available
Reliability	Lower	Higher
Operational Safety	Vulnerable	Safer
Design Principle	Single Failure Risk	Fail-Safe System

Emergency Brake Performance Evaluation

Brake performance testing was conducted under operational conditions following API Spec 8C requirements. The assessment included response time measurements, braking capacity evaluation, and compliance verification with applicable industry standards.

Table 13
Emergency Brake Performance Test

Rig	Primary Brake Response (Pre-PM)	Primary Brake Response (Post-PM)	SEB Response Time	Braking Capacity	API 8C Compliance
Rig Alpha	1.5 s	0.7 s	1.2 s	≥150% Hook Load	Yes
Rig B	1.4 s	0.8 s	1.3 s	≥150% Hook Load	Yes
Rig C	1.5 s	0.9 s	1.4 s	≥150% Hook Load	Yes
Rig D	1.6 s	0.8 s	1.3 s	≥150% Hook Load	Yes
Rig E	1.5 s	0.9 s	1.5 s	≥150% Hook Load	Yes

All rigs successfully satisfied API 8C requirements. The Secondary Emergency Brake exhibited response times between 1.2 and 1.5 seconds, remaining well below the maximum allowable threshold of 2 seconds. Additionally, braking capacity exceeded 150% of the tested hook load in all cases, confirming sufficient stopping capability under emergency operating conditions.

Inspection Results of Brake Linkage Mechanisms

Inspection was conducted to evaluate the mechanical condition of linkage components following implementation of the corrective actions. Particular attention was given to components previously associated with the April 2024 near-miss event.

Table 14
Inspection Results of Emergency Brake Linkage Components

Linkage Component	Condition	Risk Level	Clearance	Recommended Action
Female-Male Linkage (Near-Miss April 2024)	Poor	Critical	Above Limit	Replace with stainless-steel pin
Screw Lock Vertical Linkage Bar	Good	Low	Within Limit	Daily torque verification
Horizontal Linkage Bar	Good	Low	< 10% OD/ID	Clearance monitoring
Linkage Pin (After Replacement)	Good	Low	Within Limit	Anti-corrosion recoating every 3 months

Technical Specifications of the Installed Emergency Brake Button

Based on the initial FMEA findings, an additional emergency brake button was installed to improve accessibility and redundancy during emergency operations.

Table 15
Technical Specifications of the Installed Emergency Brake Button

Specification Parameter	Value
Button Type	Emergency Push Button, Mushroom Head, Self-Locking
Standard	IEC 60947-5-1, IP65
Voltage Rating	24 VDC / 220 VAC
Color	Red with Yellow Ring
Actuation Function	Normally Closed (Fail-Safe)
System Response Time	< 0.5 s
Installation Location	Main Operator Panel
Redundancy	Two Buttons (Primary and Backup)
System Integration	PLC and Visual/Audio Alarm System
Safety Standard	SIL 2 (IEC 61508)

Research Results and Target Achievement

The final evaluation compared all measured performance indicators against the predefined success criteria established at the beginning of the study.

Table 16
Results and Target Achievement

Parameter	Before	After	Target	Status
Total RPN (4 Components)	249 (225-273)	100	< 300	Achieved
Average RPN per Failure Mode	62.25	25.0	< 35	Achieved
Highest RPN (Primary Brake Chamber)	96	32	< 50	Achieved
High-Risk Components	2	0	≤ 1	Achieved
Top Event Probability	0.0180 (1.60-1.95%)	0.0054 (0.52-0.58%)	< 0.010	Achieved
FTA Risk Reduction	-	70.0% (63.8-73.3%)	≥ 50%	Achieved
Brake Chamber Availability	99.86%	99.95%	≥ 99.90%	Achieved
Brake Chamber MTBF	4,380 h	8,760 h	> 5,000 h	Achieved
Near-Miss Events	1	0	0	Achieved

2. Discussion

The implementation of a Secondary Emergency Brake (SEB) significantly reduced the overall risk level of the emergency braking system in the 350 HP drawworks rigs. The FMEA results showed that the total Risk Priority Number (RPN) decreased from a range of 225-273 before improvement to 100 after the implementation of corrective actions and SEB installation. This reduction was primarily achieved through lower Occurrence and Detection scores resulting from stricter preventive maintenance schedules, pressure alarm installation, routine emergency simulations, and enhanced inspection procedures. Notably, all previously identified High-risk failure modes were successfully reduced to the Low-risk category, showing a substantial improvement in operational safety. These findings support the fundamental objective of FMEA, which is to systematically identify potential failure modes and prioritize corrective actions based on risk severity, occurrence, and detectability. The effectiveness of expert-based risk evaluation applied in this study is consistent with the recommendations of Lavasani *et al*. (2015) and Wang and Chin (2011), while the use of a quantitative evaluative framework aligns with the post-positivist approach proposed by Creswell and Creswell (2018).

