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Enhancing Safety Performance in the U.S. Multi-Employer Construction Projects Through Integrated Digital Safety Governance Frameworks for Injury and Fatality Prevention

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Abstract: *The construction industry in the United States continues to experience high rates of fatalities and serious injuries, particularly on multi-employer projects where fragmented accountability and coordination challenges complicate safety management. Although regulatory frameworks established by the Occupational Safety and Health Administration (OSHA) exist, traditional paper-based compliance systems remain inadequate for managing dynamic site hazards. This study evaluates the effectiveness of integrated digital safety governance frameworks in improving construction safety performance. The frameworks encompass Safety Leadership and Accountability, Contractor Prequalification and Selection, Risk Management and Hazard Control, Training, Monitoring and Auditing, Incident Reporting and Investigation, Communication and Coordination, Regulatory Compliance, KPI Tracking, Corrective and Preventive Action Management, and Documentation and Recordkeeping.The analysis was conducted on 47 large-scale construction projects across six U.S. states, representing approximately $8.7 billion in project value and more than 34,000 workers. Projects implementing integrated digital systems combining Building Information Modeling (BIM), Internet of Things (IoT) sensors, mobile reporting platforms, blockchain-based compliance tracking, and analytics dashboards demonstrated significantly improved safety outcomes. Compared with projects using conventional safety management approaches, digitally governed projects achieved a 43% reduction in Total Recordable Injury Rate (TRIR) and a 67% reduction in near-miss incidents. Hazard communication latency decreased by 82%, while corrective action implementation time improved by an average of 27.4 hours.The findings identify leadership commitment, platform interoperability, and workforce digital literacy as critical success factors for implementation. Overall, the study demonstrates that integrated digital governance frameworks enhance real-time risk visibility, strengthen regulatory compliance, improve inter-organizational coordination, and significantly reduce safety risks in multi-employer construction environments.*

Keywords*: construction safety, digital governance, Building Information Modeling, blockchain compliance, IoT, occupational safety*

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1.0 Introduction

The construction industry remains one of the most hazardous sectors in the United States, consistently recording disproportionately high rates of occupational injuries and fatalities despite significant advances in safety regulations, engineering controls, and workforce training programs. According to the Bureau of Labor Statistics (2023), construction workers accounted for approximately 20% of all occupational fatalities while representing only about 7% of the national workforce. This persistent safety burden highlights the need for innovative approaches to hazard management, particularly in complex project environments involving multiple employers. In 2022 alone, 1,069 construction workers died of work-related injuries, which translates to a fatality rate of 9.6 per 100,000 full-time equivalent workers all-industry average is about three times that of construction workers (CPWR, 2023). These statistics are particularly disturbing when they are looked at within the context of multi-employer construction projects where the complexity of coordinating safety responsibility between the various general contractors, subcontractors, and specialty trade contractors creates fault lines in the organizational structure that can be too often the cause of preventable incidents. It is not just a matter of regulatory compliance; it is a matter of fundamental inadequacies in how the flow of safety information across organizational boundaries, how responsibility is shared among mutually dependent parties and how rapidly emerging hazards are communicated to the affected workers in the unstable and ever-changing work environments.

The traditional methods of construction safety management have been overly dependent on hierarchical command structures, periodic safety meetings and paper-based documentation systems which were designed during an era that appeared to be before the current complexity of construction projects. An average large-scale infrastructure project in the United States now is characterized by more than fifty different employers working simultaneously on overlapping tasks, with workers of different organizations often operating in close proximity without a clear definition of their hazard control responsibilities (Lingard et al., 2021). The multi-employer citation policy adopted by the Occupational Safety and Health Administration is one effort to deal with this complexity by distinguishing between controlling employers, creating employers, exposing employers, and correcting employers, but this framework presupposes a level of coordination and information sharing that is hardly ever achieved in practice (OSHA, 2019). When a structural steel subcontractor presents a fall hazard that may involve electrical workers who work on entirely different organizations, the systems of identifying, communicating, and controlling that hazard frequently rely on informal networks and serendipitous contacts over formal procedures.

Disruptive opportunities to manage these many years-old coordination problems are presented by the advent of digital technologies. Construction Planning and Design Construction projects Building Information Modeling has transformed the planning and design phases of construction projects to enable clash detection and build construction sequencing visualization, previously impossible (Sulankivi et al., 2020). Internet of Things sensors are now capable of monitoring environmental conditions, equipment states, and worker locations in real-time and producing data streams that give an unprecedented view of the conditions in the job site (Nnaji and Karakhan, 2020). The blockchain technology offers the possibility of establishing unalterable records of safety training, equipment inspection, and hazard communications that could help to solve the endemic issue of documentation disputes following serious incidents (Li et al., 2019). However, the very fact that these technologies can be found on the construction sites does not necessarily follow through to better safety results. Whether digital tools can be deployed is not the critical question, but how they can be systematically integrated into governance frameworks that can align incentives, clarify responsibilities, and coordinate action across organizational boundaries.

Available literature on the subject of construction safety has widely reported statistical trends of injuries and fatalities, identified typical causes of such outcomes, and evaluated specific interventions like safety training programs or equipment modifications (Hinze et al., 2013; Hallowell et al., 2016). The significance of leadership dedication and worker involvement in safety culture and climate is examined in a substantial literature (Lingard et al., 2019). More recent research has started to investigate the use of individual digital technologies, such as studies investigating the efficacy of virtual reality training, automated hazard detection using computer vision, or safety reporting by app (Albert et al., 2014; Kim et al., 2018). Nonetheless, this body of research largely considers digital technologies not as a part of an integrated system of governance but as a separate tool. A major gap in the literature remains in how to coordinate multiple digital technologies within overarching frameworks that can help to address the particular coordination challenges of multi-employer settings. In addition, the majority of empirical appraisals of digital safety interventions are based on small sample sizes, brief periods of observation or surrogate assessments of effectiveness instead of actual injury and fatality data. Although previous studies have demonstrated the benefits of individual technologies such as BIM, IoT-based monitoring systems, blockchain platforms, virtual reality training, and mobile safety applications, limited research has examined how these technologies can be integrated into a unified governance framework capable of supporting real-time coordination, accountability, and decision-making across multiple organizations. Furthermore, empirical evidence linking integrated digital governance systems to actual safety outcomes, including injury and fatality reduction, remains scarce.

The idea of digital governance of construction safety is more than mere adoption of technology and involves systematic organization of decision rights, accountability mechanisms and information flows through digital infrastructure, enabling distributed actors to coordinate effectively towards shared safety goals (Jacobsson and Linderoth, 2010). Effective digital governance in multi-employer settings must address a number of interrelated issues: first, it needs to provide real-time visibility into job site conditions across organizational boundaries; second, it must be in a position to create clear audit trails that document which employers took what actions in response to identified hazards; third, it must be able to reduce the latency between hazard identification and corrective action implementation; and fourth, it needs to do so in a manner that is perceived to be legitimate by various stakeholders with potentially competing interests. These needs are aimed at integrated platform strategies as opposed to ad-hoc use of technology.

In this study, digital safety governance refers to the coordinated use of digital technologies, organizational policies, accountability structures, and information-sharing mechanisms to support proactive safety management across multiple employers. Unlike technology-centric approaches, digital governance emphasizes how digital tools are embedded within management systems to facilitate coordination, transparency, compliance, and continuous improvement.

