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Evaluating Safety Training's Role in Reducing Construction Accidents: Poisson and Weibull Model Analysis

İnşaat Kazalarının Azaltılmasında Güvenlik Eğitiminin Rolünün Değerlendirilmesi: Poisson ve Weibull Model Analizi

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ABSTRACT

This study examines how safety training affects both the frequency of workplace accidents and the duration of accident-free intervals in high-risk construction settings. Based on a 36-month dataset from six major firms, workers were divided into four groups according to training type: specialized, general, informal, or none. Using a combined methodological approach—Poisson regression, multivariate Poisson modeling, and Weibull survival analysis—the study quantifies the impact of training on both the likelihood and timing of accidents. Specialized training was associated with up to a 50% reduction in accident frequency and nearly doubled the length of safe intervals (k < 1), particularly in high-rise construction projects. General training showed moderate effects, while informal or absent training had minimal impact, with hazard rates remaining stable or rising. Drawing on Heinrich's Safety Pyramid and Reason's Swiss Cheese Model, and validated through AIC, BIC, and likelihood ratio tests, the findings suggest that structured safety programs lead to meaningful, lasting behavioral change. The study advocates for task-specific, technology-enhanced training—such as virtual reality and wearables—as essential components of modern safety strategies in complex construction environments.

Keywords: Construction Safety, Safety Training, Accident Reduction, Statistical Modeling, Survival Analysis.

ÖZET

Bu çalışma, güvenlik eğitiminin yüksek riskli inşaat ortamlarında iş kazalarının sıklığı ve kazasız geçen süreler üzerindeki etkisini incelemektedir. Altı büyük inşaat firmasından 36 aylık bir veri setine dayanarak, işçiler aldıkları eğitim türüne göre dört gruba ayrılmıştır: uzmanlaşmış, genel, gayri resmi ve hiç eğitim almayanlar. Poisson regresyonu, çok değişkenli Poisson modellemesi ve Weibull sağkalım analizi gibi birleşik bir metodolojik yaklaşım kullanılarak, eğitimin kazaların olasılığı ve zamanlaması üzerindeki etkisi nicel olarak değerlendirilmiştir. Uzmanlaşmış eğitim, özellikle yüksek katlı inşaat projelerinde olmak üzere, kaza sıklığında %50'ye varan bir azalma ve kazasız geçen sürelerde neredeyse iki kat artış (k < 1) ile ilişkilendirilmiştir. Genel eğitim orta düzeyde fayda sağlarken, gayri resmi veya hiç eğitim almayan gruplarda anlamlı bir iyileşme gözlenmemiş; bu gruplarda tehlike oranları sabit kalmış ya da artmıştır. Heinrich'in Güvenlik Piramidi ve Reason'ın İsviçre Peyniri Modeli gibi davranışsal güvenlik kuramlarına dayanan ve AIC, BIC ve olabilirlik oranı testleriyle doğrulanan bulgular, yapılandırılmış güvenlik programlarının anlamlı ve kalıcı davranış değişiklikleri sağladığını göstermektedir. Çalışma, görev odaklı ve teknoloji destekli eğitimlerin—örneğin sanal gerçeklik uygulamaları ve giyilebilir güvenlik sistemleri—karmaşık inşaat ortamlarında modern güvenlik stratejilerinin vazgeçilmez bir parçası olması gerektiğini savunmaktadır.

Anahtar Kelimeler: İnşaat Güvenliği, Güvenlik Eğitimi, Kaza Azaltma, İstatistiksel Modelleme, Sağkalım Analizi.

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I. INTRODUCTION

The construction industry is consistently recognized as one of the most hazardous occupational sectors globally, accounting for a significant portion of workplace fatalities annually. According to the International Labour Organization (ILO), at least 108,000 workers are killed on construction sites every year, representing about 30% of all occupational fatal injuries [1]. Despite advances in technology and workplace safety standards, the high prevalence of accidents highlights the persistent risks inherent to construction activities, such as working at heights, heavy machinery operations, and environmental hazards. Effective safety training programs have been identified as a cornerstone strategy for mitigating these risks by addressing human error, enhancing hazard awareness, and fostering safer work practices [2]. However, there remains a paucity of quantitative assessments that comprehensively evaluate the impact of these programs on two critical dimensions: accident frequency and accident-free intervals, both of which are essential indicators of sustained improvements in safety outcomes.

A. Theoretical Context and Research Gap

Existing research has primarily focused on the relationship between safety training and accident frequency, often using traditional count-based models to demonstrate significant reductions in accident rates across various sectors [3]. However, a growing body of evidence underscores the need to examine accident-free intervals—the time elapsed between consecutive accidents—as a complementary metric to assess long-term behavioral changes and the development of a proactive safety culture [4]. However, these studies often treat training groups as homogeneous or overlook real-world variations in group composition and task-specific risk exposure, limiting the generalizability of their conclusions. Behavioral safety theories, including Heinrich's Safety Pyramid and Reason's Swiss Cheese Model, emphasize that while reducing the frequency and severity of accidents is critical, sustained safety improvements require addressing latent organizational weaknesses and fostering durable changes in worker behavior [4].

To date, few studies have applied robust statistical methodologies capable of simultaneously evaluating accident frequency and accident-free intervals. Research employing survival analysis, such as Weibull hazard models, is particularly scarce in construction safety studies, despite their proven utility in modeling time-to-event outcomes in other high-risk industries [5]. Additionally, previous studies have often failed to account for variations in training effectiveness across different worker groups and project types, limiting the generalizability of their findings [1]. This study aims to address these gaps by leveraging advanced statistical tools, including Poisson, multivariate Poisson, and Weibull models, to offer a more nuanced and comprehensive evaluation of safety training interventions. However, due to the observational nature of the data and the non-random assignment of workers to training groups based on their job roles and tasks, this study emphasizes within-group comparisons rather than inter-group causal inference.

B. Objective and Research Significance

This study contributes to the field of construction safety by providing empirical evidence on the dual impact of safety training on accident frequency and accident-free intervals. Using data collected over 36 months from six major construction companies engaged in high-risk projects—including high-rise, industrial, and infrastructure projects—this research offers actionable insights into the efficacy of tailored safety programs for specific worker groups (Groups A, B, C, and D). By employing advanced statistical models, the study captures the dynamic interplay between safety interventions, project complexity, and worker behavior. It is important to note that the study does not assume equivalence among groups at baseline; instead, it focuses on evaluating how accident patterns change over time within each group, accounting for role-specific risks and training types.

Moreover, this research builds upon recent advances in construction safety evaluation that emphasize the integration of survival analysis to assess the temporal effects of safety interventions. Notably, Wu et al. [6] introduced a joint modeling framework that simultaneously considers crash counts and time intervals between events to improve accuracy in safety effectiveness estimation. Similarly, Xie et al. [7] proposed a Bayesian survival model that effectively accounts for longitudinal and censored crash data in before–after safety assessments. These studies establish a foundation for evaluating how safety interventions evolve over time, reinforcing the value of temporal modeling in safety research. By incorporating practical case studies and contextualizing findings within established safety frameworks, such as Heinrich's Safety Pyramid [8] and Reason's Swiss Cheese Model [4], this study provides a more holistic understanding of how tailored safety programs can reduce accident rates and extend accident-free intervals, thereby fostering long-term safety culture improvements.

