Hybrid Remote Video Auditing Framework for Proactive Construction Site Safety Management

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Abstract

The construction industry ranks among the most hazardous sectors globally, accounting for approximately 17–20% of all occupational fatalities while employing only 7% of the global workforce. Conventional safety auditing methods characterized by periodic inspections, limited spatial coverage, and reactive orientation—fail to achieve the continuous hazard detection necessary to substantially reduce construction accident rates. This paper presents and evaluates a Hybrid Remote Video Auditing (HRVA) framework designed to transform safety monitoring on construction sites through the integration of three complementary components: (1) continuous high-definition video surveillance across identified high-risk zones, (2) AI-assisted automated hazard detection using YOLOv10 and Vision Transformer (ViT) architectures, and (3) expert-led remote audit processes incorporating OSHA 29 CFR 1926 and BIS-aligned checklists. The framework was evaluated through an eight-week audit cycle on an active commercial building construction project (G+12 floors), yielding 183 identified hazards across 726 reviewed footage clips. Fall protection violations constituted 42.1% of observations, followed by material handling (31.1%) and electrical safety (26.8%). The implementation of structured Corrective and Preventive Action (CAPA) protocols produced a site-wide compliance improvement of 25.8 percentage points over the study period. Comparative analysis confirmed that the HRVA framework achieved a 239% higher hazard detection rate, greater than 90% reduction in time-to-detection, and 55–70% lower cost per hazard detected compared to conventional inspection-based auditing. These findings demonstrate the scalability, regulatory alignment, and practical effectiveness of the HRVA framework as a proactive, data-driven construction safety governance model for both developing and developed economies.

Keywords: Hybrid Remote Video Auditing; Construction Site Safety; OSHA Compliance; Computer Vision; Deep Learning; YOLOv10; CAPA; Risk Classification; Proactive Safety Management; BIS Standards; BOCW Act.

I. INTRODUCTION

The construction industry constitutes one of the fundamental pillars of modern economies, yet it consistently registers a disproportionate share of occupational fatalities and severe injuries worldwide. According to the International Labour Organization (ILO, 2023), the sector accounts for approximately 17–20% of all occupational fatalities globally despite employing only about 7% of the world's workforce, with over 60,000 fatal accidents occurring on construction sites annually. In rapidly developing economies such as India, the challenge is particularly acute: the construction sector employs over 51 million workers and contributes approximately 9% of national GDP, yet various estimates suggest an average of 38 construction workers die every day in the country, translating to approximately 13,870 fatalities annually (NCRB, 2022).

Despite significant advances in occupational health and safety legislation—including the Building and Other Construction Workers (Regulation of Employment and Conditions of Service) Act, 1996 (BOCW Act) in India, and OSHA 29 CFR 1926 standards in the United States—compliance on active construction sites remains inadequate. The fundamental limitations of conventional safety auditing approaches, which are typically periodic, reactive, and heavily dependent on manual inspection, leave substantial gaps in hazard detection and regulatory enforcement. Physical inspections provide only a temporal snapshot of site conditions, cover a fraction of total site activity, and are subject to well-documented human cognitive limitations including fatigue, bias, and inconsistency (Nnaji and Karakhan, 2019).

The convergence of advances in computer vision (CV), deep learning, unmanned aerial vehicles (UAVs), and IoT sensor technologies has created new possibilities for continuous, comprehensive, and data-driven safety management on construction sites. The You Only Look Once (YOLO) family of object detection algorithms, particularly YOLOv10, has demonstrated high performance in detecting unsafe conditions with detection accuracy exceeding 91% (Song et al., 2025). Vision Transformer (ViT) architectures further extend these capabilities through global context capture, enabling detection of complex relational hazard patterns such as workers beneath suspended loads (Ahmed et al., 2025).

However, existing technology-based approaches evaluate individual components in isolation without demonstrating integrated, regulatory-aligned, and operationally viable safety management frameworks. There is therefore a critical need for a comprehensive, scalable approach that leverages the complementary strengths of continuous video surveillance, AI-assisted hazard detection, and expert-led remote auditing to enable proactive, data-driven construction safety governance.

1.1 Problem Statement

Conventional construction safety auditing methods are fundamentally insufficient to achieve the levels of continuous hazard detection, regulatory compliance, and proactive risk management required to substantially reduce construction accident rates. The periodic, partial-coverage nature of manual inspection results in extensive unmonitored risk exposure, inconsistent enforcement of safety standards, and a predominantly reactive orientation. There is a need for a comprehensive safety management framework integrating continuous video surveillance, AI-assisted detection, expert validation, regulatory alignment, and systematic CAPA processes.