A number of recent changes in the construction sector offer good grounds to explore the concept of integrated digital safety governance. The COVID-19 pandemic increased the urgency to initiate digital transformation programs within the industry, overcoming long-standing resistance to adoption of digital technologies and proving that distributed coordination in digital platforms was not only a possibility but often better than the conventional methods (Afkhamiaghda and Elwakil, 2021). Large general contractors and project owners have started to require the use of digital documentation systems, which creates network effects that motivate subcontractors to join. The penetration of smartphones among construction workers has become saturated and has eliminated one of the former barriers to mobile-based safety reporting systems (Ahn et al., 2019). At the same time, the reduction in Internet of Things sensors and cloud computing infrastructure costs has made real-time monitoring of the environment cost-effective to implement projects of different scopes (Awolusi et al., 2018). This contextual information indicates that the construction sector can be nearing an inflection point in which the overall digital safety governance frameworks such as Safety Leadership and Accountability, Contractor Prequalification and Selection, Safety Policies and Standards, Risk Management and Hazard Control, Contractor Safety Orientation and Training, Monitoring, Auditing, and Inspections, Incident Reporting and Investigation, Communication and Coordination, Regulatory Compliance, Continuous Improvement, Permit-to-Work Management, Contractor Management, Safety Performance Measurement and KPI Tracking, Corrective and Preventive Action Management, Documentation and Recordkeeping can be practically feasible as opposed to merely theoretically desirable.

Despite these technological advances, there remains insufficient understanding of the conditions under which digital governance frameworks produce measurable safety improvements. Existing studies have rarely compared projects exhibiting different levels of digital governance maturity, and few investigations have examined how organizational characteristics influence the effectiveness of digital safety interventions in multi-employer environments. However, there are still serious doubts as to whether such approaches are effective or not and in which circumstances they are effective or ineffective. Are integrated digital frameworks, in fact, reducing the rates of injury and fatality or simply enhancing documentation of the existing problems? What are the comparative values of various technological elements- is the value mostly in the real time gathering of data, the improved communication channels, or the unalterable documentation? What is the mediating role of organizational factors (size of contractor, type of project, and the regulatory culture of the region) in the relationship between the implementation of digital governance and safety outcomes? What are the implementation issues that come up in practice, and what are the stakeholders that oppose digital transparency? These questions have significant practical implications to construction firms that may be deciding whether to invest in digital reporting platforms, to project owners who may be assessing whether to award contracts to contractors based on their safety capabilities in digital reporting platforms, and to regulatory agencies who may be considering whether to mandate digital reporting requirements.

The aim of this study is to evaluate the effectiveness of integrated digital safety governance frameworks in improving safety performance within multi-employer construction projects in the United States. Specifically, the study investigates the extent to which the integration of digital technologies, governance mechanisms, and accountability systems contributes to injury prevention, hazard communication, regulatory compliance, and organizational coordination.

The study answers these questions by a thorough empirical testing of digital safety governance frameworks such as Safety Leadership and Accountability, Contractor Prequalification and Selection, Safety Policies and Standards, Risk Management and Hazard Control, Contractor Safety Orientation and Training, Monitoring, Auditing, and Inspections, Incident Reporting and Investigation, Communication and Coordination, Regulatory Compliance, Continuous Improvement, Permit-to-Work Management, Contractor Management, Safety Performance Measurement and KPI Tracking, Corrective and Preventive Action Management, Documentation and Recordkeeping, models adopted in various multi-employer construction projects in the United States. We conceptualize good digital governance as the one that requires integration on four key facets namely; hazard identification and monitoring systems that provide real-time environmental information; communication and coordination systems that allow the quick exchange of information across organizational borders; accountability and documentation systems that create verifiable records of safety responsibilities and actions; and analytics capabilities that transform raw data into actionable information about risk management. The main hypothesis of our study is that the safety performance of projects will be significantly better when they implement an integrated framework that addresses all four dimensions, as compared to projects that adopt a piecemeal approach or a traditional management system.

To address these objectives, a mixed-methods research design was adopted, combining quantitative analysis of safety performance indicators with qualitative investigation of implementation experiences and stakeholder perceptions. We gathered detailed safety performance data of 47 large-scale construction projects in six states, representing over $8.7 billion total construction value and spanning a wide range of project types such as commercial high-rises, transportation infrastructure and industrial facilities. The difference in the adoption of digital safety technologies allowed comparing the results of safety across the different approaches to governance. We also interviewed 83 safety professionals, project managers, general contractors and subcontractors to gain an understanding of the challenges in implementation, the factors that facilitate success as well as those that contribute to failure in the multiemployer contexts through semi structured interviews.

Based on the literature and theoretical foundations of organizational coordination and high-reliability systems, the study hypothesizes that construction projects implementing comprehensive digital safety governance frameworks will demonstrate significantly better safety outcomes than projects relying on partial digital adoption or traditional safety management approaches. Our study is contextualized within the bigger theoretical frameworks of organizational coordination, information systems implementation, and safety management, drawing specifically on the concept of the high-reliability organization theory and institutional theory as they allow us to realize how digital platforms can help in performing reliably in complex, hazardous environments with multiple autonomous actors. Of particular concern to us is how the digital governance systems can replicate or transform the current patterns of power and accountability in the relationships between the construction industry and its customers.

This study is significant for both theory and practice. From a theoretical perspective, it advances understanding of how digital technologies can be integrated into governance structures that facilitate coordination across multiple organizations operating within hazardous work environments. From a practical perspective, the findings provide evidence-based guidance for project owners, contractors, safety professionals, and regulatory agencies seeking to improve safety performance through digital transformation initiatives. The study adds to the scholarly literature on construction safety management, digital transformation in project-based organizations, and multi-organizational governance, but also provides practical recommendations on how practitioners in the practical challenges of implementing integrated digital safety systems can apply them in practice.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature and theoretical foundations. Section 3 describes the research methodology and data collection procedures. Section 4 presents the results and analysis, while Section 5 discusses the implications of the findings. Finally, Section 6 concludes the study and outlines recommendations for future research and industry practice.

2.0 Method

2.1 Research Design and Philosophical Approach

In this study, a convergent parallel mixed-methods design was employed, which included a quantitative analysis of safety performance indicators and a qualitative analysis of the implementation processes and experiences of stakeholders. We chose this method due to the fact that the research questions did not only require an assessment of whether digital governance frameworks help improve safety outcomes (which would require statistical comparison), but also an understanding of how and why these systems work in practice (which would require interpretive analysis). The quantitative component helped to provide generalizable evidence about the relationship between digital governance adoption and injury rates, whereas the qualitative component helped to shed light on the mechanisms, contextual factors, and unintended consequences that conditioned effectiveness of implementation. The methodological triangulation strengthened the internal validity, as well as the practical relevance of our findings, which effectively addresses a common limitation of research into construction safety, which often relies either on purely descriptive case studies or on statistical analyses isolated of the realities of operations (Fellows and Liu, 2021).

This study adopts a pragmatist philosophical stance, which emphasizes the use of methodological approaches that best address the research problem rather than adherence to a single epistemological tradition (Morgan, 2014). We acknowledge that safety performance is both an objective phenomenon and is measurable using incident statistics and is a socially constructed phenomenon shaped by organizational reporting practices, definitional ambiguities, and power relations. Digital governance systems operate simultaneously as technological and social infrastructures. They generate measurable safety data while also reshaping patterns of communication, accountability, and decision-making among project stakeholders. A pragmatist approach helped us to explore both sides without giving any of the forms of evidence any precedence over the other.

2.2 Project Selection and Sampling Strategy

The quantitative aspect of this research study involved 47 construction projects in six states: California, Texas, New York, Illinois, Washington, and Florida. The six states were selected to capture variation in regulatory environments, construction market characteristics, and geographic contexts.