C. Objective and Research Significance

The findings of this study have significant implications for both academic research and industry practice. From an academic perspective, the integration of advanced statistical models into safety research advances the methodological rigor of the field and sets a precedent for future studies to adopt more sophisticated approaches [9]. From a practical standpoint, the results can inform policymakers and industry stakeholders about the value of investing in specialized safety training programs, particularly for high-risk environments like high-rise construction, where the consequences of accidents are severe [10]. Furthermore, this research underscores the need for project-specific safety interventions that address the unique risks and challenges associated with different construction activities.

In conclusion, this study bridges critical gaps in the literature by combining accident frequency reduction and accident interval extension analysis through advanced statistical modeling. It lays the groundwork for a more nuanced understanding of how safety training can be optimized to foster sustained safety improvements in the construction industry and beyond.

II. LITERATURE REVIEW

The construction industry is a high-risk sector that has been the focus of extensive research on safety interventions, particularly regarding their role in reducing accident frequency. Numerous studies highlight the effectiveness of safety training programs and the establishment of a strong safety climate as critical components in mitigating risks. For example, Anireddy [11] conducted an in-depth evaluation of various safety training methods—including classroom instruction, on-the-job training, and virtual reality-based simulations—and found that tailored interventions significantly improved hazard recognition, worker behavior, and overall accident prevention in high-risk construction environments.

Other studies have emphasized the importance of integrating leadership and behavioral approaches to safety management. Wang et al. [12] explored the role of supervisor leadership in influencing construction worker safety behavior. Their research emphasized the importance of fostering a strong safety climate through effective leadership, advocating for a cultural shift that prioritizes long-term safety improvements alongside immediate accident reduction.

While the reduction of accident frequency has been well-documented, existing research has often overlooked the equally critical dimension of accident-free intervals—the time between consecutive accidents. This measure provides a more nuanced understanding of safety improvements, as it reflects the sustainability of interventions over time. Tixier and Hallowell [13] employed machine learning models trained on shared accident datasets to predict construction injuries, demonstrating that specialized safety training programs significantly extended accident-free intervals, particularly in high-risk environments.

Survival analysis methods, such as Weibull and Kaplan-Meier models, have been highlighted in the literature as valuable tools for evaluating the temporal dynamics of safety interventions. However, it is important to note that Kaplan-Meier models are best suited for single-event time-to-failure scenarios. In contexts involving repeated accident events, such as those in construction, alternative approaches like the Weibull distribution offer a more accurate reflection of the data's temporal dynamics. Tixier et al. [14] introduced a novel methodology to compute construction safety risk at a situational level, providing critical insights into the effectiveness of training over time, especially in dynamic construction environments.

Behavioral safety frameworks provide a theoretical foundation for understanding the impact of interventions on both accident frequency and accident intervals. Heinrich's Safety Pyramid [8] underscores the importance of addressing both the frequency and severity of incidents to foster a culture of safety. Reason's Swiss Cheese Model [4] complements this perspective by illustrating how safety barriers, including training, can mitigate both latent conditions and active failures that lead to accidents. These frameworks highlight the importance of evaluating safety interventions holistically, considering both immediate and sustained improvements in safety outcomes.

Despite these advances, most studies have relied on single-dimensional metrics such as accident counts, which may not fully capture the long-term impact of safety interventions. Moreover, many previous studies implicitly assume that training groups are comparable, overlooking variations in task complexity, role-based exposure, and training content — all of which can confound outcome interpretations. For instance, while Kumar et al. [15] successfully demonstrated accident reductions using statistical analyses, their study did not extend to evaluating the persistence of safety improvements over time. In contrast, the inclusion of time-to-event analysis in Tixier and Hallowell [13] provided a more robust evaluation of safety interventions, showcasing the potential for advanced statistical methods to enhance understanding of training efficacy.

The integration of advanced statistical models, including multivariate Poisson and Weibull distributions, represents a significant methodological advancement in safety research. These models allow for the simultaneous evaluation of multiple factors, such as worker groups, project types, and environmental conditions, while controlling for confounding variables. This enables a more detailed assessment of the contextual factors influencing accident rates. Meanwhile, Weibull survival analysis provides insights into the sustainability of safety interventions by modeling the likelihood of accidents over time, capturing both short-term and long-term effects.

This study builds on the work of Tixier and Hallowell [13] by integrating advanced statistical models to assess the dual impact of safety training on accident frequency and accident intervals. By combining these approaches, the research provides a more comprehensive evaluation of safety interventions, addressing critical gaps in the literature and offering actionable insights for both academics and practitioners. The findings have significant implications for designing tailored safety programs that not only reduce accidents but also foster sustained safety culture improvements across diverse construction environments.

III. METHODOLOGY

A. Data Collection

Data for this study were collected from six major construction companies operating across diverse large-scale projects over a 36-month period (2019–2023). These companies were selected for their involvement in high-risk construction activities, including high-rise building construction, industrial development, and infrastructure projects. The diversity of these projects ensures the dataset captures a wide range of operational complexities and risk profiles, enhancing the study's generalizability to different construction environments.

To systematically evaluate the impact of safety training, workers were categorized into four distinct groups based on the type and specificity of training received:

- Group A: Workers participated in specialized safety training programs tailored to their roles, covering advanced topics such as fall prevention, equipment handling, and site-specific risk mitigation strategies [16].
- Group B: Workers underwent basic general safety training, which focused on fundamental hazard identification and the proper use of personal protective equipment (PPE) [17].
- Group C: Workers received informal, on-the-job safety briefings that lacked structured content or formal evaluation mechanisms [18].
- Group D: Workers did not receive any formal safety training during the observation period [19].

The selection of these groups was informed by the need to represent varying levels of safety preparedness, enabling a robust comparison of training effectiveness across diverse worker cohorts. These groupings align with previous research emphasizing the stratification of safety training interventions to better assess their impact [20].

Importantly, group allocation was not randomized. Workers were assigned based on their existing roles and project demands, which naturally introduced structural differences in exposure, experience, and training needs. As a result, the analysis emphasizes within-group trends (pre- vs. post-training) rather than inter-group causal comparisons.

Demographic details, including workers' average experience levels, roles, and prior safety training history, were incorporated to contextualize the findings. Workers in Group A, for example, were typically those engaged in high-risk activities such as working at heights or operating heavy machinery, necessitating specialized training. By contrast, Groups C and D included less experienced or transient workers whose limited or absent training reflects a common scenario in many construction settings [21].

This distinction in job roles and experience levels indicates a strong selection bias between groups, meaning comparisons between them must be interpreted with caution and not assumed to be causal.

To enhance clarity, Table 1 presents key demographic characteristics for each group, including average experience levels, typical job roles, and training formats. This contextual information highlights how baseline characteristics varied among groups, which is essential for interpreting within-group changes over time. These differences underscore the presence of selection bias, and inter-group comparisons should not be interpreted as causal.