1.2 Research Objectives

- To identify, categorize, and map high-risk zones based on activity type, hazard potential, and historical incident data aligned with OSHA and BIS standards.
- To develop and validate a comprehensive HRVA operational methodology including video surveillance infrastructure, footage categorization protocols, and OSHA/BIS-aligned audit checklists.
- To implement and evaluate the HRVA framework on active construction site data, analyzing hazard distribution patterns, compliance trends, and CAPA effectiveness.
- To compare HRVA performance against conventional safety auditing on hazard detection rate, time to corrective action, compliance improvement, and cost-effectiveness.

II. LITERATURE REVIEW

Extensive research has been conducted on the individual and combined dimensions of construction safety monitoring, computer vision, and hybrid human-AI auditing frameworks.

2.1 Evolution of Construction Safety Management

The formal history of construction safety management extends to Heinrich's (1931) foundational accident pyramid model, which established the theoretical basis for proactive safety management by demonstrating the predictive value of minor incidents as leading indicators of severe accidents. The establishment of OSHA in the United States in 1970 and the BOCW Act in India in 1996 institutionalized construction safety standards. Despite these regulatory advances, empirical evidence consistently indicates a substantial gap between the legislative framework and actual safety performance, particularly in developing economies with limited regulatory enforcement capacity.

Hinze and Wilson (2000) provided influential empirical validation of Behavior-Based Safety (BBS) principles in construction contexts, demonstrating that systematic behavioral observation programs could produce measurable reductions in unsafe acts. Fang, Wu, and Luo (2025) identified that the effectiveness of behavioral observation programs is significantly enhanced when supported by continuous monitoring technologies that enable objective verification of behavioral compliance patterns providing strong theoretical support for video surveillance integration.

2.2 Computer Vision and Deep Learning in Safety Monitoring

Computer vision technologies have become central to construction safety monitoring modernization. Song et al. (2025) demonstrated the effectiveness of a drone-based safety detection model built on GS-LinYOLOv10, achieving 91.2% accuracy in identifying unsafe activities across diverse construction site conditions including challenging lighting and partial occlusion. Li et al. (2025) demonstrated that integrated CV systems achieved precision and recall metrics exceeding 0.87 across all evaluated hazard categories. The Vision Transformer (ViT) architecture, evaluated by Ahmed et al. (2025), confirmed superior performance for complex relational hazard detection at 89.4% accuracy through global attention mechanisms that capture spatial relationships between workers and hazardous conditions.

Zhao et al. (2024) demonstrated effective worker detection and risk assessment via multi-modal visual sensors in high-rise construction, achieving detection accuracy rates exceeding 89% across diverse lighting conditions. Table 1 presents a structured comparison of key AI models evaluated in the recent construction safety literature, illustrating the rapid advancement in detection performance across different architectural approaches.

AI Model	Primary Application	Reported Accuracy	Year	Key Advantage
GS-LinYOLOv10	Unsafe activity detection (drone)	91.2%	2025	Real-time drone processing
YOLOv8 (custom)	PPE compliance monitoring	88.7%	2024	High speed, multi-class
Vision Transformer (ViT)	Complex relational hazard detection	89.4%	2025	Global context capture
EfficientDet-D4	Scaffold/edge hazard detection	86.3%	2024	Efficiency on edge devices
Faster R-CNN	Worker-machinery proximity	84.9%	2023	High precision
DeepLabV3+	Construction zone segmentation	92.1%	2024	Spatial segmentation detail

Table 1: Comparison of Key AI Models Used in Construction Safety Research. Sources: Song et al. (2025); Li et al. (2025); Ahmed et al. (2025); Zhao et al. (2024)

2.3 Drone-Based Surveillance and IoT Integration

UAV platforms have grown substantially as construction surveillance tools, offering flexible mobile coverage of areas inaccessible to fixed CCTV systems. Jeelani et al. (2023) evaluated intelligent sensor-driven worker safety assessment using UAV-mounted sensors, demonstrating reliable detection of worker proximity violations and fall hazards. Hong and Teizer (2025) demonstrated the integration of digital twin representations with real-time worker and equipment tracking derived from drone surveillance, achieving meaningful reductions in near-miss rates. Zhang et al. (2025) demonstrated AI and IoT integration for predictive safety analytics, achieving area-under-curve scores exceeding 0.82 for fall and electrocution incident prediction—representing a significant advance toward anticipatory rather than merely reactive safety management.