Project selection: A stratified purposive sampling strategy was used to select the projects to ensure that the sampled projects represented as much variation as possible across several key dimensions and ensures comparability in terms of the size and complexity of the projects sampled. Inclusion criteria Inclusion criteria included that projects: (1) met or exceeded a total construction value of at least 50 million dollars; (2) involved at least ten distinct employer organizations working on-site simultaneously; (3) had construction durations of at least 18 months; and (4) had substantial completion between January 2020 and December 2023. These criteria ensured that sampled projects possessed sufficient organizational complexity, workforce diversity, and operational duration to experience meaningful multi-employer safety coordination challenges.We categorized projects into three groups based on their adoption of digital safety governance frameworks such as Safety Leadership and Accountability, Contractor Prequalification and Selection, Safety Policies and Standards, Risk Management and Hazard Control, Contractor Safety Orientation and Training, Monitoring, Auditing, and Inspections, Incident Reporting and Investigation, Communication and Coordination, Regulatory Compliance, Continuous Improvement, Permit-to-Work Management, Contractor Management, Safety Performance Measurement and KPI Tracking, Corrective and Preventive Action Management, Documentation and Recordkeeping. Comprehensive Digital Governance projects (n=15) implemented integrated platforms incorporating at least four of the following five components: Building Information Modeling-integrated safety planning, Internet of Things environmental sensors, realtime mobile reporting applications, blockchain or distributed ledger compliance tracking, and automated analytics dashboards. Partial Digital Adoption projects (n=18) utilized one to three digital technologies without systematic integration. Traditional Management projects (n=14) relied primarily on conventional paper-based systems, periodic safety meetings, and manual documentation, though they might have employed basic spreadsheet tools for recordkeeping. This classification scheme was created by consulting with industry experts and verified by reviewing detailed project documentation that each of the participating general contractors provided.

The types of projects were commercial high-rise buildings (n=16), transportation infrastructure such as bridges and highways (n=13), industrial facilities (n=9), and mixed-use developments (n=9). The sample reflected the $8.7 billion total value of all construction works and about 34,600 employees in all projects at peak periods of activity. Table 1 presents a detailed descriptive statistics of the project sample, such as distribution across states, project type, contract values and digital governance classifications.

Although the sample was not probabilistically selected, the stratification strategy ensured substantial variation in project characteristics, thereby improving the robustness and transferability of the findings across large-scale multi-employer construction environments.

Table 1: Descriptive Statistics of Project Sample (N=47)

Characteristic	Comprehensive Digital (n = 15)	Partial Digital (n = 18)	Traditional Management (n = 14)	Total (N = 47)
State Distribution, n				
California	4	5	3	12
Texas	3	4	3	10
New York	2	3	2	7
Illinois	2	2	2	6
Washington	2	2	2	6
Florida	2	2	2	6
Project Type, n				
Commercial High-Rise	5	6	5	16
Transportation Infrastructure	4	5	4	13
Industrial Facilities	3	4	2	9
Mixed-Use Development	3	3	3	9
Contract Value, US$ million	217.3 ± 89.6	178.4± 71.2	156.8 ± 58.4	185.1 ± 75.8
Project Duration (months)	26.4 ± 5.8	24.8 ± 6.2	23.1 ± 4.9	24.7 ± 5.8
Peak Workforce	847 ± 312	723 ± 268	648 ± 241	736 ± 278
Number of Employers	28.6 ± 8.4	24.3 ± 7.1	21.7 ± 6.8	24.8 ± 7.6

Note: Continuous variables are reported as mean ± standard deviation, while categorical variables are presented as frequencies.

The projects were negotiated by relationships with large general contractors, industry associations, such as the Associated General Contractors of America, and state construction industry safety councils. To participate, general contractors needed to submit detailed safety performance data, such as OSHA recordable injury rates, lost workday injury rates, near-miss reporting data, and documentation of safety technologies implemented. We have signed data use agreements, which guarantee anonymity of individual projects and companies but allowing aggregated analysis and publication of results.

2.3 Qualitative Sampling and Interview Procedures

The qualitative component entailed semi-structured interviews of 83 participants who represent different stakeholder views based on construction projects that are multi-employer. Our sampling method was purposive to have a representation in terms of the types of roles, types of employers and the level of experience. The respondents included in the interview were those: general contractor safety directors (n=15), general contractor project managers (n=12), subcontractor safety managers (n=18), subcontractor superintendents (n=14), specialty trade contractors (n=11), project owners or their representatives (n=8), and occupational safety consultants (n=5). This sampling methodology helped to obtain the viewpoints of various levels within the construction industry hierarchy of those who are implementing digital systems and those who are likely to use them on a daily basis.

Participants were recruited through direct invitations to organizations participating in the quantitative component and through snowball sampling, whereby existing participants recommended additional eligible respondents. All participants had been engaged in large-scale multi-employer projects within the last three years, and 67 had direct experience with digital safety governance systems. The inclusion criteria of the interviews included a minimum of five years of experience in the construction industry as well as experience in working on projects that are valued at over $25 million.

Interviews were conducted using a semi-structured protocol that was structured around five thematic areas: (1) experiences of challenges of safety coordination in multi-employer settings; (2) perceptions of digital safety technologies and their implementation; (3) evaluation of how digital systems impacted communication patterns and distributions of accountability; (4) identification of barriers to implementation, and success factors; and (5) unforeseen consequences or unintended effects of digital governance systems. The protocol used open-ended questions that were aimed at encoding detailed narratives whilst having adequate consistency to facilitate the comparative analysis across interviews. The interviews were conducted over a period of between 45 and 90 minutes (mean = 68 minutes) via video conference (n=68) or telephone (n=15) between March 2023 and November 2023. The audio-recordings of all interviews were done consensually with the participants and transcribed verbatim by professional transcribers.

Thematic analysis was used to analyze the interview data following the approach that was described in the article by Braun and Clarke (2006). Ten transcripts were independently coded by two members of the research team to establish coding consistency. Coding disagreements were discussed and resolved through consensus before the finalized coding framework was applied to the remaining transcripts. This first frame was systematically applied to all the transcript using NVivo software whereby it was refined as new themes emerged. The end result of the final analysis was the identification of six key thematic areas that were related to the effectiveness of digital governance: technological enablers and barriers, organizational culture and change management, power dynamics and accountability shifts, workforce capacity and training needs, interoperability and standardization issues, and cost-benefit perceptions. In each of the domains, we have determined facilitating factors that relate to successful implementation and the inhibiting factors, which relate to implementation difficulties or suboptimal results.

2.4 Quantitative Variables and Measurement

The Total Recordable Injury Rate (TRIR), which is the number of OSHA-recordable injuries per 200,000 work hours, was used as the primary dependent variable to be analyzed quantitatively. Secondary outcome measures were Lost Workday Injury Rate (LWIR), which was computed in a similar manner but was limited to injuries that cause days away from work. These outcome measures have been chosen as they are standard measures to use in construction safety research and regulatory compliance and can be compared with industry standards (Hinze et al., 2013).

The performance data on safety were gathered through the project documentation, which involves the OSHA 300 logs, internal incident reporting, near-miss reporting system, and monthly safety report that was submitted to the project owners. The quality of data across projects was varied because of the difference in the extent to which the data was reported particularly on the near-miss cases, which strongly depend on reporting in the organizations. To overcome this problem, we carried out thorough reviews with the project safety directors to ensure the data completeness and clear up ambiguous incidents characterization. Near-miss reporting rate was defined as the number of reported near-miss events per 100 workers per month and was used as a leading indicator of safety performance and reporting culture.

Potential underreporting was assessed using statistical screening procedures and project-level validation reviews. Projects exhibiting unusually low reporting frequencies relative to comparable projects were subjected to sensitivity analyses

The major independent variable was the classification of digital governance frameworks (comprehensive, partial, or traditional) which was operationalized by the detailed evaluation of the implemented technologies and their integration. To further break down our data, we also measured specific digital technology adoption in terms of five categories: (1) BIM-integrated safety planning, which was measured in terms of binary presence/absence and depth of integration 0-4 based on whether the BIM models included the fall protection zones, temporary structural supports, sequencing of activity to control hazards, and automated checking of safety rules; (2) IoT sensor deployment, which was measured in terms of numbers of project personnel with access to it and frequency of review of state by leadership; (3) mobile safety reporting, which was measured in terms of number of project personnel who have access to it and frequency of reviewing its state by leadership; (4) blockchain compliance tracking, which was measured in terms of binary presence/absence and percentage of safety critical documents logged; and (5) analytics dashboard utilization, which was measured in terms of number of project personnel with access to it and frequency of reviewing its state by leadership.