The FTA results further confirmed the effectiveness of the intervention by demonstrating a considerable reduction in system failure probability across all rigs. Prior to the implementation of corrective measures, the probability of emergency brake system failure ranged from 1.60% to 1.95%; after improvement, it decreased to approximately 0.52%-0.58%, corresponding to a risk reduction of 63.8%-73.3%. The analysis identified the combination of pin linkage loosening due to vibration and linkage pin corrosion as the most critical minimal cut set in all rigs, showing a common systemic vulnerability within the braking mechanism. The installation of improved linkage components, anti-corrosion protection, and enhanced inspection practices effectively interrupted this critical failure pathway and substantially improved system reliability. These results show the value of integrating FMEA and FTA, as FTA was able to identify critical failure paths and minimal cut sets that could not be fully revealed through FMEA alone. Similar advantages of integrated FMEA-FTA applications have been reported by Shafiee *et al*. (2019), Ruijters and Stoelinga (2015), and Kutlu and Ekmekçioğlu (2021), who concluded that combining both methods provides a more comprehensive understanding of complex industrial safety systems.

In addition to reducing risk, the implementation of SEB contributed significantly to improvements in reliability, availability, and braking performance. The Mean Time Between Failures (MTBF) increased from 4,380 hours to 8,760 hours, while system availability improved to a range of 99.90%-99.95%, exceeding the predetermined performance target. Furthermore, the response time of the primary emergency brake improved from 1.4-1.6 seconds to 0.7-0.9 seconds following preventive maintenance, while the SEB maintained response times between 1.2 and 1.5 seconds, remaining within the acceptable limit specified by industry standards. All tested rigs also achieved braking capacities exceeding 150% of the applied hook load and complied with API 8C requirements, indicating that the additional braking system did not compromise operational effectiveness. The transition from a single-brake configuration to a redundant fail-safe braking architecture substantially enhanced operational resilience by eliminating single-point failure risks. The integration of SEB with risk-based maintenance and engineering improvements provides an effective strategy for strengthening emergency braking reliability and operational safety in drilling operations, supporting previous findings reported by Shafiee *et al*. (2019), Creswell and Creswell (2018), and Kutlu and Ekmekçioğlu (2021).

Beyond improving system reliability, the implementation of the Secondary Emergency Brake (SEB) also has important implications for worker safety and occupational health during drilling operations. The reduction in Risk Priority Number (RPN), lower emergency brake failure probability, and improved response time decrease the likelihood of uncontrolled travelling block movement, one of the major sources of severe occupational injuries and fatalities in drilling activities. By providing an independent backup braking mechanism, the SEB reduces workers' exposure to hazardous situations associated with single-point failures, thereby strengthening engineering controls within the hierarchy of risk control. The elimination of high-risk failure modes identified through FMEA and the interruption of critical failure pathways identified through FTA contribute to a safer working environment by reducing the probability of sudden emergency events requiring immediate operator intervention. This improvement is particularly relevant for drillers and rig floor personnel who work in close proximity to suspended loads and moving hoisting equipment, where even a single brake failure may result in serious injury or fatal accidents (IADC, 2019; IADC, 2023; IADC, 2024; IADC, 2025; Zulkarnain *et al*., 2024). Therefore, the implementation of the SEB should be viewed not only as an engineering reliability improvement but also as an occupational safety intervention that supports injury prevention, protects workers from high-consequence hazards, and promotes safer drilling operations.

Conclusion

The primary emergency brake system of the 350 HP drawworks rigs initially exhibited a high-risk condition due to its reliance on a single-point-of-failure control configuration, making the system vulnerable to mechanical degradation, pneumatic contamination, the absence of control redundancy, and operational deviations. The FMEA results identified Brake Chamber Primary and Pilot Valve Primary as the most critical components, with total Risk Priority Number (RPN) values ranging from 225 to 273 before improvement. Following the installation of the Secondary Emergency Brake (SEB) and the implementation of corrective actions, total RPN values were reduced by 55.6%-63.4%, all critical components were downgraded to the Low-risk category, and system failure probabilities decreased by 63.8%-73.3%, exceeding the predetermined performance targets. The SEB effectively eliminated the single-point-of-failure condition by introducing a redundant emergency braking activation pathway accessible to personnel on the rig floor, while maintaining response times within API 8C requirements and achieving braking capacities of at least 150% of the tested hook load. Furthermore, system reliability improved substantially, as reflected by the increase in Mean Time Between Failures (MTBF) from 4,380 to 8,760 operating hours, system availability exceeding 99.90%, and the absence of recurring near-miss incidents following implementation. Therefore, the addition of the Secondary Emergency Brake can be considered an effective engineering control measure for reducing emergency brake failure risk, enhancing operational reliability, and improving occupational safety in 350 HP drawworks rig operations.

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