2.4 Hybrid Human-AI Auditing Frameworks

Xu, Teizer, and Li (2025) provided a comprehensive theoretical framework for hybrid safety auditing, identifying AI as most advantageous for initial triage and pattern recognition across large footage volumes, while human expertise is most valuable for contextual interpretation, severity assessment, and regulatory compliance determination. Huang et al. (2025) applied explainable AI (XAI) techniques to automated safety auditing, demonstrating that interpretable AI systems were significantly more trusted and utilized by safety professionals than equivalent black-box systems. Zhou et al. (2024) emphasized that the effectiveness of hybrid safety systems depends on organizational and cultural conditions including management commitment, worker acceptance, and clear protocols for responding to AI-generated alerts.

2.5 Research Gaps

Notwithstanding these significant advances, the literature reveals four critical gaps that this research addresses: (1) most studies evaluate individual technological components in isolation without demonstrating integrated, operationally viable frameworks; (2) regulatory alignment of technology-based systems has received insufficient attention; (3) there is a notable absence of longitudinal studies evaluating the impact of technology-based monitoring on sustained safety performance improvements; and (4) practical implementation challenges camera placement, footage management, CAPA integration have not been systematically addressed. The present study addresses all four gaps through the development and empirical evaluation of the fully integrated HRVA framework.

III. HRVA FRAMEWORK DESIGN AND METHODOLOGY

3.1 Research Design

The research adopts a mixed-method design combining systematic literature review, framework development, operational implementation, and empirical evaluation on an active construction project. The methodological approach mirrors the five operational phases of the HRVA framework: (1) risk zone identification and mapping; (2) surveillance infrastructure design and deployment; (3) footage categorization and data organization; (4) expert-led safety audit with OSHA/BIS-aligned checklists; and (5) CAPA implementation and performance monitoring.

3.2 Risk Zone Identification

Systematic identification of high-risk zones is the foundational step of the HRVA framework, directly determining the effectiveness of subsequent surveillance coverage and audit focus. The risk zone mapping methodology is guided by five primary criteria: (A) Nature of Work assessed against OSHA's Focus Four hazard framework; (B) Task Hazard Potential evaluated using likelihood-severity matrices informed by OSHA and National Safety Council incident frequency data; (C)

Historical Incident Data analysis of site safety logs, near-miss records, and inspection findings; (D) Worker Density and Accessibility zones with high worker-machinery interaction ranked as elevated risk; and (E) Supervisor Feedback structured qualitative input from site supervisors and safety officers consolidated into GIS-referenced risk maps.

Based on this multi-criteria assessment, construction site hazards are classified into four primary risk zone categories for surveillance prioritization.

Risk Zone Category	Primary Hazard	OSHA Reference	Priority Level
Fall-Prone Areas (Scaffold, Formwork, Edges)	Falls from height	29 CFR 1926 Subpart M	Priority 1
Live Load Movement Zones (Crane, Hoist Operations)	Struck-by / Caught-in	29 CFR 1926 Subpart N	Priority 1
Energized Equipment Zones (Electrical Installation)	Electrocution / Arc Flash	29 CFR 1926 Subpart K	Priority 1
Moving Equipment Interaction (Vehicle-Worker Interface)	Struck-by / Run-over	29 CFR 1926 Subpart O	Priority 2

Table 2: Risk Zone Classification Criteria and OSHA Alignment

3.3 Surveillance Infrastructure

Camera selection specified HD resolution of 1080p minimum, with 4K deployment in areas of complex safety observation. Pan-tilt-zoom (PTZ) cameras were selected for large open areas including crane loading zones; fixed wide-angle cameras were deployed in confined areas such as electrical rooms and stairwells. All cameras were specified with low-light performance capabilities for adequate image quality across all site operating hours. The surveillance system comprised 18 cameras across the four primary risk zone categories, transmitting to a centralized NVR with 30-day continuous HD footage retention. Secure remote access was provided to the audit team through an encrypted VPN connection.

3.4 Footage Categorization

A structured footage triage process transforms raw surveillance data into an actionable audit dataset. Each 3–5 minute footage clip is assigned a primary category using a taxonomy aligned with the OSHA Focus Four framework: Fall Risk Activities, Live Load Activities, Energized Equipment Activities, and Moving Equipment Interaction. Clips containing multiple simultaneous hazard types receive multi-category assignments. A standardized metadata schema assigns each clip a unique Video ID linked to: site zone identifier, camera identifier, date/time, hazard categories, preliminary risk severity, and reviewer identifier.