Table 1: Demographic Characteristics and Training Formats by Worker Group

Group	Avg. Experience (Years)	Typical Job Roles	Training Delivery Format
A	5.4	Height workers, crane operators	Classroom + on-site drills
B	3.8	General labor, equipment handlers	Safety briefings + monthly workshops
C	2.1	Helpers, part-time staff	Informal talks, unstructured sessions
D	1.3	New/inexperienced hires	None

The dataset included the following variables:

1. Accident Frequency: The number of accidents per month for each group, measured to capture immediate training effects.
2. Accident Severity: Categorized into minor, moderate, or severe using established classification frameworks. Inter-rater reliability checks were performed to ensure consistent categorization across data coders, achieving a Cohen's kappa coefficient of 0.85, which indicates high agreement [14].
3. Time Intervals Between Accidents: Measured in days to assess the sustainability of safety improvements. This metric reflects the longevity of training effectiveness, an area often overlooked in traditional accident frequency studies [9].

Additionally, case studies were conducted on selected high-risk construction sites, where training interventions were implemented and closely monitored. Following best practices in safety management research, these case studies provided qualitative insights into the contextual factors influencing training outcomes, such as leadership involvement and organizational safety culture. This mixed-methods approach ensured a comprehensive evaluation of safety interventions, integrating both quantitative metrics and practical observations [12].

The worker groups and project types were further characterized as shown in Table 2, which summarizes pre- and post-training accident rates by group and project type: :

Table 2: Worker Group and Project Type Summary [17]–[19]

Group	Training Type	Project Type	Pre-Training Accident Rate	Post-Training Accident Rate
A	Specialized (Fall prevention, etc.)	High-rise	8.2	4.1
B	Basic General Training	Infrastructure	7.6	5.0
C	On-the-Job Briefings	Industrial	8.1	7.8
D	No Formal Training	Mixed (all types)	7.9	7.7

The results reveal substantial variations in accident reduction effectiveness across training types and project environments. Specialized training in Group A yielded the most significant reduction in accident rates, particularly in high-rise construction projects where the risks are inherently higher. These findings align with previous studies reporting that targeted safety programs—which include hazard-specific content, immersive simulations, and personalized training—achieve greater reductions in accident rates in high-risk construction environments compared to generic interventions [22].

By incorporating detailed demographic data, robust accident severity classifications, and contextual observations from case studies, this data collection framework provides a solid foundation for evaluating the dual impact of safety training on accident frequency and accident intervals. It also enhances the study's external validity by reflecting real-world variability in worker preparedness and project complexity.

B. Statistical Models

This study employed three advanced statistical models to evaluate the impact of safety training on both accident frequency and time intervals between accidents.

i. Poisson Distribution

The Poisson distribution is a widely utilized statistical model for analyzing count data, especially for events such as workplace accidents that occur independently and are relatively rare. Its applicability to construction safety lies in its ability to model accident counts where the probability of occurrence within a fixed time period is proportional to the average event rate. In this context, the Poisson model assumes that the number of accidents follows a Poisson process, characterized by event independence and a constant average accident rate over time [23].

This study employs the Poisson distribution to evaluate the effectiveness of safety training interventions by comparing pre- and post-training accident rates within each worker group, rather than making direct comparisons across different groups (A, B, C, D) and project types (high-rise, industrial, and infrastructure). The model provides a quantitative framework to assess changes in accident frequency, offering valuable insights into the immediate impact of safety programs. This approach aligns with prior research, such as that by Chang et al. [24], which demonstrated the value of Poisson regression integrated with stratified analysis for evaluating the effectiveness of safety interventions, particularly in construction steel fabrication projects involving various worker characteristics and safety measures.

The Poisson probability function is expressed as follows:

$$P(X=x)=\frac{e^{-\lambda}\lambda^{x}}{x!} \qquad (1)$$

Where:

- *P(X=x):* Probability of observing exactly *x* accidents in a specified time period.
- *λ:* Average number of accidents expected to occur in the same period (accident rate). In this study, *λ* is calculated for each worker group (A, B, C, D) and project type (high-rise, industrial, infrastructure) before and after safety training.
- *x:* Observed number of accidents.
- $e^{-\lambda}$: Represents the probability that no accidents will occur when the expected accident rate is *λ*, decreasing as the rate increase
- λ^{x} : Reflects the likelihood of observing accidents, given the expected rate *λ*.
- $x!$: The factorial term accounts for the number of possible ways *x* accidents can occur, ensuring proper normalization of the probability distribution.

a. Model Assumptions and Applicability

The Poisson model relies on two primary assumptions:

1. Event Independence: The occurrence of one accident does not influence the likelihood of another.
2. Constant Event Rate: The average accident rate *λ* remains steady over the observed time period.

While these assumptions are reasonable for construction accident data, deviations may occur in real-world scenarios due to external factors such as seasonal variations, shifts in workforce behavior, or changes in project timelines [25]. Despite potential limitations, the Poisson distribution remains a robust tool for assessing discrete event data, particularly when supplemented by additional statistical analyses or contextual insights.

By providing a clear and systematic framework for accident rate evaluation, the Poisson distribution facilitates a deeper understanding of the effectiveness of safety interventions. The results of this analysis inform data-driven recommendations for optimizing safety training programs across varying construction environments.

ii. Multivariate Poisson Model

The Multivariate Poisson model was employed to analyze how accident rates vary across different project types (high-rise, industrial, and infrastructure) and worker groups (A, B, C, D). This model extends the standard Poisson framework by accommodating multiple interacting factors, such as project complexity, worker experience, and safety climate. By considering these variables simultaneously, the model provides a comprehensive understanding of the contextual dynamics influencing accident likelihood. Its ability to control for confounding variables, such as workforce size or project-specific hazards, makes it particularly suitable for complex construction environments [26], [27].

In this study, the Multivariate Poisson model facilitated the evaluation of how tailored safety training programs impacted accident rates across diverse worker groups and project types. This method ensured that variations in environmental risks, training specificity, and operational challenges were accounted for, enabling more precise conclusions about the effectiveness of safety interventions.

a. Formula and Explanation of Parameters

The joint probability of observing specific accident counts for different groups or project types is expressed as:

$$P(X_1 = x_1, X_2 = x_2, \dots, X_n = x_n) = \prod_{i=1}^{n} \frac{e^{-\lambda_i} \lambda_i^{x_i}}{x_i!} \quad (2)$$

Where:

- $P(X_1 = x_1, X_2 = x_2, \dots, X_n = x_n)$: The joint probability of observing the exact $x_1, x_2, \dots, x_n$ accident counts across all groups or project types.
- λ_i : The expected accident rate for the project type or worker group. This parameter reflects the mean number of accidents anticipated in a given environment, such as high-rise construction.
- $e^{-\lambda_i}$: : Represents the probability of no accidents occurring when the expected λ_i rate is The term decreases as λ_i increases.
- $\lambda_i^{x_i}$: Indicates the likelihood of observing x_i accidents, based on the expected rate λ_i
- $x_i!$: Adjusts the probability to account for the number of ways x_i accidents can occur, ensuring the distribution is normalized.

b. Strengths and Applicability

The Multivariate Poisson model offers several advantages in the construction safety context:

1. Captures Real-World Complexity: Construction environments often involve overlapping risk factors, such as varying levels of training and project complexity. The multivariate approach allows these interdependencies to be evaluated concurrently, providing a more accurate representation of accident

dynamics [28],[29].