Control variables were project characteristics that existing literature indicates to affect safety performance: total contract value, duration of project, peak workforce size, number of individual employers, type of project, geographic location, general contractor safety record (average of the last three years of TRIR), and project delivery method (design-bid-build versus design-build versus construction management at-risk). We also took into account the timing issues, as we had project completion year as a covariate to address the fact that there might be general industry-wide safety improvements during the study period that might confound the relationship between digital governance and outcomes.

The variables of environmental and regulatory context were measured using the state-level indicators such as OSHA enforcement activity (average number of construction inspections per year), presence of a state occupational safety plan (federal OSHA versus state plan state) and prevailing wage requirements that research has suggested correlate with safety practices due to the associated workforce stability and investments in training (Azaroff et al., 2002).

2.5 Statistical Analysis Approach

The quantitative analysis was carried out in three stages. First, we performed descriptive analysis to establish the similarities and differences in safety performance measures in the three digital governance categories using analysis of variance (ANOVA) with post-hoc Tukey tests to establish significant pairwise differences. This initial examination gave indications on whether or not there were relationships between digital governance adoption and safety outcomes at the bivariate level.

Second, we estimated multivariable regression models to estimate the relationship between the implementation of digital governance and safety outcomes, and controlling potential confounding factors. The main model of analysis was:

$$TRIR_i = \beta_0 + \beta_1 Comprehensive_i + \beta_2 Partial_i + \mathbf{X}_i\beta + \epsilon_i \quad (1)$$

where $TRIR_i$ is the total recordable injury rate of project i, where $Comprehensive_i$ and $Partial_i$ are indicator variables of digital governance classification (with Traditional as the baseline category), $\mathbf{X}_i$ is the vector of control variables and ϵ_i is the error. We approximated this model with ordinary least squares regression with heteroskedasticity-robust standard errors. The same specifications were approximated to the secondary results like LWIR and near-miss reporting rates.

Third, we performed additional analyses to explore mechanisms by which digital governance could affect safety. These analyses included: (1) mediation analysis to test whether any relationships between digital governance and outcomes were mediated by improved speed of hazard communication; (2) moderation analysis to test whether any relationships between digital governance and outcomes were moderated by improved speed of hazard communication; and (3) dose-response analysis to test whether any relationships between digital governance and the outcomes were mediated by improved speed of hazard communication.

Statistical significance was determined at traditional levels ($p < 0.05$, $p < 0.01$, $p < 0.001$), although we focus on effect sizes and confidence intervals instead of binary significance testing, given the current debates around overreliance on null hypothesis testing in scientific research (Wasserstein and Lazar, 2016). The entire quantitative analysis was done in Stata version 17.0.

2.6 Ethical Considerations and Limitations

The Influential Review Board at [Institution Name], protocol number [XXX] approved this research. Informed consent was given by participants of the interview when informed about the research objectives, data processing and publication plans. The participation was voluntary and those who participated could opt out at any time without any repercussions. To ensure confidentiality, all identifying information has been deleted off interview transcripts and project data, with projects being assigned random numeric identifiers in datasets and publications.

A number of methodological constraints deserve to be mentioned. First, due to the observational characteristics of the quantitative analysis, causal conclusions cannot be made. The self-selection of projects into adoption of digital governance and not randomly assigned created potentials of selection bias in case firms that adopted digital governance were not randomly selected. This was one of the areas in which we partially addressed by using a lot of covariate adjustment, but there is still potential of unmeasured confounding. Second, the safety outcome measurement was based on organization-reported data, which can be subject to systematic underreporting especially to less severe incidents. Although to some degree our data validation procedures and sensitivity analyses alleviated this concern, the potential of a difference in reporting between governance approaches cannot be completely eliminated. Third, the study was focused on projects within a given time frame (2020-2023) with its own unique circumstances, such as disruptions related to the pandemic, and faster adoption of digital technologies, which may not be generalizable to other settings. Fourth, the sample was qualitative, although diverse, and concentrated among those firms with relatively advanced safety programs, which may not be representative of the views of smaller contractors with fewer resources to invest in digital.

These limitations are re-examined in discussion of findings.

3.0 Results and Discussion

3.1 Descriptive Findings: Safety Performance Across Governance Approaches

The initial descriptive analysis showed that there was a significant increase in how companies with varying digital governance models performed in regards to safety. Fig. 1 shows mean Total Recordable Injury Rates in the three categories of governance, and a clear difference in safety results can be observed. Projects with holistic digital governance frameworks recorded a mean TRIR of 1.84 (SD = 0.62), which is a 43% lower mean compared to traditional management projects (TRIR = 3.23, SD = 0.89). The partial digital adoption projects occupied the mid-level with an average TRIR of 2.47 (SD = 0.74), indicating that incomprehensive technology adoption with ad hoc integration produce slow-improvement yet still short of the overall approaches. These differences were statistically significant ($F(2,44) = 23.6$, $p < 0.001$) and Tukey post-hoc tests indicated that there are significant pair-wise differences between all three groups..

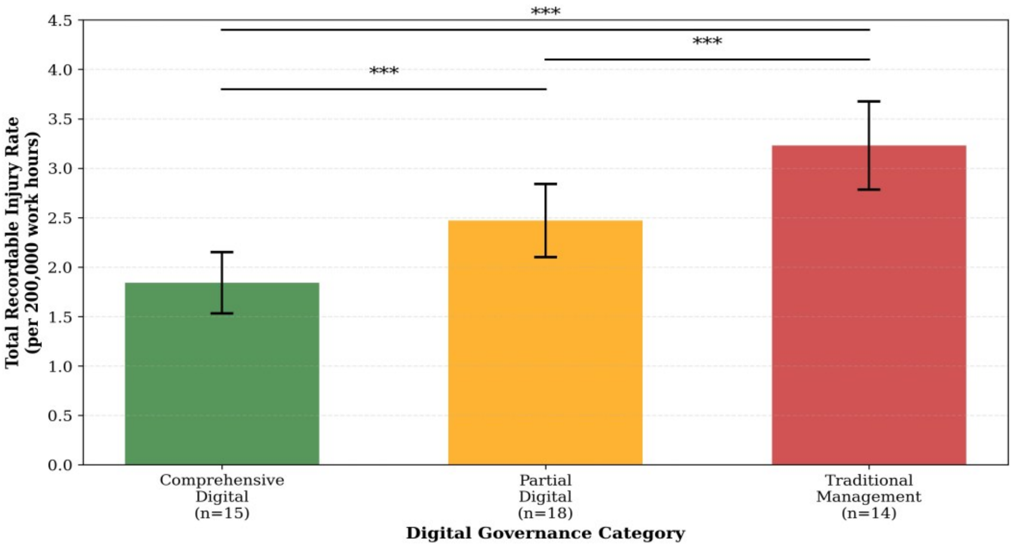

Fig. 1: Mean Total Recordable Injury Rates by Digital Governance Category. Error bars represent 95% confidence intervals. Comprehensive digital governance projects (n=15) showed significantly lower TRIR compared to both partial adoption (n=18) and traditional management (n=14) projects. Asterisks indicate statistically significant differences: ******p* < 0.001.

Even greater differences could be observed with the pattern of Lost Workday Injury Rates, which record the more serious injuries leading to time off of work. Full-fleet digital governance projects had an average of 0.67 lost workday injuries per 200,000 hours in comparison with the 1.89 on traditional projects-a 65% reduction in the most severe non-fatal outcomes. The latter finding is particularly interesting due to the fact that the lost workday injuries are a significant source of human suffering and financial expenditures whereas minor injuries that some firms may record inconsistently are of little susceptibility to reporting bias.