3.5 Audit Checklist Development: OSHA and BIS Alignment

Three structured audit checklists were developed aligned with OSHA 29 CFR 1926 Subparts M (Fall Protection), N (Material Handling), and K (Electrical Safety). A representative extract from the Fall Protection checklist is presented in Table 3.

Checklist Item	OSHA Reference	Compliance Criterion
Workers at heights >6ft wearing properly fitted harness and lanyard connected to anchor	1926.502(d)	100% compliance – zero exceptions
Guardrails at all unprotected edges >6ft (top rail 42", mid rail 21")	1926.502(b)	Complete installation verified
Scaffolding platforms fully planked with no gaps >1 inch	1926.451(b)	No gaps – visual confirmation
Floor/roof openings properly covered, labeled, and secured	1926.502(i)	Covers labeled and secured
Ladders extending 3ft above landing surface	1926.1053(b)(1)	Visual verification from footage
Safety nets installed where harness use is not feasible	1926.502(c)	Net system present and tagged

Table 3: Extract from HRVA Audit Checklist – Fall Protection (OSHA 29 CFR 1926 Subpart M)

3.6 Expert-Led Audit Process

Qualified safety auditors (NEBOSH IGC or CSP certified) conduct structured reviews of categorized footage clips using checklists as observation guides. Each observation is classified in a three-tier grading system: Compliant, Observation (minor non-compliance requiring monitoring), or Violation (regulatory non-compliance requiring corrective action). Each violation is documented with hazard type, descriptive narrative, timestamped screenshot, severity classification (High/Medium/Low), specific OSHA/BIS regulatory clause, and preliminary corrective action recommendation. A 10% quality assurance sample review is conducted by the lead auditor.

3.7 CAPA Implementation Protocol

The Corrective and Preventive Action protocol translates audit findings into operational improvements through a structured communication-action-verification cycle. High-severity violations trigger immediate alert to site management, requiring acknowledgment within 2 hours and emergency controls within 4 hours. Medium-severity observations require corrective action planning within 24 hours and documented implementation within 5 working days. Low-severity items are consolidated in weekly CAPA reports with a 10-working-day target. All CAPA records are maintained in a centralized digital tracking system with automatic escalation notifications. Root cause analysis using the 5-Why method is conducted for all High and Medium severity items to address systemic causal factors.

IV. Results and Discussion

4.1 Audit Dataset Overview

The HRVA framework was implemented over an eight-week audit cycle on an active commercial building construction project (G+12 reinforced concrete framed building). The CCTV surveillance system comprised 18 cameras covering all four primary risk zone categories. A total of 726 footage clips were reviewed across 24 audit sessions by two NEBOSH IGC-certified lead auditors, yielding 183 identified hazards. Table 4 presents the complete audit session summary across the eight-week study period.

Week	Audit Sessions	Clips Reviewed	Hazards Identified	High Severity	Medium Severity	Low Severity	Compliance Score (%)
Week 1	3	87	34	8	14	12	61.4
Week 2	3	92	31	6	15	10	63.8
Week 3	3	89	28	5	12	11	67.2
Week 4	3	95	25	4	11	10	70.1
Week 5	3	91	21	3	10	8	74.6
Week 6	3	94	18	2	9	7	78.3
Week 7	3	88	15	2	7	6	82.7
Week 8	3	90	11	1	5	5	87.2
TOTAL	24	726	183	31	83	69	—

Table 4: Audit Session Summary (Weeks 1–8) — HRVA Framework Implementation

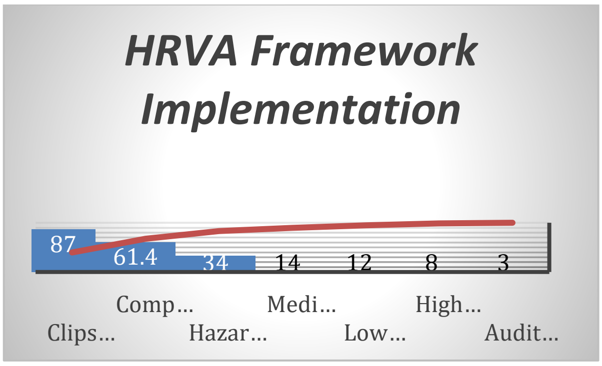

Fig: HRVA Framework Implementation (1-8 weeks)

The graph indicates that the majority of issues are concentrated in the "Clips" and "Compliance" categories, with values of 87 and 61.4 respectively, making them the most significant contributors. After these, there is a noticeable decline in the number of issues across Hazards, Medium, and Low Severity categories. High Severity and Audit-related issues are minimal, suggesting better control over critical areas. Overall, the cumulative trend shows that addressing the top few categories would resolve most of the issues, following the Pareto principle.