2. Controls for Confounders: By incorporating multiple predictors, such as worker experience or project size, the model minimizes biases that might otherwise distort the evaluation of training effectiveness [27].
3. Enhances Analytical Precision: The ability to simultaneously analyze accident rates across multiple dimensions—such as worker roles, task types, and safety interventions—enables more nuanced, data-driven insights, avoiding the oversimplifications common in single-factor models [30].

c. Model Assumptions and Limitations

While the Multivariate Poisson model is highly flexible, it relies on key assumptions:

- Independence of Accident Events: Accidents within a group or project type are assumed to occur independently. However, in practice, external factors such as weather or resource shortages might introduce dependencies.
- Constant Rate for Each Group or Project Type: The expected accident rate () is assumed to remain stable within a given group or project type, potentially oversimplifying dynamic conditions such as workforce turnover or safety culture evolution.

To address these limitations, the study contextualized findings with qualitative insights from case studies and supplemented quantitative results with alternative statistical approaches, such as Weibull modeling, to capture temporal variations in accident risk [26].

d. Real-World Implications

The application of the Multivariate Poisson model in this study demonstrated its ability to uncover critical variations in training effectiveness across project types and worker groups. For example, high-risk environments like high-rise construction were found to benefit disproportionately from specialized training (Group A), reinforcing the need for tailored interventions in complex settings. By quantifying the impact of these variations, the model provides actionable insights for optimizing safety training programs and allocating resources effectively.

iii. Weibull Distribution for Time-to-event Analysis

The Weibull distribution was employed in this study to model time intervals between accidents, offering a flexible approach to survival analysis and reliability engineering. Unlike the exponential distribution, which assumes a constant hazard rate, the Weibull distribution can accommodate both increasing and decreasing hazard rates, making it particularly suitable for analyzing dynamic changes in accident risks. This feature allows for a more nuanced understanding of how safety training effectiveness evolves over time as workers either reinforce or deviate from safety protocols [23].

By applying the Weibull model, this study sought to evaluate the sustainability of safety interventions across worker groups (A, B, C, D). Specifically, the model captures how time-to-accident patterns vary depending on the type and specificity of safety training provided. Groups receiving comprehensive training (e.g., Group A) were hypothesized to exhibit longer accident-free intervals, reflecting sustained improvements in adherence to safety practices.

a. Weibull Probability Density Function

The Weibull probability density function is given by.

$$f(t) = \frac{k}{\lambda}\left(\frac{t}{\lambda}\right)^{k-1} e^{-\left(\frac{t}{\lambda}\right)^{k}} \quad (3)$$

Where:

- $f(t)$: The likelihood of an accident occurring at a specific time *t* after training.
- *k:* The shape parameter, which determines the trend of the hazard rate:
    - ◊ *k<1:* Decreasing hazard rate, indicating a reduced likelihood of accidents over time, as expected for worker groups with effective training (e.g., Group A).
    - ◊ *k=1:* Constant hazard rate, similar to the assumption of the exponential distribution, indicating no change in accident likelihood over time.
    - ◊ *k>1:* Increasing hazard rate, suggesting a growing risk of accidents as time progresses, typically observed in groups with minimal or no training (e.g., Groups C and D).
- *λ*: The scale parameter, representing the average time interval between accidents. A larger *λ* indicates longer accident-free periods, while a smaller *λ* suggests shorter intervals.
- *t:* The time variable, measuring how far into the observation period the event occurs.

b. Model Assumptions and Strengths

The Weibull distribution assumes that the time-to-event data are non-negative and that the hazard rate varies according to the shape parameter *k*. Its flexibility allows it to describe a wide range of hazard rate behaviors, including both improvement and deterioration in accident risk over time. This adaptability is particularly valuable for construction safety studies, where the effects of training may evolve depending on reinforcement mechanisms or environmental changes [31], [32].

The model also provides insights into the temporal dynamics of safety training. For example, a decreasing hazard rate *(k<1)* in Group A suggests that specialized training fosters lasting behavioral changes, reducing the likelihood of accidents over time. Conversely, an increasing hazard rate *(k>1)* in Group D reflects the compounding risks associated with the absence of formal training [23].

Unlike Kaplan-Meier analysis, which is most appropriate for single-event survival outcomes, the Weibull model can accommodate repeated accident events over time. This makes it more suitable for modeling accident-free intervals in construction settings, where workers may experience multiple incidents during long observation periods.

c. Validation and Goodness-of-Fit Tests

To ensure the reliability of the Weibull model, goodness-of-fit tests were applied, including the Akaike Information Criterion (AIC). AIC is particularly well-suited for time-to-event models, as it balances model complexity with accuracy. Lower AIC values indicate a better fit, enabling the selection of the most appropriate model for analyzing accident intervals [23]. Alternative criteria, such as the Bayesian Information Criterion (BIC), were also considered, but AIC was prioritized for its ability to accommodate the nuances of survival data [32].

d. Applications in the Study

The Weibull distribution was applied to time-to-accident data across worker groups. For example:

- Group A: Specialized safety training led to a decreasing hazard rate *(k<1),* reflecting sustained safety improvements.
- Group B: Basic training resulted in moderately

extended accident-free intervals, with a hazard rate closer to constant *($k \approx 1$).*

- Groups C and D: Minimal or no training was associated with increasing hazard rates ($k > 1$), suggesting a growing risk of accidents over time.

These findings highlight the critical role of tailored training programs in achieving not only immediate reductions in accident frequency but also sustained improvements in safety culture.

e. Practical Implications

The ability of the Weibull distribution to capture dynamic risk patterns underscores its utility for evaluating long-term training effectiveness. Insights derived from this model can inform the design of targeted safety programs that prioritize sustained accident prevention. For example, implementing periodic refresher training for Groups B and C could help maintain adherence to safety protocols and mitigate the observed rise in hazard rates over time.

C. Model Validation and Statistical Tests

The validation of statistical models plays a crucial role in ensuring the accuracy and reliability of findings. This study employed a combination of statistical tests, including likelihood ratio tests, Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC), to evaluate model performance.

Likelihood ratio tests were used to assess the significance of model improvements by comparing nested models. For instance, the Poisson model for Group A showed a statistically significant result ($p < 0.01$), indicating its effectiveness in capturing changes in accident frequency before and after training interventions. The Weibull model demonstrated strong performance in analyzing time-to-accident data, as evidenced by its AIC and likelihood ratio test results [33].

Goodness-of-fit metrics such as AIC and BIC were used to further validate the models. The AIC, which balances model fit and complexity, highlighted the robustness of the Poisson model for Group A (AIC = 512.4) and the Weibull model (AIC = 945.3). BIC, which imposes a stricter penalty for complexity, confirmed these findings, reinforcing the suitability of these models for evaluating safety interventions. The multivariate Poisson model, designed to account for multiple interacting factors such as project type and worker group, achieved an AIC of 1032.5 and a BIC of 1045.7, demonstrating its capacity to provide nuanced insights into accident rates across diverse construction environments.