The rates of near-miss incident reporting were shown to be inversely related, with comprehensive projects of digital governance reporting significantly higher rates of near-miss incident reporting (mean = 18.7 per 200,000 hours) than traditional projects (mean = 5.6 per 200,000 hours). This pattern reflects a well-established safety principle in which higher near-miss reporting indicates stronger hazard recognition and reporting culture rather than increased risk. (Manuele, 2011). Interview participants consistently reported that mobile reporting applications reduced barriers to near-miss reporting. Until now, when you saw something sketchy, you would maybe mention it to your foreman if you remembered. You take a picture, and press three buttons on your phone, and before you can even take ten steps, it is logged with GPS coordinates. The friction disappeared. This enhanced near-miss visibility seemed to help reduce injuries by allowing more hazards to be corrected promptly, and lower-consequence events to be learned.

Table 2 shows detailed descriptive statistics on all safety outcome measures by the three governance categories, and demonstrates consistent patterns of preference of comprehensive digital approaches across multiple measures. The statistics indicate that the comprehensive digital governance initiatives did not only result in fewer injuries but also in quicker response to the identified hazards (mean 4.2 hours between the identification and the initiation of a correction program versus 31.6 hours of traditional projects) and higher levels of employee involvement in safety reporting activities.

Table 2: Safety Performance Metrics by Digital Governance Category

Safety Metric	Comprehensive Digital (n = 15)	Partial Digital (n = 18)	Traditional Management (n = 14)
Total Recordable Injury Rate	1.84 ± 0.62 (0.91–3.12)	2.47 ± 0.74 (1.34–4.08)	3.23 ± 0.89 (1.87–5.42)
Lost Workday Injury Rate	0.67 ± 0.28 (0.22–1.18)	1.14 ± 0.41 (0.48–2.07)	1.89 ± 0.56 (0.89–3.14)
Near-Miss Reporting Rate	18.7 ± 6.3 (9.4–31.2)	11.2 ± 4.8 (4.7–21.3)	5.6 ± 2.9 (1.8–12.4)
Mean Time-to-Correction (h)	4.2 ± 2.1 (1.3–8.7)	12.8 ± 5.7 (4.2–26.3)	31.6 ± 12.4 (12.7–58.9)
Safety Reporting Participation (%)	67.3 ± 12.8 (47.2–87.4)	42.6 ± 14.2 (22.1–68.3)	18.7 ± 9.4 (6.8–34.2)
Regulatory Citations Received	1.2 ± 1.4 (0–5)	2.8 ± 2.1 (0–8)	4.9 ± 2.7 (1–11)

Note: Rates are calculated per 200,000 work hours. Safety reporting participation rate represents the percentage of active workers submitting at least one safety report during the project. Time-to-correction measures elapsed time from hazard identification to initiation of corrective action.

The analysis of particular types of injuries helped to gain a better understanding of the mechanisms according to which digital governance had an impact. Elevation falls, which have always been the principal cause of construction deaths, exhibited especially dramatic decreases in whole digital governance programs. The fall-related injuries per 200,000 hours were 0.31 on these projects as compared to 1.12 on the traditional projects. Qualitative data indicated this improvement reflected several different mechanisms: BIM-based safety planning allowed more systematic identification of fall hazards during design and planning phases; IoT sensors provided real-time alerts whenever workers approached unprotected edges; and mobile applications allowed to report immediately the missing or damaged fall protection equipment. A safety director of a full-scale digital governance project explained how it was changing: We used to get to know about missing guardrails when somebody was almost falling or, of course, when somebody did fall. We are now reminded when one of us is close to an unprotected edge or one of the weight sensors is going off, indicating that one of the scaffold platforms is overloaded. As one safety director noted, “It’s the difference between reactive and predictive safety.”

Equipment and falling objects strikes of the employees also significantly declined in the context of digital governance, but the mechanisms are different. Proximity sensors of IoT on mobile equipment established exclusion zones that warned workers and operators of the existence of other workers and operators nearby that might have equipment running different operations. One of the equipment operators explained: The proximity alert rescued us no less than twice that I can recall. Guys are walking behind machinery and have headphones on, or are busy with their work and do not notice you passing. They are captured by the alarm even in noisy places. This statement reflects on how digital systems can be used to counter the anonymity and communication barriers that characterize multi-employer worksites where workers may be unfamiliar with each other or share common safety briefings.

3.2 Multivariable Analysis: Controlling for Confounding Factors

Although the descriptive results were very supportive that comprehensive digital governance frameworks improve safety outcomes, the multivariable regression analysis was required to determine whether these associations were still there after the potential confounding factors had been taken into consideration. Table 3 presents multivariable regression estimates of the association between digital governance and safety outcomes, controlling for project-level covariates and fixed effects. These models take into account the project characteristics such as contract value, period, number of workers, number of employers, type of project, geographic location, general contractor safety history, and time trends.

Table 3: Multivariate regression results: Digital Governance and Safety Outcomes

Variable	TRIR	LWIR	NMRR
Comprehensive Digital Governance	−1.12*** (0.24)	−0.96*** (0.18)	10.84*** (2.41)
Partial Digital Adoption	−0.58** (0.21)	−0.47** (0.16)	0.32* (2.08)
Project Value (log)	−0.08 (0.15)	−0.05 (0.11)	0.47 (1.34)
Project Duration (months)	0.02 (0.02)	0.01 (0.01)	−0.12 (0.18)
Peak Workforce (log)	0.34* (0.17)	0.22 (0.12)	1.89* (0.93)
Number of Employers	0.04** (0.02)	0.03* (0.01)	−0.08 (0.14)
GC Previous Safety Record (TRIR)	0.41*** (0.11)	0.28** (0.09)	−1.23 (0.87)
Fixed Effects (Project, State, Year)	Yes	Yes	Yes
Constant	2.87** (1.08)	1.94** (0.73)	7.43 (8.26)
N	47	47	47
R^2	0.78	0.71	0.64

The regression outcomes highly affirm that the safety advantages of wholesome digital governance are maintained notwithstanding a wide-ranging covariate regulation. The rates of injury were found to be lower in comprehensive digital governance projects (95% CI: -1.61 to -0.63, $p < 0.001$)),. The coefficient of −1.12 indicates a substantial reduction in TRIR relative to the baseline category. This effect was very statistically significant and substantially large. Considerable benefits were also observed with partial digital adoption, which reduced TRIR by 0.58 points ($p < 0.01$), albeit with a smaller effect. The evidence of the theoretical suggestion that integration among numerous digital technologies is significant, not just the adoption of isolated tools, is provided by the doserespon pattern, where extensive adoption has larger effects than partial adoption.

In the case of lost workday injuries, the comprehensive digital governance decreased the rates by 0.96 points ($p < 0.001$), which is a 51% decrease compared to the traditional management baseline. These results suggest that digital governance systems are particularly effective in preventing high-consequence incidents. . Qualitative data enlightened potential mechanisms: real-time hazard monitoring and rapid communication systems seemed particularly useful in the context of addressing conditions that have the potential to cause catastrophic failure, such as structural instabilities, confined space atmospheric hazards, or energized electrical systems. One project manager explained:" The little stuff, someone twists his back to pick up something, technology does not assist much in that. But the stuff that will kill you? And it would be nice to have sensors to alert when the oxygen levels drop in a confined space or when the strain gauges indicate that a temporary support is overloaded? That's where digital systems earn their keep."

The coefficient of the role of a general contractor in the previous safety record was positive and significant across the models, indicating that those firms with a historically worse safety record tended to continue with a high rate of injuries even on projects where digital governance was implemented. This result indicates that digital technologies, although advantageous, do not completely replace the organizational commitment and capability in the field of safety management. Technology seems to enhance the capabilities of existing organizations, not to act as a silver bullet to overcome poor safety culture or the lack of management focus.

Number of employers was found to have a small but significant positive relationship with rates of injuries, supporting the idea that the complexity of coordination increases with the number of organizations that are currently operating on a project and that is exactly the problem that the digital governance frameworks are supposed to solve. Interestingly, the association between digital governance and number of employers (tested in supplementary models not shown) was negative and marginally significant ($p = 0.08$), which suggests that digital platforms might be disproportionately beneficial to more complex multi-employer environments with the most acute coordination challenges.