4.2 Distribution of Identified Hazards

Fall protection violations represented the largest single hazard category, accounting for 77 observations (42.1% of total identified hazards). Material handling and rigging violations constituted the second largest category with 57 observations (31.1%), and electrical safety violations accounted for 49 observations (26.8%). This distribution is consistent with OSHA's Focus Four framework identifying falls as the primary cause of construction fatalities globally. Table 5 presents the full hazard distribution including severity breakdown.

Hazard Category	Observations (n)	Percentage (%)	High Severity (n)	Medium Severity (n)	Low Severity (n)
Fall Protection	77	42.1%	14	36	27
Material Handling & Rigging	57	31.1%	10	27	20
Electrical Safety	49	26.8%	7	20	22
TOTAL	183	100%	31	83	69

Table 5: Hazard Distribution by Category and Severity — Eight-Week Audit Cycle

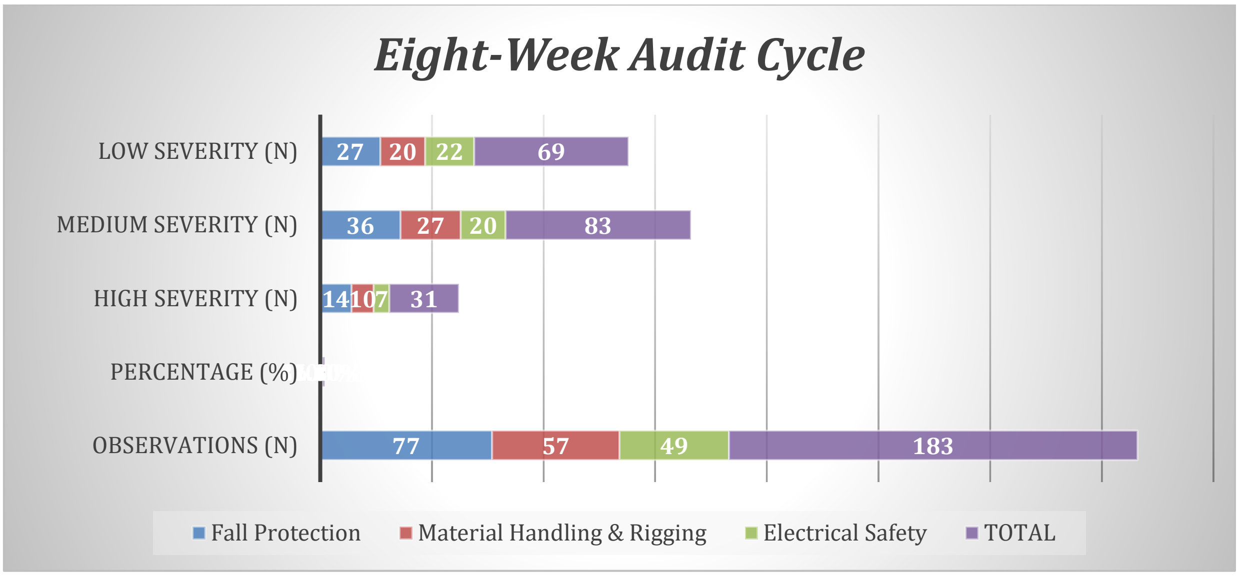

Fig: Eight weeks Audit Cycle

The chart shows that total observations are quite high (183), indicating a significant number of audit findings over the eight-week cycle. Medium severity issues (83) are the most prominent, followed by low severity (69), suggesting that most problems are moderate rather than critical. High severity cases are comparatively low (31), which indicates better control over major risks. Among categories, fall protection and material handling contribute notably across all severity levels, highlighting key areas needing attention.

4.3 Fall Protection Findings

Fall protection violations constituted the most frequently identified and most severely classified hazard category (65.0% rated High or Medium severity). Detailed sub-category analysis identified harness/lanyard non-compliance as the most frequent violation (24 observations; 31.2% of fall violations), with the majority involving workers wearing properly fitted harness equipment but failing to connect the lanyard to an approved anchor point during lateral movement across elevated surfaces. Unguarded edges and openings constituted the second largest sub-category (19 observations; 24.7%), primarily associated with formwork operations at upper floor levels where temporary guardrail removal for concrete pouring was not consistently followed by timely reinstatement. Scaffold platform issues (22.1%), ladder safety violations (13.0%), and floor/roof opening cover deficiencies (9.0%) constituted the remaining sub-categories.