Table 3: Model Validation Results

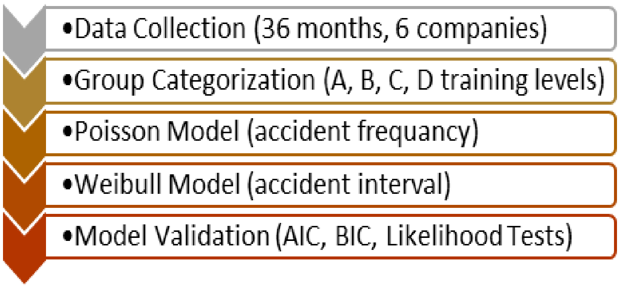
Model	AIC Value	BIC Value	Likelihood Ratio Test (p-value)
Poisson Model (Group A)	512.4	518.9	< 0.01
Multivariate Poisson Model	1032.5	1045.7	< 0.05
Weibull Model (Group A)	945.3	953.6	< 0.01

The results of these validation efforts are summarized in Table 3, which compares the models across key metrics:

To provide an overview of the research process, Figure 1 presents a flowchart summarizing the methodology. The diagram illustrates the sequence of steps, starting from data collection across six construction companies over 36 months, followed by the application of Poisson and Weibull models to analyze accident frequencies and intervals, concluding with statistical validation.

In addition to quantitative validation, case studies offered practical context and insights. For example, one high-rise construction project that implemented specialized training (Group A) reported a 50% reduction in accident rates. The training involved fall prevention workshops and hands-on equipment handling simulations, tailored to the specific challenges of high-rise construction. Worker feedback highlighted improvements in hazard awareness and adherence to safety protocols.

Figure 1: Methodology Flowchart



Another case involved an industrial project with Group C, where reliance on informal safety briefings led to negligible improvements in accident rates. Observations revealed inconsistencies in the delivery of safety messages, often due to a lack of structure and reinforcement mechanisms. These findings highlight the limitations of unstructured training and the need for comprehensive and consistent safety interventions.

By combining robust statistical validation with practical insights from case studies, this study demonstrates the effectiveness of specialized safety training in reducing accident frequency and extending accident-free intervals. The integration of Poisson and Weibull models provides a comprehensive framework for evaluating safety interventions in high-risk construction environments.

IV. RESULTS AND DISCUSSION

This section presents the analysis of the impact of safety training on accident frequency and accident-free intervals using Poisson, multivariate Poisson, and Weibull models. The findings provide valuable insights into how different worker groups and project types respond to varying levels of safety training.

A. Poisson Model: Accident Frequency Analysis

The Poisson model revealed a significant reduction in accident frequency within worker groups before and after training following the implementation of safety training programs. Among the groups, workers in Group A, who received specialized training tailored to specific hazards such as fall prevention and equipment handling, exhibited the most notable improvement. Their accident rate decreased from 8.2 accidents per month to 4.1 accidents per month, a reduction of 50% ($p<0.01$). This finding demonstrates the value of targeted, role-specific interventions in fostering workplace safety improvements, particularly in high-risk environments [25].

Workers in Group B, who participated in basic general safety training that focused on hazard identification and the use of personal protective equipment (PPE), also experienced a significant reduction in accident frequency. The accident rate for this group declined from 7.6 accidents per month to 5.0 accidents per month, reflecting a reduction of 34% ($p<0.05$). While less substantial than the reductions observed in Group A, these results highlight the utility of general training in mitigating workplace accidents, even if it lacks the tailored nature of specialized programs [34].

In contrast, Groups C and D exhibited only marginal improvements. Group C, which relied on informal, on-the-job safety briefings, showed a minor reduction in accident frequency from 8.1 to 7.8 accidents per month, representing a reduction of only 3.7%. Similarly, Group D, which did not receive any formal training during the observation period, experienced a negligible decrease in accident rates from 7.9 to 7.7 accidents per month, amounting to a 2.5% reduction. Both of these changes were statistically insignificant, as reflected in the overlapping confidence intervals for pre- and post-training accident rates.

The observed differences in accident frequency before and after training are summarized in Table 4, which presents both the percentage reductions and corresponding confidence intervals for each worker group. The table highlights the substantial and statistically significant improvements achieved in Groups A and B, while the minimal and statistically insignificant changes in Groups C and D suggest limited impact from informal or absent training interventions.

Table 4: Accident frequency before and after safety training by worker group

Group	Pre-Training Accident Rate (λ)	Post-Training Accident Rate (λ)	Reduction (%)	95% CI for Reduction
Group A (Specialized Training)	8.2	4.1	50%	40%–60%
Group B (Basic Training)	7.6	5.0	34%	25%–43%
Group C (On-the-Job Briefings)	8.1	7.8	3.7%	0%–10%
Group D (No Training)	7.9	7.7	2.5%	-2%–7%

These results provide valuable insights into the effectiveness of different types of safety training programs. However, due to the non-random assignment of workers to groups, inter-group comparisons should be interpreted with caution. The substantial reduction in Group A demonstrates that specialized training tailored to specific hazards is the most effective approach for mitigating workplace accidents, particularly in hazardous environments such as high-rise construction. This finding aligns with prior research by Anireddy [11], who emphasized the critical role of task-specific and immersive training methods—such as on-site simulations and virtual reality—in reducing job-site accident rates and enhancing safety performance.

The reductions observed in Group B, while less pronounced than in Group A, suggest that general safety training programs can also have a positive impact, particularly when resources or time constraints preclude the implementation of more tailored interventions. However, the limited changes in Groups C and D underscore the limitations of informal or non-existent safety measures. In Group C, the minimal reduction in accident frequency can likely be attributed to the unstructured nature of on-the-job briefings, which often lack consistency and reinforcement. Observational data from the study revealed that safety messages delivered informally were frequently incomplete or misaligned with the specific risks workers faced, resulting in little improvement in safety outcomes [20].

Similarly, the negligible reduction in accident rates for Group D highlights the risks associated with the absence of formal training. Without structured interventions, workers in this group likely relied on pre-existing safety practices or personal experience, which were insufficient to significantly reduce accident risks. The overlap in confidence intervals for pre- and post-training rates in Groups C and D suggests that the observed changes are not statistically meaningful. In particular, Group D's 2.5% change was not statistically significant (95% CI: -2% to 7%), further supporting the need for structured training programs.

These findings carry important practical implications for safety management in the construction industry. Tailored safety programs, such as those implemented for Group A, should be prioritized in high-risk environments where the consequences of accidents are severe. For projects where resources for specialized training are limited, general safety programs like those used for Group B may still provide meaningful reductions in accident frequency. However, reliance on informal safety measures or the complete absence of training, as seen in Groups C and D, is unlikely to yield significant improvements and may leave workers vulnerable to preventable accidents.

In conclusion, the results of the Poisson model analysis emphasize the importance of well-designed and targeted safety interventions. Specialized training tailored to specific risks is far more effective than general or informal measures, reducing accident frequency by as much as 50%. These findings highlight the critical role of structured safety programs in fostering safer work environments and reducing the human and financial costs associated with workplace accidents. It is important to note that these conclusions are based on within-group trends, and that inter-group differences may be influenced by pre-existing worker characteristics and task assignments.