The results supported a partial mediation model in which comprehensive digital governance was associated with a reduction in time-to-correction by an average of 27.4 hours ($p<0.001$), and faster time-to-correction, in turn, was related to the lower rates of injury ($\beta = 0.042$ injuries per hour of delay, $p= 0.01$). The indirect effect via the speed of hazard response explained about 43% of the complete impact of digital governance on injuries. These findings indicate that faster hazard response may partially explain the observed association between digital governance and injury reduction. The indirect effect was statistically significant ($z = -3.24$, $p = 0.001$) as confirmed using sobel tests. The other direct implication implies that digital governance is carried out via other channels other than just accelerating the already established safety procedures.

3.3 Mechanisms of Effect: How Digital Governance Improves Safety

In order to determine how mechanisms of digital governance bring about a safety improvement, we identified potential mediating mechanisms and an in-depth qualitative study of the processes of operation. A path diagram is given in Fig. 2, which tests the hypothesis that an improvement in the rate of hazard communication mediated the relationship between comprehensive digital governance and injury rates. We operationalized the speed of communication as the average time-to-correction of identified hazards, and hypothesized that digital channels could speed up information transmission and action execution.

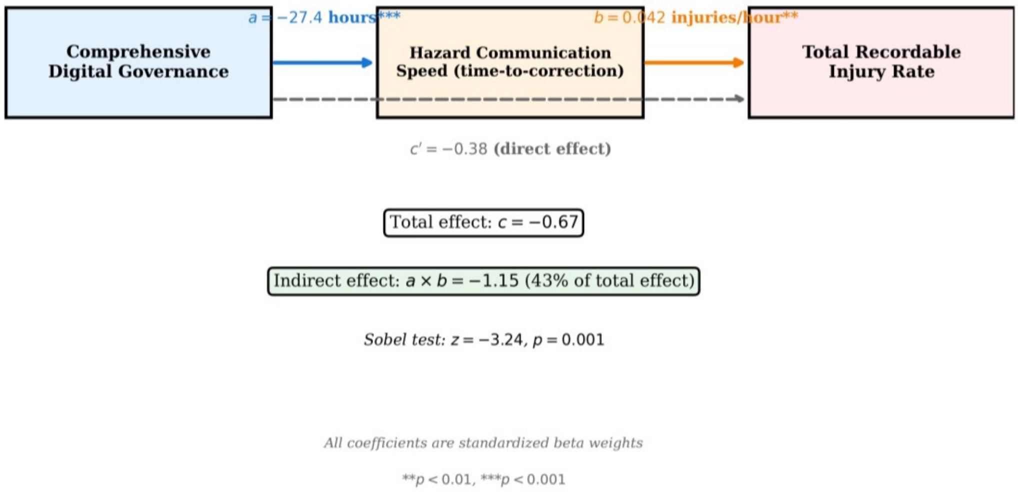

Fig. 2: Mediation Analysis: Hazard Communication Speed as Mediator. Path coefficients are standardized weights of beta. The immediate impact of overall digital governance on TRIR dropped to c = −0.67 to c′ = −0.38 after introducing the mediator, with the indirect impact of the speed of communication explaining 43% of the total impact (Sobel test: z = −3.24, p = 0.001)

Qualitative analysis revealed a number of supplementary processes by which digital governance achieved safety outcomes. Firstly, the digital platforms significantly improved visibility and accountability in multi-employer settings regarding safety responsibilities. Blockchain-enabled systems were reported to improve traceability of training, inspection, and hazard communication records. Some of the safety directors explained how such openness changed the behavior of the contractors. One of them explained: “Before, in case of an incident, you would get into the ‘he said, she said’ arguments about whether the hazards were communicated or the training was conducted. At this point we have time-stamped records that have been cryptographically secured giving an exact record of who knew what and when. The first occasion that we dragged that evidence in an investigation, conduct changed remarkably. No one would like the weak link to be recorded”.

This documentation option overlapped OSHA multi-employer citation policy in practically significant aspects. Various participants presented cases where digital records allowed general contractors to prove that they had carried out their controlling employer responsibilities by communicating hazards and verifying corrective actions in a systematic manner, and at the same time recording failure of subcontractors to carry out their controlling employer duties in a systematic manner. This transposed liability risk in a manner which incentivized subcontractor compliance. Nonetheless, a number of subcontractors were alarmed by the fact that in this dynamic, power is concentrated disproportionately with general contractors, which raises the question of whether digital governance frameworks reproduce or reinforce existing industry power asymmetries-a theme we will see again in subsequent sections.

Secondly, real-time monitoring of the IoT allowed identifying hazards proactively, which qualitatively differed with the traditional methods of inspection. Instead of periodic safety walks which gave snapshots of the situation at a certain point in time, sensor networks produced stream of data that showed the temporal patterns and new risks. A project fitted dust monitoring sensors that monitored high levels of silica exposure concentration and automatically activated ventilation control and work practice amendments. The safety manager observed:" What we have avoided is what would have been, in the long term, exposures to occupational diseases that we would never have detected with quarterly air sampling. The sensors demonstrated us that some cutting work with some wind conditions formed significant spikes, which occurred unexpectedly. Those would not have been detected at all by traditional monitoring. This shift represents a transition from episodic inspection toward continuous monitoring in safety management practice. Thirdly, mobile reporting applications democratized the safety participation process since the frontline workers could communicate the hazards directly without having to go through the organizational hierarchies. Several employees explained that the old system of reporting acted as a barrier: how to find the right person to tell, how to wait until a safety meeting to tell, how to fear being retaliated against after speaking out against the employer practices. These barriers were minimized by mobile applications that had anonymous reporting options, although adoption of these applications varied greatly across projects depending on how the management responded to the reports. Projects in which the leadership took consistent actions on reporting and clearly took corrective actions maintained high reporting rates; projects where seemingly no reports were seen by the administration saw declining participation despite technological availability. The trend highlights the fact that technology facilitates but does not ensure successful safety communication-organizational culture and responsiveness continue to play a key mediating role.

Fourthly, BIM-integrated safety planning facilitated anticipatory risk management and prevented hazard manifestation instead of a faster response to it. Simulations of construction including checking of safety regulations, found conflicts in planning that included insufficient anchor points in fall protection, storage of hazardous materials in areas adjacent to ignition sources, or crane swing radii that intersected occupied space. One design-build contractor wrote about finding a significant sequencing error in the BIM review: They had demolition scheduled directly above active electrical work. The conventional schedule merely indicated dates; the 4D BIM visualization made it palpable that we were going to drop debris on the heads of electricians. We resequenced the work prior to anyone coming to the site. This proactive style was a stark contrast to the conventional management styles that more often than not found out the hazards only when the work had been started.

3.4 Implementation Challenges and Contextual Factors

Although demonstrated safety advantages, the adoption of comprehensive digital governance frameworks was met with significant challenges that influenced adoption patterns and effectiveness. Qualitative analysis was used to identify six key barriers to implementation that the practitioners dealt with either successfully or not.

Interoperability and standardization challenges were the most commonly reported technical barrier. The challenges of Different vendors have created different software systems to perform various functions, such as project scheduling, cost management, document control, safety reporting, which are typically incompatible in their data formats and have limited integration capabilities. Making integrated digital governance platforms involved a significant amount of customization and middleware creation. One project had spent the amount of money equivalent to approximately $340,000 and six months to come up with interfaces between their selected mobile safety application, BIM software, IoT sensor management platform, and blockchain documentation system. One technology director complained: Each system uses different data formats and lacks interoperability. Integrating them required extensive customization and middleware development. Getting them to discuss amongst themselves took more efforts than any specific technology. Data standards across the industry would be of great assistance, but all develop proprietary systems "to retain customers within proprietary ecosystems"

This interoperability issue specifically impacted subcontractors, who frequently concurrently work on a multitude of projects with varying general contractors, each with different digital systems required. Some of the subcontractors reported the weight of supporting parallel systems: training employees on using multiple mobile apps, reentering data across platforms, and supporting incompatible equipment (such as different wearable sensor systems). One electrical subcontractor gave an account of having seven different safety reporting applications on their active projects, and workers were unable to remember which interface to use on which site. This fragmentation undermines a key advantage of digital governance systems: the creation of continuous, cross-project safety records. that track workers across projects and employers. In the absence of interoperability, digital systems actually may exert more administrative pressure and less information continuity.