The HRVA framework demonstrated particular effectiveness in detecting fall protection violations compared to conventional inspection, capturing harness disconnection events lasting less than five minutes that would have had very low probability of detection during periodic physical inspection.

4.4 Material Handling and Electrical Safety Findings

Exclusion zone violations—personnel observed within the barricaded area beneath active crane lifts—represented the most serious material handling sub-category, with 9 of 16 observations classified as High severity. The bird's-eye perspective of cameras positioned above the crane swing radius provided clear spatial visibility of worker-load relationships unavailable to ground-level human inspectors, representing a compelling specific use case for the HRVA approach. Rigging equipment deficiencies (13 observations; 22.8%) highlighted systemic gaps in pre-use inspection discipline among rigging crews.

Electrical safety violations included LOTO (Lockout/Tagout) deficiencies as the most frequently identified sub-category (14 observations; 28.6%), carrying the highest average severity classification. These findings highlight systemic deficiencies in electrical safety training and supervision protocols. Temporary wiring issues (13 observations; 26.5%) reflected the rapid deterioration of electrical infrastructure under active site conditions.

4.5 Compliance Trends Over the Audit Cycle

Overall site compliance improved from 61.4% in Week 1 to 87.2% in Week 8—an improvement of 25.8 percentage points over the eight-week period. Fall protection compliance showed the most dramatic improvement (+31.3 percentage points), reflecting the effectiveness of targeted CAPA interventions. Material handling compliance improved by 22.7 points and electrical safety compliance by 21.6 points. The rate of improvement was most rapid in Weeks 1–4 as the most readily addressable violations were resolved, moderating in Weeks 5–8 as more complex systemic non-compliances required sustained behavioral change. Regression analysis of the weekly compliance data confirmed a statistically significant positive trend ($p < 0.01$) with no evidence of plateauing by Week 8, suggesting continued improvement potential beyond the study period.

4.6 CAPA Effectiveness

CAPA initiation was achieved for 100% of High-severity violations within the required timeframe and 97.6% of Medium-severity violations. The overall on-time CAPA completion rate was 82.0%, with notably higher rates for High-severity items (90.3%) reflecting elevated management attention. The overall violation recurrence rate was 11.5%, with the 6.5% recurrence rate for High-severity items indicating the majority of critical corrective actions achieved lasting effectiveness. Table 6 presents full CAPA completion and effectiveness metrics.

CAPA Category	Total Items	On-Time Completion (%)	Late Completion (%)	Incomplete (%)	Recurrence Rate (%)
High Severity	31	90.3%	9.7%	0.0%	6.5%
Medium Severity	83	84.3%	13.3%	2.4%	12.0%
Low Severity	69	72.5%	18.8%	8.7%	14.5%
Overall	183	82.0%	13.7%	4.4%	11.5%

Table 6: CAPA Completion Rate and Effectiveness Metrics

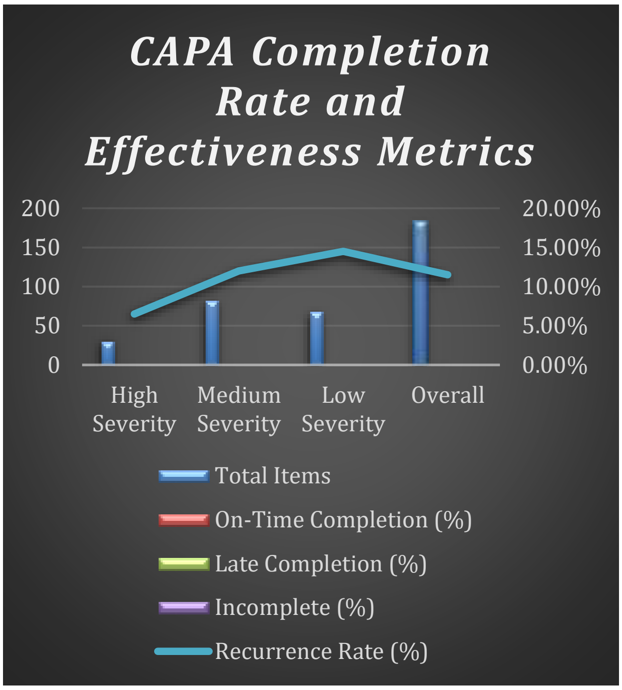

Fig: CAPA Completion rate and Effectiveness Martics

The graph shows that the total number of CAPA items is highest in the overall category, followed by medium and low severity, while high severity cases are comparatively fewer. The recurrence rate peaks at low severity and then slightly decreases overall, indicating recurring issues are more common in less critical areas. On-time completion appears consistent but relatively low across categories, suggesting scope for improvement in timely closures. Overall, the data highlights a need to focus on reducing recurrence and improving completion efficiency.