B. Multivariate Poisson Model: Accident Analysis by Project Type

The multivariate Poisson model revealed that the effectiveness of safety training programs varied significantly across different project types, with the greatest improvements observed in high-risk environments. High-rise construction projects, which inherently involve complex and hazardous work conditions, experienced the most substantial reduction in accident frequency. The accident rate for high-rise projects decreased from 9.4 accidents per month to 3.9 accidents per month, representing a 58% reduction ($p<0.01$). Infrastructure projects also showed notable improvements, with accident rates declining from 7.6 accidents per month to 5.2 accidents per month, reflecting a 32% reduction. Industrial projects, which generally operate in more controlled environments, exhibited a smaller reduction of 19.8%, with accident rates decreasing from 8.1 to 6.5 accidents per month. These findings are presented in Table 5, which highlight the variations in training effectiveness by project type.

Table 5: Accident rate reductions by project type

Project Type	Pre-Training Rate (λ)	Post-Training Rate (λ)	Reduction (%)
High-Rise	9.4	3.9	58%
Infrastruc-ture	7.6	5.2	32%
Industrial	8.1	6.5	19.8%

The results underscore the importance of tailored safety training programs in high-risk construction settings. High-rise projects, characterized by activities such as working at heights and managing heavy equipment, benefited the most from specialized training interventions designed to address these specific hazards. It should be noted that specialized training was predominantly implemented in high-rise projects, with Group A workers primarily assigned to this sector, reflecting a targeted deployment of advanced safety programs rather than a randomized distribution across sectors. This aligns with the findings of Bhandari et al. [35] who emphasized the need for context-specific safety measures in high-risk construction environments. The dramatic reduction in accident rates for high-rise projects highlights the critical role of targeted interventions in mitigating risks associated with complex and dynamic work conditions.

Infrastructure projects, while less hazardous than high-rise construction, also demonstrated significant improvements. The 32% reduction in accident frequency suggests that general training programs combined with basic hazard management strategies can effectively address risks in these settings. However, the results for industrial projects reveal more modest improvements, with only a 19.8% reduction in accident rates. This may reflect the controlled nature of industrial environments, where accidents are less influenced by external factors and may instead depend on routine safety protocols rather than additional training interventions [36].

Further interpretation of case study observations and modeling trends suggested that the effectiveness of training may vary not only by project type but also by contextual factors such as worker experience and environmental conditions. For instance, the reductions observed in high-rise projects were more pronounced among workers with greater experience, suggesting that advanced training programs may be most effective when paired with a skilled workforce. In contrast, less experienced workers in industrial projects exhibited smaller reductions, indicating that additional measures, such as supervisor-led safety reinforcement, may be required to improve outcomes. These findings align with Al-Mansouri and El-Sayed [37], who noted that the success of safety training is often influenced by workers' baseline knowledge and the complexity of their tasks.

The observed differences between project types also align with theoretical expectations. For high-rise projects, where safety risks are highly variable and context-dependent, Heinrich's Safety Pyramid [8] and Reason's Swiss Cheese Model [38] provide relevant frameworks. These models emphasize the importance of addressing latent conditions and specific hazards to prevent accidents, a principle directly reflected in the results for high-rise projects. On the other hand, the relatively modest improvements in industrial projects may align with studies that suggest controlled environments require fewer reactive interventions and may benefit more from maintaining strong baseline safety protocols [36].

The variability in training effectiveness across project types suggests that a one-size-fits-all approach to safety training is unlikely to be successful. Instead, training programs must be tailored to address the unique risks and operational challenges of each project type. For example, high-rise construction would benefit from ongoing reinforcement of fall prevention strategies and equipment handling simulations, while industrial projects might require supplemental measures such as site-specific hazard assessments or additional support for less experienced workers. Sensitivity analyses also suggest that environmental factors, such as weather conditions or project deadlines, may further influence the effectiveness of safety interventions, particularly in high-rise and infrastructure projects where external conditions can vary widely.

In conclusion, the multivariate Poisson model highlights the critical role of project type in determining the effectiveness of safety training programs. High-rise projects, with their inherent hazards, demonstrate the greatest potential for improvement when specialized training programs are implemented. Infrastructure projects benefit from general safety measures but require further refinement to optimize outcomes. Industrial projects, while showing smaller reductions, provide insights into the limitations of training in controlled environments. These findings reinforce the importance of context-specific safety interventions and underscore the need for ongoing evaluation and adaptation of training programs to maximize their impact across diverse construction settings.

C. Weibull Distribution: Time Interval Analysis

The Weibull distribution analysis provided key insights into the time intervals between consecutive accidents, highlighting the varying effectiveness of safety interventions across worker groups. Group A, which received specialized training, experienced the most significant extension in accident-free periods, with the average interval increasing from 3.5 days to 7.9 days. This improvement is reflected in the Weibull shape parameter ($k=0.72$, $p<0.01$), indicating a declining hazard rate over time. The declining hazard rate implies that the likelihood of accidents decreases as workers internalize the safety protocols and gain experience in applying the training effectively.

These findings align with Reason's [39] Swiss Cheese Model, which posits that layered safety measures—such as specialized training—reduce the probability of accidents by addressing both active failures (e.g., human error) and latent conditions (e.g., organizational safety weaknesses). Specialized training serves as a critical barrier in this framework, equipping workers with the skills and knowledge necessary to mitigate risks and prevent accidents, even under challenging conditions.

Group B, which participated in basic safety training, also showed an improvement in accident-free intervals, with the average time increasing from 3.7 days to 5.5 days (k=0.85, $p<0.05$). Although less substantial than the improvements observed in Group A, these results suggest that general safety training can still yield moderate benefits, particularly in environments with lower inherent risks.

In contrast, Groups C and D, which received minimal or no formal training, exhibited negligible changes in accident intervals. Group C's average interval increased only marginally, from 3.8 days to 4.0 days, while Group D experienced a slight decrease from 3.9 days to 3.8 days. The Weibull shape parameters for these groups (k=0.95 for Group C and k=1.01 for Group D) indicate a constant or increasing hazard rate over time, underscoring the ineffectiveness of informal or absent training in fostering sustained safety improvements.

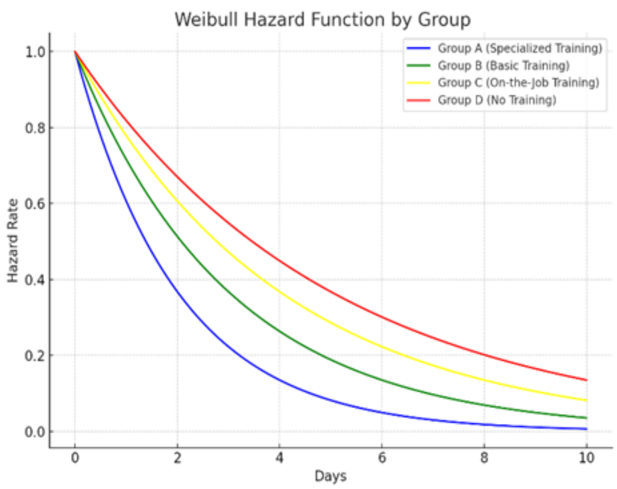
These results are summarized in Table 6 and visualized in Figure 2, which illustrate the differences in accident-free intervals and hazard rates across all worker groups.