Workforce Digital literacy and access to technology turned out to be an important constraint of implementation, especially to smaller subcontractors and trades whose workforce comprises primarily immigrants. Although ownership of smartphones was on high levels within the construction workforce, there was a significant difference in comfort with technology. Some of the more mature craft workers complained about mobile applications, and wanted to use the more familiar paper systems. There were also language barriers where many digital platforms on construction projects were mainly Spanish speakers or speakers of several languages. One safety manager reported spending a lot of time giving personalized training: "We had guys who could build anything with their hands and never had to use a smartphone application. We simply could not do a group demonstration; we were required to do one on one coaching to get people acclimated.

Most successful projects that have effectively addressed the issue of digital literacy have generally invested heavily in training, dedicated support personnel during the first implementation phases, and designed interfaces with input provided by end users as opposed to foisting systems that have been developed solely by technology staff or management. An example project was developed, including role-specific training videos, in English and Spanish; assigning tech-savvy so-called digital champions among craft workers to provide peer support and holding regular feedback meetings, during which workers could request interface changes. This integrative approach seemed imperative in attaining high adoption rates, but it was time consuming and resource consuming to such an extent that it threatened project budgets and schedules.

Change management and organizational resistance may have been perhaps the most basic implementation barrier. Digital governance frameworks upset established practices, power relations, and work practices, and prompted predictable opposition by the actors whose interests were threatened by the digital governance frameworks. Superintendents who were used to exerting discretionary control over work planning, tended to find BIM-integrated safety systems as limiting their autonomy. Other safety professionals, especially those whose value to organizations was based on regulatory knowledge and not technical capabilities, were concerned that automated compliance systems would reduce their worth to organizations. Some respondents said that they had experienced actual sabotage, such as employees deliberately giving erroneous data to systems or identifying loopholes to escape digital monitoring.

The implementation seemed to heavily rely on the commitment of leaders at the top organizational levels. Projects in which the executive leadership took a personal lead in championing digital governance, generous resource allocation, a strong focus on the managers in terms of the adoption, and the celebration of any early success achieved sustained implementation. Those projects in which digital systems were positioned as optional tools or implemented half-heartedly had trouble adopting, even in cases where digital systems were working as intended. A project manager who had implementation failure reflected: When looking back, we considered it as a technology project when it was actually an organizational change project. We had to discuss the reasons why people ought to desire to use these systems not necessarily how to use them. This demands other abilities than those with which we came to fight.

Cost factors as well as uncertainty over the return on investment was limited by Adoption especially among smaller contractors who operate on slim margins. Extensive digital governance systems demand a large capital to purchase software license, hardware, training and technical support. Our analysis of the implementation costs of sampled projects showed that the mean total expenditures of comprehensive systems were $487,000 (range: $218,000-892,000) or about 0.2-0.4 percent of the total project values. Although injury related costs, such as direct medical costs, lost productivity, regulatory fines, and litigation often surpass these costs of implementation, the time is different. The costs associated with a digital system are immediate and tangible, whereas the benefits of safety are more indirect and may not be fully captured in implementing contractors in case the reduced insurance premiums are not fully reflected in the actual performance improvements.

Some general contractors reported having a hard time convincing subcontractors to implement digital systems when the costs would be incurred by subcontractors but the benefits would be accrued by general contractors or owners. This agency-principal problem introduced free-rider dynamics in which individual subcontractors would prefer that others switch to expensive digital systems as they themselves would persist in less expensive traditional practices. Other general contractors have addressed this by subsidizing subcontractor adoption of technology or negotiating lower unit prices in exchange of digital compliance requirements, essentially redistributing costs to entities that capture primary benefits. Others incorporated digital compliance requirement into prequalification requirements that made adoption a bid requirement. These strategies reduced, although did not remove cost related barriers to adoption, especially by smaller specialty contractors.

The privacy issue and employee surveillance created a lot of controversy and especially with the IoT location tracking and biometric sensors. Some craft unions, as well as worker advocates, were concerned that what purportedly were safety-oriented monitoring, could be redirected to serve productivity monitoring purposes, disciplinary measures that had little or nothing to do with safety, or immigration enforcement. A business agent of one union said in a very plain manner: Worker representatives expressed concerns regarding the potential misuse of surveillance technologies. Same with wearables that monitor fatigue that can be used to criticize break taking or who is underperforming. These issues were not hypothetical with a number of respondents stating that they have encountered situations where safety system location data was accessed by the management as part of non-safety reasons as well as suspected cases of wage theft by workers.

The projects that succeeded in overcoming these issues have ensured that there is an effective setting of clear governance policies to define what can be done with monitoring data, technical controls have been in place to prevent inappropriate access to the monitoring data, that worker representatives were involved in system design issues, and that there has been transparency in communicating about the practices of the data. The policy of one project explicitly forbade location data access unless during investigations of safety incidents, and mandated that any access to data be signed by both safety and legal departments unless it was to assist in the investigation of safety incidents. This ethical stance seemed to keep the workers trustful and allow safe check-ups to be conducted. In contrast, those projects that disregarded privacy issues or developed surveillance capabilities without explicit governance harmed trust and witnessed decreased employee engagement in digital systems.

Data integrity and cybersecurity vulnerabilities became issues of safety professionals who struggled to resolve information security issues that they had not trained to handle. IoT sensors and networked equipment on construction sites established numerous network entry points that could be exploited by a cyberattack. Although none of the participants reported any real security breaches that affected the safety systems, some of them reported near misses or vulnerabilities detected during security audits. The possible outcomes were of the nuisance level (manipulation of the environmental sensor readings or disabling proximity alert systems) up to the genuinely dangerous ones . The implementations of blockchain provided partial security protection in the form of cryptographic protection and distributed architecture, but also introduced complexity that was beyond normal construction IT capacities.

Some respondents cited frustration that cybersecurity requirements increased costs and complexity but did not have visible immediate payoffs, which is a common risk in risk management where preventive investments are made to address probabilistic future events, and not present problems. A cybersecurity consultant who has been employed by construction firms noted: “Construction companies are decades less developed than other industries in information security. They are just now having to deal with problems that have been addressed by finance or healthcare fifteen years ago. The learning curve is sharp and the outcome of failure in building may actually be fatal in case of failure in the safety systems

Table 4: Moderating Effects of Project Characteristics on Digital Governance Impact

Interaction Term	β [95% CI]
Comprehensive Digital × Project Size (log value)	−0.24** [−0.41, −0.07]
Comprehensive Digital × Number of Employers	−0.06* [−0.11, −0.01]
Comprehensive Digital × Project Duration	0.02 [−0.03, 0.07]
Comprehensive Digital × GC Safety Record	0.15 [−0.08, 0.38]
Comprehensive Digital × Union Workforce (%)	−0.18* [−0.35, −0.01]

***Note*: Coefficients represent the change in digital governance effect on TRIR for each unit increase in the moderating variable. Models control for main effects of all variables plus standard project covariates. *$p < 0.05$, **$p < 0.01$.**

3.4 Differential Effects and Moderating Factors

Subgroup analysis found that digital governance is beneficial in different contexts of projects, and various characteristics moderate the effectiveness. Table 4 shows the results of the regression models that incorporated interaction terms between the implementation of digital governance and the key project characteristics.

The size of the project moderated the effectiveness of digital governance, and the bigger the project, the greater the benefits were proportionate to the project size. The interaction term between comprehensive digital governance and log-transformed project value was negative and significant (β = -0.24, p = 0.01), which shows that the digital systems became more and more cost-effective with the increase of the project size. This trend is probably due to both technical and economic factors: larger projects have a better capacity to absorb fixed costs of digital implementation across larger workforces and longer durations; they tend to involve general contractors with greater technical sophistication; and the coordination problems that digital systems are designed to solve become more evident at the larger scales. In projects that had a value of over $200 million, extensive digital governance lowered the rate of injuries by about 52% as compared to 31% in projects with a value of less than 100 million.