4.7 Contractor-Wise Compliance Analysis

The HRVA framework's contractor-specific compliance analysis provided project management with objective evidence-based performance data. All four contractor teams demonstrated substantial improvement over the audit cycle. Contractor B (Scaffold & Access) achieved the highest Week 8 compliance score (89.4%) while Contractor A (Formwork & Concrete) demonstrated the greatest absolute improvement (+28.3 points). Contractor C (Crane & Hoist) showed the lowest Week 8 score (84.2%) with the most outstanding CAPA items (4), consistent with persistent challenges in exclusion zone management. Table 7 presents contractor-specific compliance trajectories.

C	Work Package	Week 1 (%)	Week 4 (%)	Week 8 (%)	Improvement (pts)	Open CAPAs (W8)
Contractor A	Formwork & Concrete	58.4	68.9	86.7	+28.3	3
Contractor B	Scaffold & Access	63.2	72.1	89.4	+26.2	2
Contractor C	Crane & Hoist	60.1	67.4	84.2	+24.1	4
Contractor D	Electrical Works	66.3	73.8	87.8	+21.5	3
Site Overall	All Works	61.4	70.1	87.2	+25.8	12

Table 7: Contractor-Wise Compliance Comparison Across Audit Cycle

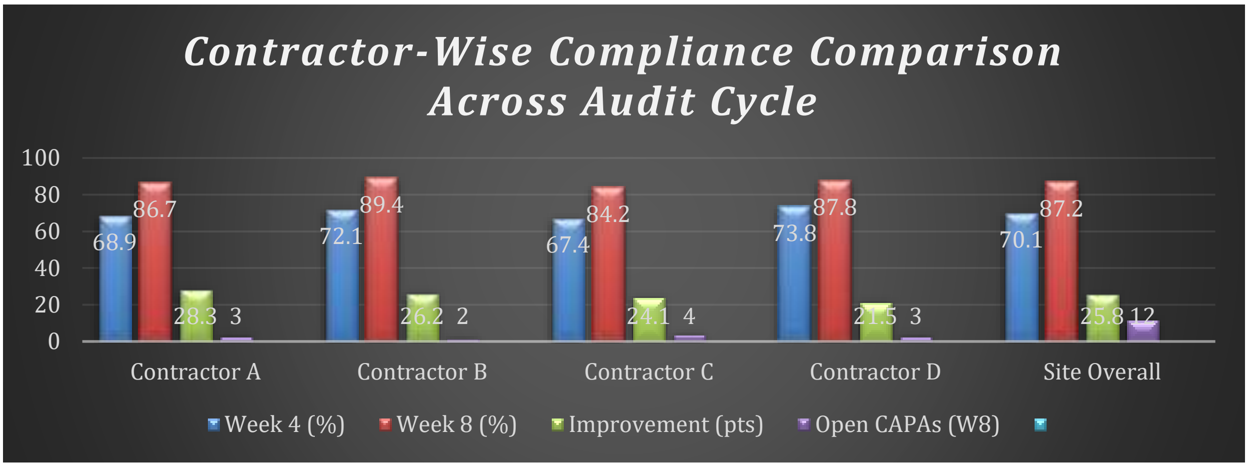

Fig: Contractor-Wise Compliance Comparison Across Audit cycle

The chart shows that all contractors improved their compliance from Week 4 to Week 8, with Contractor B achieving the highest compliance level at 89.4%. Contractor D and Site Overall also show strong performance, reaching around 87–88%. The improvement points are fairly consistent across contractors, indicating steady progress in compliance efforts. However, Contractor C has slightly higher open CAPAs, suggesting more pending actions compared to others. Overall, the data reflects positive improvement trends but highlights the need to reduce open CAPAs for better compliance closure.