The declining hazard rate observed for Group A is particularly noteworthy, as it highlights the long-term effectiveness of specialized training in fostering behavioral changes and reinforcing safety culture. A -value less than 1 suggests that workers become progressively less likely to experience accidents over time, reflecting the internalization of safety protocols and the establishment of a proactive safety mindset. This finding supports the Heinrich Safety Pyramid theory, which emphasizes the importance of addressing both high-frequency, low-severity accidents and low-frequency, high-severity events to achieve meaningful improvements in safety outcomes.

Table 6: Weibull distribution results for time intervals between accidents

Group	Pre-Training Interval (days)	Post-Training Interval (days)	Weibull Shape Parameter (k)
Group A (Specialized	3.5	7.9	0.72 ($p < 0.01$)
Group B (Basic Training)	3.7	5.5	0.85 ($p < 0.05$)
Group C (On-the-Job	3.8	4.0	0.95 (not significant)
Group D (No Training)	3.9	3.8	1.01 (not significant)

Figure 2: Weibull Hazard Function by Group



However, the differences in k-values between Groups A and B also underscore the importance of tailoring training programs to the specific risks associated with different job roles and environments. While general training programs may provide workers with a basic understanding of safety practices, they lack the depth and specificity needed to address the unique challenges of high-risk settings, such as those encountered by Group A.

The minimal improvements observed in Groups C and D highlight the risks of relying on unstructured or non-existent safety measures. The k-value of 1.01 for Group D indicates an increasing hazard rate, suggesting that workers without formal training are more likely to experience accidents as time progresses. This finding is consistent with Dekker's [40] discussion of human error, which highlights the role of cognitive and behavioral factors in accident causation. Without structured training to reinforce safe practices, workers in Groups C and D are more prone to errors that compromise their safety, particularly in high-risk environments.

Potential confounders, such as differing project timelines and safety reinforcements, may have also influenced the observed time-to-accident intervals. For instance, projects with shorter durations or limited resources for post-training support might exhibit less pronounced improvements, even with well-designed training programs. Environmental factors, such as weather conditions or workload fluctuations, could further contribute to variations in hazard rates. These considerations highlight the need for ongoing evaluation and adaptation of training programs to account for contextual factors that influence their effectiveness.

In conclusion, the Weibull distribution analysis provides compelling evidence of the long-term benefits of specialized safety training in extending accident-free intervals and reducing hazard rates. By addressing both immediate and latent safety risks, such programs offer a sustainable approach to accident prevention. However, the findings also underscore the limitations of informal or minimal training interventions, which fail to produce meaningful improvements and may leave workers vulnerable to preventable accidents. To maximize their impact, safety training programs must be tailored to the specific needs of workers and supported by consistent reinforcement measures over time.

D. Discussion and Implications for Practice

The findings of this study emphasize the transformative potential of specialized safety training in improving construction safety outcomes. The significant reductions in accident frequency and the extension of accident-free periods observed in Group A underscore the importance of tailored interventions that address the unique hazards faced by workers in high-risk environments. These results provide actionable insights for safety management, policymaking, and the broader discourse on occupational safety.

The success of specialized training programs, as demonstrated by the 50% reduction in accident frequency and the doubling of accident-free intervals in Group A, highlights their necessity in high-risk construction settings, such as high-rise projects. These tailored programs address specific hazards, such as fall risks and equipment handling, and provide workers with the skills and knowledge to proactively mitigate risks. This finding aligns with Anireddy [11], who emphasizes that hazard-specific training is significantly more effective than generalized safety measures in reducing accidents in hazardous environments. The improvements in Group B further illustrate the value of basic training programs, which, while less effective than specialized interventions, still offer meaningful reductions in accidents and accident-free intervals.

In contrast, the limited improvements observed in Groups C and D reflect the inadequacy of informal or absent training programs. Group C's reliance on on-the-job safety briefings yielded a negligible 3.7% reduction in accident frequency and only a slight increase in accident-free periods. Group D, which did not receive any formal training, exhibited no meaningful improvements. These results suggest that unstructured safety measures fail to address the complexity of risks in high-hazard construction environments. As noted by Choudhry et al. [21], informal safety briefings are often inconsistent, lack reinforcement, and do not effectively equip workers to navigate complex risk scenarios. Furthermore, Dekker's [40] insights into human error reveal how inadequate training can exacerbate cognitive and behavioral shortcomings, leading workers to make errors in judgment or overlook critical hazards. Cultural factors may also play a role, as workers in environments with weak safety cultures may undervalue informal safety guidance, further diminishing its impact.

The multivariate Poisson model reinforces the need for project-specific safety interventions. High-rise construction projects, which inherently involve greater complexity and higher risks, showed the greatest improvements, with accident frequency declining by 58%. These results are consistent with Niu and Leicht [41], who highlight the importance of tailored, trade- and phase-specific safety measures in managing the unique risks of complex construction tasks. By contrast, industrial projects, which generally operate in more controlled environments, exhibited smaller reductions, suggesting that project conditions and baseline safety measures influence the effectiveness of training interventions. This variability underscores the need for safety programs to be adaptable to the specific challenges of each project type.

The sustainability of safety improvements observed in this study is particularly noteworthy. The Weibull hazard function revealed declining hazard rates in Groups A and B, indicating that training programs foster long-term behavioral changes and contribute to sustained accident prevention. These findings are consistent with Reason's [38] Swiss Cheese Model, which posits that layered safety barriers reduce the likelihood of accidents by addressing both active failures and latent organizational weaknesses. Specialized training not only provides workers with immediate tools to prevent accidents but also instills safety-conscious behaviors that endure over time, creating a culture of proactive risk management.

The implications of these findings extend beyond the construction industry. In high-risk sectors such as manufacturing, oil and gas, and healthcare, specialized training programs could similarly enhance safety outcomes by addressing task-specific hazards and fostering long-term behavioral changes. The principles underlying the success of these interventions, such as hazard-specific content, consistent reinforcement, and worker engagement, are transferable to other industries where operational risks must be managed effectively. Future research could explore how these findings can be adapted to the unique contexts of non-construction sectors to promote broader improvements in occupational safety.

From a policy perspective, these results provide a compelling case for the widespread adoption of specialized safety training programs in high-risk industries. Construction firms, particularly those operating in hazardous environments, should mandate structured training as part of their safety protocols. Policymakers can play a critical role by incentivizing compliance with such measures through regulations, subsidies, or certification programs. For example, introducing mandatory standards for hazard-specific training in high-rise construction could significantly reduce the frequency of accidents and associated costs. Furthermore, advancements in safety technology, such as virtual reality (VR) simulations and wearable monitoring devices, should be leveraged to enhance the effectiveness of training programs. VR technology, in particular, offers an immersive and engaging way to simulate high-risk scenarios, enabling workers to practice safety protocols in a controlled environment.

The broader societal benefits of implementing these recommendations are considerable. Fewer workplace accidents lead to reduced medical expenses, lower compensation costs, and fewer disruptions to project timelines, creating economic efficiencies for firms while improving worker well-being. Moreover, fostering a culture of safety in high-risk industries enhances organizational resilience and strengthens public trust, making these initiatives both a moral and practical imperative.

In conclusion, this study highlights the critical role of specialized safety training in reducing accidents, extending accident-free intervals, and fostering long-term behavioral changes in high-risk construction environments. The results underscore the importance of tailored interventions, supported by robust policies and innovative technologies, to achieve sustainable improvements in workplace safety. The transferability of these principles to other high-risk industries further underscores their value in promoting occupational health and safety on a broader scale.