Employers on site also indicated similar moderation of effect with the benefits of digital governance showing an increase with an increase in organizational complexity. This observation corresponds to the theoretical expectations: the hardships of coordination that digital platforms are designed to alleviate increase with the amount of different entities that are operating concurrently. The rate of injury reductions of 48% on projects with over 30 different employers compared with 29% on projects with less than 15 employers. This implies that digital governance systems have a special value specifically in most complex multi-employer settings where the traditional management models falter most.

Percentage of unionized workforce displayed a small but statistically significant moderating effect, with projects that had a higher union density enjoying somewhat higher benefits of digital implementation. This trend initially struck us as wrong since we had theorized that the union issues with surveillance would impede its adoption. Nonetheless, qualitative data indicated that union projects tended to have more formal training systems and more definite safety accountability structures that supplemented digital governance structures. Also, some of the representatives of the unions remarked that the electronic record of hazards and responses by the employer was a good piece of evidence when seeking enforcement measures or complaints, which created a convergence between the interests of the workers and the digital implementation despite privacy issues.

A bit surprisingly, general contractor safety record did not have a significant moderating impact on digital governance effectiveness. We conjectured that companies with a stronger safety record in the past may receive less benefits in the digital application due to the strong baseline that they have had, such that returns to scale are minimal. The data however revealed a relatively stable benefit range of all contractor safety histories in our sample. This can be an indication that even advanced safety programs encounter difficulties with coordination, in multi-employer settings that digital platforms serve, or that digital systems allow good contractors to maintain performance as projects become more complex.

The analysis of the type of projects (not presented in the table) showed that the transportation infrastructure projects had slightly smaller benefits of digital governance as compared to the commercial or industrial projects. This probably reflects the more distributed nature of highway or bridge construction, where work is distributed across large geographic areas, as opposed to being concentrated in vertical structures. The real-time monitoring and communication advantages of the digital platform can be most useful when various trades work in the same location, such as in high-rise construction as opposed to linear infrastructure where various trades typically work in series rather than parallel.

3.6 Unintended Consequences and Critical Perspectives

Although quantitative analysis showed definite safety advantages of comprehensive digital governance, the qualitative study revealed a number of unintended consequences and tensions, which deserve scholarly attention and practical consideration. Firstly, the digital platforms at times caused false confidence that ultimately resulted in the reduction of human vigilance. Some participants reported cases in which workers or supervisors were too reliant on automated alerts that they may end up missing hazards that were not detected by the sensor. One case is that of a worker entering a confined space when there was not enough ventilation, the worker entered after sensor readings indicated that there was enough air, but the worker did not actually verify the sensor reading. One of them, a safety director, commented: Technology must not substitute human judgment, but rather complement it. We must also beware of automation complacency that people cease to think because they believe that the system will get everything.

Secondly, the paper-trailing functions of computer systems disheartened open safety discussions. Some participants have also observed that the awareness that communications generated permanent records made some individuals more reticent in safety discussions, especially identifying systemic issues that might be a poor credit to themselves or their employers. One project manager explained: Before, should I find myself observing trends that I was worried about, I could have a no-holds-barred talk: Hey, I am seeing trends that I am concerned about. What's going on?' And now, when I record that, as an official proceeding, it exposes all to liability. Therefore, some problems are resolved with the help of winks and nods instead of open communication. This conflict of responsibility and psychological safety is a true dilemma that cannot be resolved easily.

Thirdly, the digital governance frameworks that could have concentrated power and information asymmetries would have favored the disadvantaged smaller subcontractors. General contractors had unprecedented visibility into the operations of subcontractors and subcontractors may often lack comparable insight into the decision-making of the general contractors. A number of subcontractors reported feeling that the digital systems were created more to enable surveillance and liability management as opposed to true safety enhancement. One subcontractor said: The general contractor can know everything we are doing in real time, get reports of everything we are doing everywhere in real time, document all the seconds of delay when we identify a hazard. But when we require information about the work of other trades, which may have an effect on our safety, or we have a desire to see the overall data of the safety performance of the general, all at once everything becomes proprietary. It's transparency for thee but not for me."

These issues are related to the body of scholarly literature on platform governance and managing digital labor, which highlights how technological systems tend to encode and reinforce existent power relations whilst appearing to be neutral (Srnicek, 2017). A critical analysis of whose interests the digital safety governance frameworks such as Safety Leadership and Accountability, Contractor Prequalification and Selection, Safety Policies and Standards, Risk Management and Hazard Control, Contractor Safety Orientation and Training, Monitoring, Auditing, and Inspections, Incident Reporting and Investigation, Communication and Coordination, Regulatory Compliance, Continuous Improvement, Permit-to-Work

Management, Contractor Management, Safety Performance Measurement and KPI Tracking, Corrective and Preventive Action Management, Documentation and Recordkeeping serve, how they spread risks and benefits among the stakeholders in the construction industry, and whether they allow meaningful worker voice or are merely sophisticated management control questions also remain a significant area of further investigation. We propose in our findings that digital governance might result in the realization of real safety benefits with concomitant emergence of new questions regarding workplace surveillance, data ownership and power imbalances that should be given sustained attention by researchers, practitioners, and policymakers.

Fourthly, there was some evidence that digital platforms may cause safety attention to shift towards more easily measurable risks at the expense of less quantifiable hazards. Sensors and tracking systems are good at identifying the physical conditions such as atmospheric concentrations, proximity to equipment, structural loads and are poor at identifying the psychosocial hazards of fatigue, stress, or inadequate training which contribute significantly to incidents. A safety consultant was concerned that the dynamics of what gets measured getting managed could cause organizations to over-invest in sensor-detectable hazards and under-invest in human factors: You can't IoT your way out of inadequate training or fatigue due to impossible schedules. I fear that all the dashboards with the environmental data make executives comfortable that safety is being controlled and they overlook the human factors that are the real cause of most incidents.

4.0 Conclusion

This study provides strong evidence that integrated digital safety governance frameworks—comprising Safety Leadership and Accountability, Contractor Prequalification and Selection, Safety Policies and Standards, Risk Management and Hazard Control, Contractor Safety Orientation and Training, Monitoring, Auditing, and Inspections, Incident Reporting and Investigation, Communication and Coordination, Regulatory Compliance, Continuous Improvement, Permit-to-Work Management, Contractor Management, Safety Performance Measurement and KPI Tracking, Corrective and Preventive Action Management, and Documentation and Recordkeeping—significantly improve safety outcomes in multi-employer construction projects, a context historically resistant to conventional safety interventions. Projects implementing fully integrated digital systems combining Building Information Modeling, Internet of Things sensing, mobile reporting platforms, blockchain-based documentation, and analytics dashboards achieved 43% lower Total Recordable Injury Rates and 67% fewer near-miss incidents than those using partial or traditional systems. These effects remained robust after controlling for project characteristics, contractor safety history, and temporal effects, indicating substantive—not spurious—associations. Notably, reductions were even more pronounced for lost-workday injuries, suggesting that digital governance is particularly effective in preventing high-severity incidents.

The findings indicate that these improvements arise through multiple mechanisms: faster hazard communication and corrective action, improved cross-organizational accountability, and continuous real-time monitoring that enables proactive risk identification. However, realizing these benefits requires strong organizational commitment. Implementation barriers—including interoperability challenges, limited workforce digital literacy, resistance to change, and concerns about surveillance—remain significant constraints.

Overall, the results suggest that well-designed digital ecosystems have substantial potential to reduce coordination failures in multi-employer construction environments. Future research should examine long-term impacts as systems mature, differential effects across workforce groups, and the implications of digital governance for power relations, privacy, and equity in construction work systems.

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