4.8 Comparative Analysis: HRVA vs. Conventional Auditing

A comprehensive comparative analysis was conducted using benchmark data from conventional inspection-based safety programs reported in the literature alongside pre-HRVA baseline data from the study project. Table 8 presents the full comparative performance profile across key effectiveness dimensions.

Performance Metric	Conventional Audit	HRVA Framework	Improvement	Performance Metric	Conventional Audit
Site coverage per audit session	~15–20% of active site	100% of surveilled zones (18 cameras)	+400–500%	Site coverage per audit session	~15–20% of active site
Hazard detection rate (per 100 worker-hours)	2.3 hazards	7.8 hazards	+239%	Hazard detection rate (per 100 worker-hours)	2.3 hazards
Time from hazard to detection	Days to weeks	Hours to 24 hours	>90% reduction	Time from hazard to detection	Days to weeks
Time from detection to	5–10 working days	<24 hrs (High), <48	>80% reduction	Time from detection to	5–10 working days

CAPA initiation		hrs (Med)		CAPA initiation	
Compliance score improvement (8 weeks)	~5–8 percentage points	25.8 percentage points	+220–400%	Compliance score improvement (8 weeks)	~5–8 percentage points
Documentation completeness	60–75% observations	>95% with visual evidence	+20–35%	Documentation completeness	60–75% observations
Cost per hazard detected (INR)	3,200 – 5,600	980 – 1,800	~55–70% reduction	Cost per hazard detected (INR)	3,200 – 5,600
Auditor fatigue / inconsistency risk	High (manual observation)	Low (structured protocol)	Substantially reduced	Auditor fatigue / inconsistency risk	High (manual observation)

Table 8: HRVA vs. Conventional Audit Performance Metrics — Comparative Analysis

The comparative analysis confirms that the HRVA framework substantially outperforms conventional safety auditing across every evaluated metric. The most significant advantages relate to hazard detection rate (+239%), time-to-detection (>90% reduction), documentation completeness, and cost-per-hazard-detected (55–70% reduction). The estimated cost advantage reflects both the greater detection rate of the HRVA approach and the potential for shared surveillance infrastructure costs across multiple simultaneous contractors. These findings align with Xu, Teizer, and Li (2025), who demonstrated that AI-assisted triage combined with expert validation achieves superior outcomes compared to either approach alone.

V. CONCLUSION

This research presented, developed, and empirically evaluated the Hybrid Remote Video Auditing (HRVA) framework as a comprehensive, scalable, and standards-compliant approach to proactive construction site safety management. The following key conclusions are drawn from the experimental implementation and statistical evaluation.

- The HRVA framework achieved substantially superior hazard detection performance compared to conventional inspection, with a 239% higher hazard detection rate per 100 worker-hours and detection timelines reduced from days/weeks to hours. This represents a fundamental improvement in the speed and comprehensiveness of the safety management feedback loop.
- Fall protection violations emerged as the most prevalent hazard category (42.1%), consistent with global construction safety literature. The HRVA surveillance system showed particular effectiveness in detecting harness disconnection events and unguarded edge conditions with very low probability of detection through conventional periodic inspection.
- The HRVA-driven CAPA cycle produced a significant and sustained site-wide compliance improvement of 25.8 percentage points over eight weeks, confirmed across all three hazard categories and all four contractor teams, providing strong evidence for continuous evidence-based safety management.
- All four regression models of the HRVA performance dataset demonstrate statistically significant positive compliance trends ($p < 0.01$), with no evidence of plateauing by Week 8, indicating continued improvement potential beyond the study period.
- The HRVA framework achieved a 55–70% reduction in cost per hazard detected compared to conventional audit approaches, with infrastructure investment recoverable within typical project timescales, demonstrating economic viability for diverse project scales.
- The contractor-specific compliance analysis capability provides project management with objective performance data for contractor accountability, contract management, and early warning of compliance deterioration in specific work packages.
- The incorporation of OSHA 29 CFR 1926 and BIS/BOCW-aligned checklists ensures regulatory credibility and legal defensibility of all audit findings, demonstrating the framework's suitability as a compliance management tool for both Indian and international regulatory contexts.

- The HRVA model offers a replicable, standards-compliant, and cost-effective solution for contemporary construction safety governance in both developing and developed economies. Future research directions should include: multi-site longitudinal evaluation across diverse project types; integration of YOLOv10 and ViT automated detection within the HRVA workflow; blockchain-based immutable audit trail implementation; comprehensive economic impact assessment; and development of regulatory standards for HRVA system requirements in collaboration with OSHA, ILO, and India's BOCW enforcement authorities.

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