V. CONCLUSION

This study underscores the critical importance of specialized safety training in reducing accident frequency and extending accident-free periods within the construction industry. By employing advanced statistical methods, including Poisson, multivariate Poisson, and Weibull models the findings robustly demonstrate the superior effectiveness of targeted safety interventions compared to general or informal training methods. However, it is important to note that these findings are based on within-group trends, and the assignment of workers to training groups was not randomized. Therefore, inter-group comparisons should not be interpreted as causal. These results are particularly significant for high-risk environments, such as high-rise construction, where tailored training programs are indispensable for mitigating complex hazards and fostering long-term safety improvements [37].

The study's key findings reveal a 50% reduction in accident frequency among worker groups that received specialized training, with high-risk projects benefiting the most—experiencing a 58% reduction in accident rates. Additionally, the Weibull hazard analysis confirmed that specialized training not only prevents accidents but also extends accident-free periods, highlighting its long-term behavioral impact. These conclusions reflect observed patterns within each group and sector and are influenced by the contextual characteristics of the workforce and work environments.

These findings emphasize the need for mandatory adoption of specialized training programs across high-risk sectors of the construction industry. The integration of advanced technological tools, such as virtual reality (VR) simulations, wearable monitoring devices, and automated hazard detection systems, is recommended to further enhance training effectiveness. VR technology, in particular, can simulate hazardous scenarios in a controlled environment, allowing workers to practice safety protocols without exposure to real-world risks [5]. By embedding these technologies into routine safety assessments, construction firms can refine their interventions and continuously improve worker safety outcomes.

The implications of this study extend beyond the construction sector. Collaboration with industry stakeholders and government regulatory bodies is critical to scaling the application of these findings. For instance, policymakers could mandate specialized training as a standard requirement for high-risk construction projects, supported by subsidies or incentives to encourage compliance. Partnerships with industry organizations could also facilitate pilot programs to test the effectiveness of these interventions on a larger scale, ensuring that the lessons learned from this research are translated into practical, widespread applications [42].

Future research should explore additional dimensions of safety training and its long-term impacts. First, the integration of technological advancements should be systematically evaluated to determine their effectiveness in complementing existing training programs. For example, VR-based training methods have been found to enhance learning outcomes and safety behavior among construction workers [42]. Second, longitudinal studies are needed to examine the durability of safety training's behavioral impacts, focusing on how training influences compliance over extended periods. Such research could identify the optimal frequency for refresher programs to sustain long-term safety improvements.

Finally, cross-cultural studies are recommended to assess the implementation and effectiveness of safety training in diverse global contexts. Construction practices and workplace cultures vary significantly across regions, and understanding these differences could inform the design of more adaptable and culturally sensitive training programs. Insights gained from such studies would contribute to the global body of knowledge on safety management, enabling organizations worldwide to adopt evidence-based practices tailored to their unique needs.

In conclusion, this study offers actionable insights into improving construction safety outcomes through the implementation of specialized training programs. The demonstrated reduction in accident frequency and the extension of accident-free periods highlight the transformative potential of these interventions. By integrating advanced statistical tools, leveraging technological innovations, and fostering collaborations between industry and government stakeholders, the construction sector can achieve sustainable improvements in safety culture. These findings contribute to the broader field of occupational safety management, providing a roadmap for future efforts to enhance worker well-being and mitigate risks in high-hazard environments.

VI. RECOMMENDATIONS FOR FUTURE RESEARCH

This study has provided valuable insights into the critical role of specialized safety training in improving construction safety outcomes. However, several areas warrant further investigation to enhance the effectiveness, adaptability, and sustainability of safety interventions. Future research should adopt a multidimensional approach, integrating advanced technologies, interdisciplinary perspectives, and long-term evaluations to build on the findings presented here.

1. Technological Integration in Safety Interventions: Emerging technologies, such as virtual reality (VR) training, wearable safety devices, and machine learning algorithms, hold significant potential to revolutionize construction safety programs. VR simulations can provide immersive and risk-free environments where workers can practice responding to hazardous scenarios, enhancing their readiness to handle real-world risks. Wearable devices, such as smart helmets and location trackers, can monitor workers' movements and provide real-time feed-

back to prevent unsafe behaviors. Machine learning and predictive analytics could be integrated with Poisson and Weibull models to identify patterns in accident frequency and predict high-risk periods or areas, enabling preemptive interventions. Future studies should evaluate the feasibility and effectiveness of these technologies in different construction settings, particularly in high-risk environments like high-rise construction [42], [20].

2. Long-Term Impact of Safety Training: While this study demonstrates the immediate benefits of specialized safety training, the long-term retention of safety knowledge and behaviors remains an open question. Longitudinal studies that track workers over extended periods could provide valuable insights into how training influences sustained compliance with safety protocols. Such research could also examine the optimal frequency and content of refresher programs to reinforce safety behaviors. Understanding these dynamics is essential for designing interventions that foster enduring cultural and behavioral changes in the workforce [43].

3. Cross-Cultural and Project-Specific Adaptations: Construction practices and safety cultures vary significantly across regions and project types. Future studies should investigate how safety training programs can be adapted to different cultural and organizational contexts. For instance, research could examine how varying levels of management commitment, worker engagement, and regulatory frameworks influence the implementation and effectiveness of training interventions. Additionally, cross-project studies comparing safety outcomes in infrastructure, industrial, and high-rise construction projects would provide a deeper understanding of the contextual factors that shape training effectiveness. Such studies could identify best practices for tailoring interventions to diverse environments, thereby maximizing their impact [21].

4. Human Factors and Organizational Culture in Safety Interventions: The role of human error and organizational culture in shaping safety outcomes remains a critical area for further exploration. Research should delve into how factors such as management commitment, leadership styles, and worker engagement influence the success of training programs. Psychological theories, such as those related to motivation and cognitive processing, could provide insights into how workers internalize safety practices and overcome behavioral barriers to compliance. Additionally, organizational studies could explore how safety culture—shaped by policies, incentives, and communication—affects training implementation and outcomes. An interdisciplinary approach combining psychology, engineering, and occupational health would be particularly valuable in advancing this line of inquiry [43],[44].

5. Interdisciplinary and Collaborative Approaches: Advancing construction safety research requires collaborative efforts that bridge multiple disciplines. Combining engineering expertise with insights from occupational health, behavioral psychology, and data science could yield more holistic solutions. For instance, predictive models informed by psychological and organizational data could enhance the precision of hazard identification and intervention design. Collaboration with industry stakeholders, government agencies, and academic institutions would also facilitate large-scale pilot studies to test and refine safety training programs. Such partners-

hips could help translate research findings into practical guidelines and policies that benefit the broader construction industry [43],[44].

In conclusion, future research should focus on integrating advanced technologies, exploring long-term behavioral impacts, and examining the cultural and organizational dimensions of safety interventions. By adopting interdisciplinary approaches and leveraging emerging tools, the construction industry can continue to improve safety outcomes, reduce accidents, and foster a culture of proactive risk management. These efforts will not only benefit workers and employers but also contribute to the broader field of occupational safety by providing innovative, evidence-based solutions for managing risks in high-hazard environments.

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